UNIVERSITY OF COPENHAGEN
FACULTY OF SCIENCE

# Whole-body Movement in Virtual Reality

## Creating Better Experiences through Walking and Maneuvering

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# Preface

When I visited my partner's family in New York a couple of years ago, we went to a virtual reality (VR) arcade. The first game we played was a zombie survival shooter, where an increasing number of zombies had to be shot before they reached their brainy snack. The game was played in a device that straps you in while standing on a concave, low-friction surface so you that can step but not physically move. Still, your steps are translated to actual movement in virtual reality. It is *supposed* to feel like normal walking, but it is a miserable experience: walking forward felt unnatural, sluggish, and uncontrollable. Walking backward, strafing, or ducking for cover was nearly impossible, let alone running away Jack Sparrow-style. Standing in the middle of a virtual square, with zombies pouring in from every direction, I imagined I'd fare better in a real zombie apocalypse.

Although this story took place after I started my Ph.D. research on movement in virtual reality, it nicely summarizes some of the frustrations I've encountered with virtual reality that ultimately form the red thread of this dissertation. Moving around in virtual reality is stupid, restrictive, and disappointing. Yet, I am thoroughly fascinated by how powerful of an experience it is, how much I believe in the virtual world, and how much I *want* it to work well.

Since 2020, I have conducted and published high-quality research to improve virtual experiences. I have spoken to the general public and experts about my work. I have learned, I have taught, and I have supervised students. In this dissertation, I present the research works and my thesis. Together, my contributions show that I have completed the PhD programme's objective to "… train students to conduct top-class, international-level research, and to take responsibility for research, development and teaching tasks in the private and public sectors, for which a broad knowledge of research is required."[1]

The structure of the dissertation is as follows: In the first part, I introduce the topic, problem, and thesis, together with the motivation for this work. I then discuss how my research contributes to the thesis, followed by a critical reflection and discussion of future perspectives. In the second part, the papers are appended, including the required co-author statements, for convenience.

I have learned and grown so much over the last three years, both as a person and an academic. For these experiences, midnight paper submissions included, I am eternally grateful. I hope that you find this work as interesting as I do.

Thomas van Gemert
20 November 2023, Copenhagen

[1]Faculty of Science PhD Rules and regulations, March 2023, p.3

# Acknowledgments

I am fortunate to have been supported by many wonderful people in these past three years. Without them, I would not be here, putting the final touches on my thesis. I would have run away screaming a long time ago. So, thank you. The effort you have put in to make my research—and truthfully, a significant part of my life—a success is extraordinary and is not taken for granted. A couple of people deserve to be named in particular:

My supervisor, Joanna Bergström. Working with you and learning from you has been such a pleasure. It has been truly inspiring to see your work, your ambition, your excellence as a person. I cannot stress enough how wonderful it was to have you unconditionally on my team. Thank you.

My partner, Melissa Eskin. I realize this Ph.D. journey has sometimes taken a toll on me, you, and us. Still, you have always been there for me. Your patience, love, and unwavering support are beyond anything I dreamed possible and so much appreciated. You are amazing. Thank you.

My co-authors: Kasper Hornbæk, Eduardo Velloso, Jarrod Knibbe, Teresa Hirzle, Niels Christian Nilsson, Sean Chew, Yiannis Kalaitzoglou, and of course Joanna Bergström. I have learned so much from you, and you have been essential in creating the excellent research in this thesis. In fact, without you, there would be no thesis at all, so thank you.

Several people I have worked closely with and helped me beyond the call of duty deserve a thanks: Kasper Hornbæk and Eduardo Velloso, for your incredible dedication and support and for giving me and my research a home in your research groups. Antti Oulasvirta, who showed me the light and without whose blatant disregard for my wishes I would not be here. An honourable mention goes to Valkyrie Savage, for giving me the unique opportunity to hit colleagues with sticks every week.[2]

And finally, the people in and around the Human-Centred Computing section who have not been mentioned yet. Amidst so many memes and stereotypes of how horrible pursuing a Ph.D. is you have made it quite enjoyable. Thank you, in no particular order, Jess McIntosh, Carlos Tejada, Andreea-Anamaria Muresan, Jonas Schjerlund, Tor-Salve Dalsgaard, Martin Maunsbach, Arpit Bhatia, Hasti Seifi, Teresa Hirzle, Irina Shklovski, Barry Brown, Sonja Rattay, Mirabelle Jones, Olga Larygina, Valeria Borsotti, and Sean Chew.

See you at the Nordic reception,
Thomas van Gemert

[2] `https://juggercph.com`

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# Abstract

Virtual reality (VR) is a technology that can immerse a user in a virtual world to the point where they feel like they are really there and the things they perceive are really happening. Key to this experience is the ability to move around and interact with the virtual world. In real life, everyday movements like walking or maneuvering are easy, ubiquitous, and often enjoyable. However, using such movements in virtual reality is tricky, restrictive, and frustrating. Designing good movement experiences in virtual reality is not trivial: It is not clear how we can study virtual experiences, how movement affects the experience, and what quality aspects are important.

This thesis presents five research papers addressing this problem by demonstrating new and improved ways to apply methods to study virtual reality experiences. This work focuses on walking and maneuvering as whole-body movement: It investigates how movement affects various essential quality characteristics of virtual reality experiences, from sense of presence to VR sickness.

"Towards a Bedder Future" studies virtual reality experiences while lying down using a think-aloud protocol and semi-structured interviews. The paper highlights the crucial role of maneuvering in virtual experiences and proposes lying-down VR as a promising new application area.

"How Your Physical Environment Affects Spatial Presence" presents two theory-driven lab experiments where users walk around boundaries and obstacles. The paper uses Bayesian modeling to explain how knowledge of, and collisions with, the real world can negatively affect spatial presence in the virtual world.

"Sicknificant Steps" is a systematic review and meta-analysis of VR sickness in walking-based locomotion techniques. The paper shows how different types of walking techniques are affected by VR sickness and discusses problems with VR sickness assessment.

"Step On It" leverages human-in-the-loop Bayesian optimization to design novel transfer functions for fast walking in VR. After applying the method in a user study, semi-structured interviews produced data on what qualities of walking matter to users.

"Doorways Do Not Always Cause Forgetting" investigates a phenomenon where crossing environmental boundaries can cause forgetting. Two lab experiments with a conceptual replication showed no evidence of adverse memory effects in VR due to variation in locomotion technique or boundary visualization.

In conclusion, the thesis provides methods to study how whole-body movement affects the virtual experience. By applying these methods, we gain a more complete and detailed understanding of the quality aspects of virtual reality experiences. These contributions enable us, as researchers and designers, to create better virtual experiences for the future.

# Dansk resumé

*Virtual reality* (VR) er en teknologi som kan få dets brugere til at fordybe sig i en virtuel verden i en sådan grad at de føler sig reelt tilstede og at de ting de opfatter, sker i virkeligheden. Nøglen til denne oplevelse er muligheden for at bevæge sig i og interagere med den virtuelle verden. I den virkelige verden er dagligdagens bevægelser som gang eller manøvrering nemme, allestedsnærværende, og ofte fornøjelige. Dog er disse bevægelser i den virtuelle verden vanskelig, restriktiv og frustrerende. Vi har brug for en redegørelse for, hvordan bevægelse påvirker kvaliteten af virtuelle oplevelser.

Denne afhandling præsenterer fem forskningsartikler, der behandler problemet ovenfor ved at demonstrere nye og forbedrede metoder til at undersøge VR-oplevelser. Dette arbejde fokuserer på gang og manøvrering som helkropsbevægelse: Det undersøger, hvordan bevægelse påvirker forskellige væsentlige karakteristika ved VR-oplevelser, fra følelse af nærvær til VR-svimmelhed.

"*Towards a Bedder Future*" undersøger VR-oplevelser, hvori brugerne ligger ned, ved hjælp af en *think-aloud* protokol og semistrukturerede interviews. Artiklen fremhæver manøvreringens afgørende rolle i virtuelle oplevelser og foreslår liggende VR som et lovende nyt anvendelsesområde.

"*How Your Physical Environment Affects Spatial Presence*" præsenterer to teoridrevne laboratorieeksperimenter, hvor brugere går rundt om grænser og forhindringer. Artiklen bruger bayesiansk modellering til at forklare, hvordan viden om og kollisioner med den virkelige verden kan påvirke den rumlige tilstedeværelse i den virtuelle verden negativt.

"*Sicknificant Steps*" er en systematisk gennemgang og meta-analyse af VR-svimmelhed i gangbaserede bevægelsesteknikker. Papiret viser, hvordan forskellige typer gangteknikker påvirkes af VR-svimmelhed og diskuterer problemer med VR-svimmelhedsvurdering.

"*Step On It*" udnytter *human-in-the-loop* bayesiansk optimering til at designe nye funktioner til hurtig gang i VR. Efter at have anvendt metoden i en brugerundersøgelse, producerede semistrukturerede interviews data om, hvilke kvaliteter ved gang betyder noget for brugerne.

"*Doorways Do Not Always Cause Forgetting*" undersøger et fænomen, hvor krydsning af miljøgrænser kan forårsage forglemmelse. To laboratorieeksperimenter med en konceptuel replikation viste ingen tegn på negative hukommelseseffekter i VR på grund af variation i bevægelsesteknik eller grænsevisualisering.

Afslutningsvis giver afhandlingen metoder til at studere hvordan hele kroppens bevægelse påvirker den virtuelle oplevelse. Ved at anvende disse metoder får vi en mere komplet og detaljeret forståelse af kvalitetsaspekterne af VR-oplevelser. Disse bidrag gør os som forskere og designere i stand til at skabe bedre virtuelle oplevelser for fremtiden.

# Publications

This chapter lists the five research papers that are included in the thesis. Two papers are peer-reviewed publications in the Springer Virtual Reality journal and the ACM CHI '23 conference. Two conference papers have been accepted for revision at CHI '24 and are in revision at the time of writing. One paper is a complete research paper that will be submitted after submission of this dissertation. One workshop contribution [289] was created and published during my Ph.D. studies, but is not included in the dissertation.

## Towards a Bedder Future

Thomas van Gemert, Kasper Hornbæk, Jarrod Knibbe, Joanna Bergström. **Towards a bedder future: a study of using virtual reality while lying down**. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems,* CHI '23, New Orleans, LA, USA, Article 877, 1–18. ACM, 2023. ISBN: 978-1-4503-9421-5.
DOI: 10.1145/3544548.3580963

**Abstract.** Most contemporary Virtual Reality (VR) experiences are made for standing users. However, when a user is lying down—either by choice or necessity—it is unclear how they can walk around, dodge obstacles, or grab distant objects. We rotate the virtual coordinate space to study the movement requirements and user experience of using VR while lying down. Fourteen experienced VR users engaged with various popular VR applications for 40 minutes in a study using a think-aloud protocol and semi-structured interviews. Thematic analysis of captured videos and interviews reveals that using VR while lying down is comfortable and usable and that the virtual perspective produces a potent illusion of standing up. However, commonplace movements in VR are surprisingly difficult when lying down, and using alternative interactions is fatiguing and hampers performance. To conclude, we discuss design opportunities to tackle the most significant challenges and to create new experiences.

## How your Physical Environment Affects Spatial Presence

Thomas van Gemert, Jarrod Knibbe, Eduardo Velloso. **How your Physical Environment Affects Spatial Presence in Virtual Reality**. *Manuscript*, 2023.

**Abstract.** Virtual reality (VR) is often used in small physical spaces, requiring users to remain aware of their environment to avoid injury or damage. However, this can reduce their spatial presence in VR. Previous work and theory lack an account of how the physical environment (PE) affects spatial presence. To address this gap, we investigated the effect on spatial presence of (1) the degree of spatial knowledge of the PE and (2) knowledge of and (3) collision with obstacles in the PE. Our findings suggest that limiting spatial knowledge of the PE increases spatial presence initially but amplifies the detrimental effect of obstacle collisions. Repeatedly avoiding obstacles further decreases spatial presence, but removing them from the user's path yields a partial recovery. Our work contributes empirical evidence to theories of spatial presence formation and highlights the need to consider the physical environment when designing for presence in VR.

## Sicknificant Steps

Thomas van Gemert, Niels Christian Nilsson, Teresa Hirzle, Joanna Bergström. **Sicknificant Steps: A Systematic Review and Meta-analysis of VR Sickness in Walking-based Locomotion for Virtual Reality**. In revision at the *ACM 2024 CHI Conference on Human Factors in Computing Systems*.

**Abstract.** Walking-based locomotion techniques in virtual reality (VR) can use redirection to enable walking in a virtual environment larger than the physical one. This results in a mismatch between the perceived virtual and physical movement, which is known to cause VR sickness. However, it is unclear if different types of walking techniques (e.g., resetting, reorientation, or self-overlapping spaces) affect VR sickness differently. To address this, we conducted a systematic review and meta-analysis of 96 papers published in 2016–2022 that measure VR sickness in walking-based locomotion. We find different VR sickness effects between types of redirection and between normal walking and redirection. However, we also identified several problems with the use and reporting of VR sickness measures. We discuss the challenges in understanding VR sickness differences between walking techniques and present guidelines for measuring VR sickness in locomotion studies.

## Step On It

Thomas van Gemert, Kasper Hornbæk, Joanna Bergström. **Step On It: Asymmetric Gain Functions Improve Starting and Stopping in Virtual Reality Walking**. In *Virtual Reality*, volume 27, 777–795. Springer-Verlag, London, UK, 2023. ISSN: 1434-9957. DOI: 10.1007/s10055-022-00692-w.

**Abstract.** Transfer functions with a high translational gain can increase the range of walking in virtual reality. These functions determine how much virtual movements are amplified compared to the corresponding physical movements. However, it is unclear how the design of these functions influences the user's gait and experience when walking with high gain values. In a mixed-methods study with 20 users, we find that their best transfer functions are nonlinear and asymmetrical for starting and stopping. We use an optimization approach to determine individually optimized functions that are significantly better than a common approach of using a constant gain. Based on interviews, we also discuss what qualities of walking matter to users and how these vary across different functions. Our work shows that it is possible to create high-gain walking techniques that offer dramatically increased range of motion and speed but still feel like normal walking.

## Doorways Do Not Always Cause Forgetting

Thomas van Gemert, Sean Chew, Yiannis Kalaitzoglou, Joanna Bergström. **Doorways Do Not Always Cause Forgetting: Studying the Effect of Locomotion Technique and Doorway Visualization in Virtual Reality**. In revision at the *ACM 2024 CHI Conference on Human Factors in Computing Systems*.

**Abstract.** The "doorway effect" predicts that crossing an environmental boundary affects memory negatively. In virtual reality (VR), we can design the crossing and the appearance of such boundaries in non-realistic ways. However, it is unclear whether locomotion techniques like teleportation, which avoid crossing the boundary altogether, still induce the effect. Furthermore, it is unclear how different appearances of a doorway act as a boundary and thus induce the effect. To address these questions, we conducted two lab studies. First, we conceptually replicated prior doorway effect studies in VR using natural walking and teleportation. Second, we investigated the effect of five doorway visualizations, ranging from doors to portals. The results show no difference in object recognition performance due to the presence of a doorway, locomotion technique, or doorway visualization. We discuss the implications of these findings on the role of boundaries in event-based memory and the design of boundary interactions in VR.

# Contents

# Part I

# About My Research

# 1 Introduction

People love to move. Even if we do not *love* it, we move a lot regardless: maneuvering around the house, walking, running, commuting, doing fitness, playing sports, hiking, sailing, and so much more. Everyday movement is rich, dynamic, and generally effortless. In particular, walking (e.g., from your office to the cupboard in the kitchen) and maneuvering (e.g., by squatting down and reaching into the back of the cupboard to grab the kettle) are some of our most basic and intuitive forms of movement that are suitable for most environments. However, despite advances in hardware, software, and interaction design, whole-body movement in virtual reality is still a far cry from the ease, ubiquity, and pleasure of moving in real life. A new approach is needed to address this, one that studies the virtual *experience*.

Providing better ways to move around in virtual reality is an area of active investigation in research. However, typical contributions do not improve our understanding of a user's overall experience when moving in virtual reality: Faster travel, more accurate aiming, or less noticeable redirection—although useful improvements—do not tell us what quality aspects of a virtual experience are important, how they are affected by the proposed solution, or how we can design and evaluate good virtual experiences. In other words, the field lacks an account of virtual experiences beyond walking from A to B: the experience of movement in virtual reality.

In this thesis, I argue that we can and should investigate the experience of moving in virtual reality (VR). In doing so, I present five research papers that improve our understanding of movement in VR experiences and how to study those. Driven by my own frustrations and curiosities in VR, each paper takes a different perspective on how whole-body movement could affect the virtual experience: The study and analysis methods comprise a think-aloud protocol, semi-structured interviews, thematic analysis, Bayesian statistical modeling, lab experiments using questionnaires and sensor data, Bayesian human-in-the-loop optimization, affinity diagramming, frequentist inferential statistics, systematic review, meta-analysis, and object recognition probes. All papers share a human-centered approach and address an established problem in human-computer interaction. In particular, they address the following quality aspects of virtual experiences: user experience of using virtual reality, spatial presence, VR sickness in walking techniques, perceived usability of walking, subjective qualities of walking, and memory retrieval performance after walking through boundaries. Finally, the thesis provides a higher-level perspective on the problem-solving capacity of the papers, their position within human-computer interaction, and future directions for virtual reality research and design.

In the following sections, I will further motivate the need for research into the combination of whole-body movement and virtual reality experiences. I assume the reader has at least used modern virtual reality technology once. If you, the reader, are less familiar with this technology, do yourself a favor: find a friend, colleague, or VR arcade and give it a go! It will show you beyond 1000 words, images, or even videos why I and thousands of other researchers are so excited about this technology.

## 1.1 Movement in Virtual Reality

Movement enables active perception through interaction: "In order to perceive [virtual reality], it is necessary to act—to move and position the body, head, eyes, ears, nose, and end-effectors in active perception" [250]. The power of virtual reality is that it allows people to experience things, places, or events that are impossible or difficult to create in real life. Critically, the user often can and should play an active role in this experience: have a virtual body, interact with the virtual world, and truly believe they are there and that what they perceive is really happening. Interactivity and presence are critical elements of the VR experience where movement plays a crucial role [241].

When talking about movement, I am primarily talking about whole-body movements such as those used for travel. For clarity's sake, I define these terms as follows, following LaViola et al. [130] and Sherman and Craig [241]:

**Definition 1.1** (Navigation)**.** How we move from place to place, which in itself consists of way-finding and travel.

**Definition 1.2** (Way-finding)**.** The process of determining where we are and where we are going. The "cognitive component" of navigation.

**Definition 1.3** (Travel)**.** The physical (or virtual) process of moving from one location to another. The "motor component" of navigation.

Travel in virtual reality faces several challenges that should be addressed to create better virtual experiences. By improving our understanding of how travel and maneuvering (see below) affect the virtual experience, we can enable future research and design to tackle these challenges.

walking is the most basic and intuitive form of locomotion, allowing for effective exploration of most environments [261]. However, we cannot travel in virtual reality like in real life: The physical space is typically much smaller than the virtual space. When naively using body-based movement in virtual reality, the interaction space is restricted to the physical space. Locomotion techniques have been developed to circumvent this problem. However, they often come with significant downsides compared to real walking, for example: VR sickness [38, 230, 177, 231], limited spatial updating [124, 217, 225, 122, 195]), or lower presence [231, 319, 124, 287].

Exactly mimicking real-life movement is often less desirable and leaves much of the power of VR on the table. A recent paper by Cmentowski et al. [44] provides a nice example of this phenomenon: The authors developed locomotion techniques for *sneaking*. In their evaluation, they found that users preferred the less realistic variants because actual sneaking is effortful and difficult: Users did not want to sneak as realistically as possible; they just wanted to *feel* like they were sneaking. So, despite the benefits of body-based movement in real life, applying this to virtual reality is a non-trivial problem.

Whole-body movement also comprises *maneuvering*. For this thesis, I define maneuvering as follows, inspired by LaViola et al. [130] and Sherman and Craig [241]'s description:

**Definition 1.4** (Maneuvering)**.** Maneuvering is a series of small, precise movements in a local spatial reference frame typically used to reposition the viewpoint or alter the body's pose. Maneuvering can be done both during and outside of travel.

Although maneuvering is often overlooked in VR research and design, this type of movement can easily cause frustration and cost precious time when not properly supported [130]. Maneuvering is a ubiquitous and essential aspect of real-life interaction, such as reaching to grab something, leaning, or ducking. Maneuvering is often combined with travel, for example: turning one's torso while walking, positioning one's sword and shield while charging at an enemy, or moving across a sailboat while sailing. Walking as a locomotion technique supports maneuvering particularly well compared to others: If you teleport around a corner, you lose the ability to first lean around the corner to see if the way is safe.

At a higher level, the field of human-computer interaction agrees that movement in virtual reality is a significant problem. Several leading researchers have proposed "Grand Challenges in HCI" that relate to this: Stephanidis et al. [264] propose "human-environment interaction" as one of seven grand challenges, where "VR sickness" and "lack of realistic simulation of locomotion" are two (movement-related) problems to overcome in virtual reality. Slater [250] stresses the need for natural sensorimotor interaction to enable presence in virtual environments. Finally, Shneiderman et al. [245] argue for the need to design novel input and output devices, including those based on body movement.

In conclusion, more work is needed to understand how we should use whole-body movement in virtual reality. That is, indeed, the goal of this thesis: To improve our understanding of how we can leverage walking- and maneuvering-based movement to create better virtual experiences.

## 1.2 Experiences in Virtual Reality

As a technology, virtual reality (VR) is unique: it is exceptionally immersive, interaction is largely body-based and takes place in three-dimensional spaces, and it creates a strong sense of truly "being there" in the virtual world. This entails that standard HCI methods and measures do not necessarily apply. To understand how people use virtual reality, how we can address the main challenges, and to ultimately create better experiences with virtual reality technology, new methods and evaluation paradigms are needed.

These methods should focus on new ways to evaluate virtual reality use: Stephanidis et al. [264] call for the merging of objective and subjective evaluations of the user experience of virtual reality. Gaggioli [69] and Slater [250] point out the need to investigate ecologically valid interactions, which requires evaluation beyond performance-based evaluation of the user experience. This is not to say that constructive improvements or performance and usability evaluations are unimportant. However, as Sherman and Craig [241] point out, virtual reality appears to be at a turning point where many of the previous, pragmatic limitations have been resolved. This opens up the opportunity to shift our focus to a broader view of virtual reality experiences that focuses on subjective qualities.

This shift can also be observed in user experience research in general: experiential qualities of technology use are being increasingly prioritized over product qualities [83, 82, 164, 103]. Experiential qualities relate to emotion and affect, which are inseparable from experience [83, 157]. When thinking of technology use as experiences, the product is only of interest where it is crucial for facilitating the experience. In virtual reality and for the purposes of this thesis, we do not care about virtual reality as a product at all; all we care about are the user's thoughts, feelings, and actions *in the virtual environment*: their experience. This means that interaction techniques are only of interest inasmuch as they affect the overall experience.

There is an intuitive appeal to this view specifically for virtual reality: In a way, the experience ideally takes place *within* the technology, instead of *with* the technology. At some future point, we could imagine that user experience and usability evaluation would apply to the use of a *virtual* juicer instead of the interaction technique used to select the object or physical controller needed to control the selection. To get to this point, however, more work is needed to understand how interactions affect the virtual experience of doing something in the virtual environment. In this thesis, that interaction is based on whole-body movement, the doing is maneuvering or traveling, and the virtual experience is relates to the activity as a whole.

However, it is not clear how such interactions affect the various quality aspects of the virtual experience. Interaction techniques that enable us to move in the virtual environment can subtly or directly affect the experience in countless ways. Experiences are subjective, but Oulasvirta and Hornbæk [191] argue that "addressing subjective qualities in computer use is a requirement for any serious theory of HCI." But, objective measures related to performance and functionality often come first and foremost. Virtual reality experiences comprise many quality characteristics that can and should be evaluated [37]. Although we lack an agreed-upon set of the most important quality aspects, several are generally accepted as necessary for good virtual experiences: (Spatial) presence is essential, as is avoiding VR sickness. Standardized questionnaires for important subjective qualities—such as presence, VR sickness, or embodiment—are more common now in virtual reality research. But, they measure only a singular aspect of the experience. Furthermore, they have often been appropriated from other application areas and their validity in VR is debated (e.g., the use of the SSQ to measure VR sickness [91, 15, 240, 289, 292]). Finally, better evaluation of virtual experiences presents an opportunity to produce new guidelines and practices for the design of virtual reality environments [264]. In sum, there is a need for methods to study virtual experiences more broadly and comprehensively, focusing on hedonic and eudaimonic qualities.

# 2 Studying Virtual Experiences

The papers in this thesis address several well-known quality aspects of virtual experiences, such as spatial presence and VR sickness, as well as some unknown ones, such as memory retrieval performance. The thesis does not attempt or pretend to cover the whole spectrum of factors related to virtual experiences. Rather, it presents *methods to study virtual experiences*. These methods can be applied beyond the individual papers to shed new light on well-known quality aspects as well as uncover previously overlooked factors. By presenting and applying these methods, each paper in turn provides an improvement in our ability to leverage whole-body movement to create good virtual experiences.

Oulasvirta and Hornbæk [191] propose to view HCI research as problem solving. In this view, scientific progress is measured in terms of how much a solution proposed by the research increases our problem-solving capacity. The quality of a solution can be evaluated by examining this increase according to five heuristics: *Significance*, *Effectiveness*, *Efficiency*, *Transfer*, and *Confidence* [191]. This thesis presents an empirical problem (unknown phenomena, factors, or effects) of how whole-body movement affects virtual experiences. The five included papers propose solutions primarily in the form of methods to study the virtual experience in the context of whole-body movement. The papers provide a secondary solution in the form of empirical data generated by applying the method in lab experiments.

*Significance* refers to the importance of the problem to its stakeholders [191]. The significance of the overall thesis problem was discussed in chapter 1, so the current chapter focuses on the significance of the problem(s) directly addressed by the papers. In addition, I discuss the *Implications* of the proposed solution according to Berkel and Hornbæk [11]. Explicit implications support readers to identify takeaways, clarify the relationship between methods, data and implications, and broaden the potential applicability beyond the paper's context [11]. Significance of the problem can before the research is conducted, while implications follow directly from the results of the research. Both require critical reflection on the research and together they provide a complete view of its importance.

*Effectiveness* refers to whether the solution addresses the essential aspects of the problem [191]. In this case, we discuss both whether the paper effectively addresses the problem in the paper (e.g., unknown phenomena when using VR lying down [293]) and the problem in the thesis (e.g., unknown factors in how whole-body movement affects virtual experiences). *Efficiency* relates to the ratio of the cost of applying the solution to the gains achieved [191]. The "gain" is a combination of the significance, effectiveness, and confidence of a solution. The cost is mainly pragmatic, and thus this is a question of whether other methods could have achieved a comparable result at lower cost.

*Transfer* relates to how the solution transfers to related problems and other contexts for the same problem. In this case, that primarily relates to the methods but in some work, such as the proposed challenges and guidelines in "Towards a Bedder Future," the question of how the results apply in other contexts is also relevant. *Confidence* relates to how confident a reader can be that the solution holds [191]. This is mainly a question of reliability and validity, and it is discussed as such in this chapter. Both Transfer and Confidence are important heuristics to understand how well a solution generalizes to other contexts. This is important in this work, because it allows the proposed methods to study how whole-body movement affects virtual experience in different contexts, thus increasing our capacity to solve the problem beyond this thesis.

In this chapter, I critically discuss each paper's proposed solution at a high level. First, I present the problem(s) and how the paper addressed those. Then, I evaluate how the solution increases the problem-solving capacity in terms of the five quality heuristics. The problem-solving capacity relates to two levels: the paper's own research problem(s), and the thesis problem as laid out in chapter 1. Given the relevance between each paper's problems and the overall thesis problem, a high-quality solution at the paper level naturally comprises a high-quality contribution to the thesis problem.

The discussion below aims to avoid needless repetition, so most of the implementation details, results, and discussion items are left in the papers themselves. Although the following sections are intended to be largely comprehensible without the paper, I recommend reading the paper first to provide additional context.

## 2.1 Towards a Bedder Future

Most contemporary Virtual Reality (VR) experiences are made for standing users, with the idea that they can interact with the environment or even travel by walking and maneuvering in a room-scale space [293]. However, there are several reasons why a user would want to use VR while lying down: Not in the least because they may be bed-bound in research, therapy, or chronic illness, but also purely for comfort—the same way we may lie on the couch to watch TV. However, it is not clear what the movement requirements and user experiences are of using VR while lying down. This chapter discusses how the paper "Towards a Bedder Future" [293] addresses this problem. The paper can be found in this dissertation in chapter 6.

The paper considers a broad, open-ended research question that presents an empirical problem of unknown phenomena. In this way, it is close to the problem in this thesis. To address the problem, we used a relaxed think-aloud protocol (RTA) during VR use and semi-structured interviews afterward. We used these methods to measure the experience *in-situ* and reflect on the hedonic and pragmatic quality aspects. We applied these methods in a lab experiment where fourteen participants used popular VR applications for 45 minutes while lying in bed. The data was collected through audio and video recordings, which were transcribed and coded in a thematic analysis framework.

**Significance.** The problem is significant for (future) users of lying-down VR: the XR accessibility guidelines call for a comparable experience in non-standing poses, including lying down [104]. Similarly, the idea for this study was inspired by some chronically bed-bound Reddit users questioning how to use VR lying down. There was no solution back then, and the paper suggests that providing a comparable experience remains challenging. One of the main findings was that the ability to maneuver—which is presumed for standing users—is poorly supported by the interaction techniques of contemporary VR systems. To compensate, the users in our study came up with different physical movements and alternative interactions, which can be strenuous and challenging to use. Although the study comprised healthy participants, the key findings also translate to bed-bound users. The paper comprises a starting point for designing lying-down experiences and the required interaction techniques for future implementations.

The problem is also significant for researchers and practitioners, who may want to enable VR users to interact better while lying down. In that case we need to ensure that using VR while lying down is usable and does not introduce additional confounding effects. The study additionally found that using VR while lying down can be comfortable and enjoyable and may help prevent VR sickness. Furthermore, the illusion of standing up in the virtual world was surprisingly robust, raising new questions about embodiment. However, several challenges remain, which are outlined in the paper as concrete directions for future research and design.

**Implications.** The methods used in this study lead to implications for methodology: entirely qualitative studies are uncommon in VR research, yet this paper demonstrates that important and novel insights about VR experiences can be generated using these methods. Other researchers can use this as a guide to study experiences in other contexts, and the methods align well with the thesis' goal to provide broad and subjective evaluations of virtual experiences. The results from the study have implications for design and future research: The system used and the guidelines provided are immediately applicable in practice. Designers can leverage the presented knowledge and guidelines to design their own lying-down VR experiences. Alternatively, researchers and designers can use the overview of the outstanding challenges to create better lying-down experiences in future applications and studies.

**Effectiveness.** The paper effectively addresses its problem by providing a comprehensive overview of how users move and want to move when using VR while lying down. The careful selection of applications with different movement requirements ensures that these results can be generalized to various contemporary VR applications. The combination of in-VR think-aloud and semi-structured interviews provided a balanced account of the spontaneous, *in-situ* experience and a user-centered higher-level reflection on the quality of experience. In terms of practical applicability, the study demonstrates that using VR while lying down is, to a large degree, possible and a positive experience, and the VR system used is readily available. However, movement-rich experiences still present a significant challenge. The paper provides concrete directions to resolve this in future research and design. Several surprising and unexpected results further support the effectiveness of these methods in providing a broad measurement of virtual experiences. For example, we found participants interacting in new ways (e.g., P4 appropriating other interaction techniques to accomplish a task), and we found the illusion of standing up to be surprisingly robust despite the bed.

This paper is also particularly effective in addressing the thesis problem: the methods used provided insights about a broad range of virtual experience qualities, from comfort and VR sickness to enjoyment and embodiment. Although no physical walking was involved, all applications involved some degree of maneuvering, which turned out to be a central theme in the study.

**Efficiency.** The study aimed to be comprehensive and provide a broad baseline for future research. This led to the use of methods, data analysis, and a lab experiment design that are relatively time-consuming. Special care was taken to ensure the rigor of the experiment and data analysis methods, adding to the overall cost. However, the gains achieved in increased problem-solving capacity are significant, as discussed above. Other methods that are less expensive to apply, such as questionnaires about particular effects or performance measures in the applications, would have left out the broader context and phenomena explanations that were needed to establish the baseline in this relatively novel topic. In sum, the solutions in the paper are efficient.

**Transfer.** The relaxed think-aloud and semi-structured interview methods used in this study are well-known and well-documented in the paper and the literature. The methods transfer well to problems where individual experiences, unknown phenomena, or lack of standard measures are important considerations. The methods are effective ways to investigate virtual experiences. Either method can be applied to similar tasks in a different context (i.e., other poses) or more specific tasks to illuminate the factors in a particular phenomenon (e.g., how to control an airplane while lying down). The results and guidelines from the study are less transferable: Although they generalize to other surfaces for lying down and other contexts with restricted physical movement, they relate to a niche application area of virtual reality.

**Confidence.** Since this is a qualitative study, special care was taken to report the procedures in detail to ensure reproducible science. The methods were applied rigorously, and additional data and materials are provided with the paper. Fellow researchers should be able to replicate the study with similar users and find results that largely agree with ours despite the subjective nature of the experiences and the thematic analysis. There is a potential threat in whether other researchers would arrive at the same themes when replicating the study: Although I am confident they would find conceptually similar results, constructing themes is a highly subjective procedure. Augmenting these analysis procedures with objective methods (e.g., NLP-based analysis) to improve this may be possible.

The external validity is good due to a diverse selection of applications and participants and diverse outcomes. Some results and guidelines transfer less well to other non-vertical poses, but it is a mixed bag. For example, the challenges in head rotation may be diminished when slouching on the couch, but the novel insights about embodiment also apply to standing use. A particular limitation of this study was that it only employed healthy participants despite the original motivation relating to bed-bound users. This was necessary to conduct a controlled study with a reasonable scope, but more work is needed to study the use of VR while lying down in treatment and therapy settings. In one way, the higher-level findings, such as the challenges of interacting through movement, should apply the same or be exacerbated: bed-bound users may be less able to use alternative (physical) interactions to circumvent the limitations in maneuvering. Otherwise, our findings related to subjective experiences such as comfort, enjoyment, VR sickness, or even embodiment may vary greatly depending on the user.

Concerning the internal validity, there is a trade-off between broadly studying the experience and drawing conclusions about which factors influenced this experience. The study comprises a balancing act between providing each participant with a similar condition and ensuring their freedom to create their own experience. For one, we especially selected experienced participants to ensure that their experience would be affected by *lying down* in VR, not problems with the VR system in general. On the other hand, although we argued earlier in this thesis about the importance of presence to virtual experiences, it is unclear how the think-aloud method affected the sense of presence. Future work is needed to quantify this. However, overall, the internal validity represents an acceptable trade-off between a broad, rich overview of the experience and a controlled experiment from which conclusions can be drawn.

## 2.2 How your Physical Environment Affects Spatial Presence

When using whole-body movement in virtual reality (VR), the user may want to be aware of the boundaries of the physical space. For example, being aware that there is a TV in your real space will hopefully prevent you from charging through it towards the virtual enemy. Typically, VR systems visualize these boundaries in VR using "chaperone systems." However, when these are not visible (during regular use or when the system does not respond in time), it is unclear how user's awareness of their physical environment can affect spatial presence. Conversely, if the user is not aware of their physical boundaries, they may collide with the environment, affecting spatial presence. Previous work and theories lack an account of the role of the physical environment in the formation (and thus destruction) of spatial presence. This section discusses how the paper "How Your Physical Environment Affects Spatial Presence in Virtual Reality" addresses this problem. The paper can be found in this dissertation in chapter 7.

The problem is partly empirical (unknown effects) and partly conceptual (implausibility in theory). We formulated five research questions based on Wirth et al. [311] 's theory of spatial presence formation and our intuitions. To address these questions, we set up two lab experiments that vary what a participant knows about their physical environment and whether there is an obstacle present in the physical environment. In the first experiment, we measured spatial presence initially, before interaction with the physical environment, and finally, after participants had potentially encountered the obstacle. Additionally, we conducted a brief semi-structured interview afterward to inquire about the participants' experiences, and we video-recorded their behavior in the physical environment. This allowed us to quantify the effect of knowledge of the physical environment on spatial presence when entering VR and the effect of obstacle collisions on spatial presence and their interaction. We conducted a second lab experiment to further our understanding of how spatial presence changes over time with respect to collisions. In the second experiment, we measured spatial presence before collision, immediately after, after repeatedly avoiding the obstacle, and after returning to a "safe" path.

**Significance.** Spatial presence is the subjective sense that your self-location is in the virtual environment, and your potential actions are informed by the virtual environment instead of the real world. It is a key aspect of virtual experiences, and researchers, designers, and users generally want spatial presence to be high [251, 80, 249]. Typically, virtual reality research has considered the “virtual side” of the spatial presence equation: how improvements in hardware, software, and interaction technique design can improve presence. Little attention has been given to how the user’s context, including their personality and physical environment, can influence spatial presence. Presence theories, too, mention the role of the physical environment only to a limited degree. In sum, we need an account of how the physical environment affects the formation and destruction of spatial presence to create robust virtual experiences with high spatial presence in various real-world contexts.

**Implications.** The paper addresses this gap through three main findings: First, mere knowledge of the obstacle before entering virtual reality does not help participants avoid the obstacle nor does it affect spatial presence. However, entering VR without knowledge of the physical environment (i.e., entering the lab room “blindfolded”) significantly increases spatial presence. Second, collision with the obstacle leads, as expected, to a drop in spatial presence. However, repeatedly having to avoid the obstacle (likely by repeatedly attending to and navigating in the physical instead of the virtual environment) lowers spatial presence even further. Third, the paper identified a new phenomenon in that spatial presence does recover when returning to a “safe” path, but not to the initial level. This provides an exciting direction for future work to investigate how to recover spatial presence after it breaks. The results provide implications for theory by filling in gaps and providing additional evidence that spatial presence is a binary experience.

To analyze the data, we used a Bayesian modeling approach to quantify the effects in the study and model them according to a hypothesized causal model. In this case, the Bayesian model provided several advantages, including a measure of uncertainty for each modeled effect. Furthermore, it is relatively easy to model ordinal outcome variables (e.g., the Spatial Presence Experience Scale) standard in HCI research (i.e., questionnaires). The model provides a measure of the evidence strength for a particular outcome, which is more informative and accessible to interpret, resulting in a more credible analysis. Furthermore, Bayesian models can easily be re-used in future work (e.g., as priors). Finally, the study methods conceptually relied on breaking spatial presence to study its effects instead of the more common approach to compare two implementations on an increase in spatial presence. This method is commonly used to study some virtual reality aspects such as embodiment but not yet presence: the paper shows that it can be successfully applied. In conclusion, the data analysis method and study design provide implications for methodology.

**Effectiveness.** Earlier in this section and at the beginning of the paper, I argued that there are two ways in which the physical environment is likely to affect spatial presence. The first study in the paper effectively addresses both by operationalizing each as an independent variable. Measuring spatial presence is challenging: Currently the only way is to use questionnaires. A strong point of this work is that we employed the state-of-the-art Spatial Presence Experience Scale, whose spatial presence construct comprises the exact dimensions of the theory we build on. The second study goes beyond the initial problem statement to better understand how spatial presence changes over time and can recover, thus more effectively addressing the formation of spatial presence. In the first study, we additionally conducted a semi-structured interview afterward and deductively coded the video-recorded participant movement to better illustrate the modeled spatial presence effects. This enabled us to show the hypothesized effects and explain *why* we observed these effects and their variance. Spatial presence is a highly subjective experience that can be difficult to capture. The current mixed-methods approach effectively provides a broader context and better answers the research questions. By investigating foundational questions of spatial presence formation in the context of whole-body movement, the paper effectively addresses the thesis problem.

**Efficiency.** User studies such as these, with a singular quantitative measure, are relatively inexpensive to apply and can lead to valuable insights. In one study, we added a brief qualitative evaluation that reduced the efficiency: although it provided additional context, it was ultimately less relevant than expected. The particular requirements of our conditions also limited the efficiency: User studies in VR are hard to control, especially when the task is not entirely restricted, and the variable of interest is a subjective experience. Special care was taken to ensure that the spatial presence measurement was not confounded by knowledge of previous conditions or awareness of the physical environment. Instead of a more efficient within-subjects study, we combined the two independent variables in a mixed design. The second study was more straightforward, had fewer conditions, and re-used existing materials, resulting in a higher efficiency. Bayesian modeling is a relatively easy and inexpensive data analysis method, although it may be unfamiliar to some and thus incur a higher upfront cost. This is offset by the additional information in the results and the ability to build upon our results easily.

**Transfer.** Lab experiments such as these are standard in HCI, as is questionnaire-based assessment of spatial presence. We presented the questionnaire in VR: This in-the-moment measurement was necessary to measure spatial presence without distracting from the virtual environment (and thus possibly breaking presence), but it may not apply to other questionnaires. Furthermore, in the context of evaluating the qualities of the virtual experience, the methods in the paper work well for a well-defined construct with a standard point measure, such as spatial presence. They would transfer less well to exploring different qualities of evaluating more hedonic qualities without standard measures. The knowledge generated by the two studies is relatively agnostic to the particular physical environment and obstacle used and thus transfers well to neighboring problems or other instances. Furthermore, the work is framed within Wirth et al. [311] 's process model of spatial presence formation, further supporting the transfer of higher-level insights.

**Confidence.** The methods are described in detail, and data and data analysis source code are provided in the paper. The paper discusses several potential limitations but ultimately concludes that their impact was minimal. For example, although we suspected a potential effect of condition order and number of collisions, including this data in the model did not change the results. One potential limitation could not be addressed: the quality of the participant's spatial situation model was unclear, as we did not measure or directly manipulate it. This could potentially affect the outcomes, and creating a stronger SSM can support a more ecologically valid scenario. Although there are no standard ways to measure or control a user's spatial situation model, future work could further explore its impact on spatial presence.

The questionnaire was implemented in virtual reality to avoid breaks-in-presence due to filling out the questionnaire. Although the effect of in-VR questionnaires on presence is unclear, special care was taken to not distract from the virtual environment. The participant had to use the controller to move the slider and press the submit button on the questionnaire. Before the study, all participants had to practice filling out the questionnaire in VR to ensure minimal impact on their responses. Regardless, the measurement was the same in every condition: any effects would have equally affected each condition.

An interesting phenomenon that we observed in the qualitative analysis was that experienced users appeared to have a different level of awareness of their physical environment than our (majority) novice participants. We did not observe related effects on spatial presence, nor could we follow up due to an imbalanced participant sample in terms of VR experience. Although this means that the findings may differ for experienced users, I believe the impact on the study results is minimal since the experienced users' results were consistent with the novices'.

As with any user study where the primary measure is subjective, internal validity has several potential threats. Overall, the experiments in this paper were strictly controlled, but as discussed above, we had to allow for some participant-level variation. Two potential threats showed up in the qualitative analysis: Some participants were bothered by the virtual environment or the interaction with the application (i.e., they did not think the quality of the "game" was very high). Apart from slightly hurting my feelings, this may have changed their involvement, attention, or baseline spatial presence level in the virtual environment compared to others. This was a minority group, and with 40 participants in the study, I believe these effects are negligible. Still, it is worth considering how participant expectations and perceived realism affect presence studies in VR. Standardized interaction and training protocols for virtual reality studies can also help avoid such discrepancies. Second, we observed a significant amount of variance in the effect of collision with the obstacle that any measurements in our data could not explain. There appear to be differences in how participants cope with an unexpected collision in virtual reality. Future work should further investigate this.

## 2.3 Sicknificant Steps

Preventing VR sickness is essential in creating good virtual reality (VR) experiences. However, a problem in understanding how whole-body movement affects VR sickness is that locomotion techniques are evaluated on VR sickness using a wide variety of study designs, methods, and reporting items. Therefore, it is difficult to disentangle the causes of VR sickness from each other and, as a consequence, to assess the VR sickness effects of different types of walking-based locomotion techniques. This section discusses how the paper “Sicknificant Steps” addresses this problem. The paper can be found in this dissertation in chapter 8.

The paper considers an empirical problem of unknown factors: how do different walking-based locomotion techniques that can use vastly different types of movement manipulation cause VR sickness? To a lesser extent, the problems also concern unknown effects, as papers with similar techniques often report different VR sickness measurements and reference values are missing. To address these problems, the paper conducts a systematic review and meta-analysis of 96 papers from 2016–2022 that use walking-based locomotion and report a measure of VR sickness. To compare types of walking techniques, we group the techniques based on redirection type in a taxonomy based on Nilsson, Serafin, and Nordahl [184] ’s work. This also facilitates comparing distributions of VR sickness scores across study designs. The meta-analysis focused on the Simulator Sickness Questionnaire (SSQ) scores, the most common measure of VR sickness. Additionally, the paper provides data on alternative measures and qualitative results and discusses the observed (mis)use of the SSQ in detail.

**Significance.** Despite decades of VR sickness research, VR sickness remains a problem for many users, and its causes and primary influential factors are still poorly understood. Furthermore, some well-known hardware factors have been addressed with recent innovations, requiring a renewed focus on the role of interaction technique design and VR sickness evaluation. In particular, despite recent reviews of VR sickness and locomotion separately, an investigation into walking-based techniques is missing. The paper discusses how both normal and redirected walking will likely cause VR sickness. Previous work has questioned the suitability of the SSQ as a measure of VR sickness, yet it remains the most common measure. Few guidelines are available for properly using the SSQ, and the questionnaire and its score calculation are not intuitive (see [292, 15] for some examples). In sum, the combination of walking-based locomotion, VR sickness, and a critical evaluation of the use of the SSQ is timely and relevant and addresses a significant problem.

**Implications.** While conducting the systematic review and meta-analysis, we observed widespread inconsistencies in using and reporting the SSQ. We report on this, and its implications in detail in the paper by presenting guidelines for the use and reporting of VR sickness measures, and it discusses whether to use the SSQ as a pre-exposure measurement, the credibility of the “zero sickness” assumption, how to interpret SSQ scores, and more promising alternative methods. In doing so, the paper provides implications for methodology. The paper further provides combined effect sizes for normal walking and different types of redirected walking for which enough data was available: resetting, repositioning, reorientation, and scene manipulation. This offers implications for researchers and practitioners through the discussion of how to interpret SSQ scores and the reference values provided by the results: this enables them to make better decisions on what techniques to implement or compare.

**Effectiveness.** Through the systematic review, we better understand how the field has evaluated VR sickness in walking-based locomotion. From the meta-analysis, we better understand how walking-based techniques affect the virtual experience through VR sickness. The combination of the systematic review and meta-analysis methods is a classic and effective combination to identify relevant data and synthesize results rigorously. Although the singular focus on one quality aspect may be a limitation, VR sickness is a critical aspect, and a clear scope is needed in meta-analyses. The paper compensates partially by discussing and contrasting relevant qualitative results and data from alternative VR sickness measures. Although performing a meta-analysis on SSQ scores from varying study designs is challenging, the paper takes the opportunity to discuss the results in context and provide guidelines for future evaluations. In sum, the paper directly and effectively addresses how we evaluate the role of walking in virtual experiences regarding an essential quality aspect (VR sickness).

**Efficiency.** A more straightforward approach would have been conducting lab experiments with different representative walking-based locomotion techniques. However, using that strategy would have made it impossible to cover the breadth of configuration options or observe the commonplace challenges in VR sickness measurement within a reasonable scope. As an overview of the state-of-the-art, intended to encourage and support future research, the current methodology is more effective, and, due to a comparable cost, more efficient.

**Transfer.** Systematic review and meta-analysis are well-known methods that are broadly applied outside of HCI. Review papers are common in HCI, but systematic reviews, and, particularly, meta-analyses, are less so. This work demonstrates how to apply these methods successfully to an HCI problem. The results and discussion of the SSQ problems are largely agnostic to the use of walking-based locomotion and thus transfer to other problems where VR sickness is relevant.

**Confidence.** The methods are reported in detail using the PRISMA reporting items and data, additional material, and analysis code are provided: the reliability is high, and the study is reproducible. Coding the papers is subjective, but special care was taken to ensure and report inter-coder agreement and documentation of the codes. Finally, the paper carefully argues and reports the procedure, exclusion criteria, and data on secondary codes. The inclusion of a wide variety of study designs improves the external validity. In terms of internal validity, however, there is a question of whether the meta-analysis produced a valid combined effect size from the papers in each group. This is questionable, as indicated by the high heterogeneity across the board. As discussed, this is less a problem of the paper and its methodology and more so a problem of the included studies. More complex models may provide better results by further separating factors, but this may not be worth the effort: high-quality evaluations of prototypical techniques will be more reliable and informative. Regardless, the paper improves credibility by discussing consistent results in related work and provides guidelines to improve the validity of VR studies.

## 2.4 Step On It

A critical limitation of using real walking in virtual reality (VR) is the limited physical space. In the last decades, much research has been devoted to overcoming the limited range of travel while maintaining the benefits of physical walking [71]. An exciting approach to overcome this problem is to use repositioning techniques with a high gain (see [292]) that enable the user to walk much faster and farther in the virtual world. A transfer function controls the relation between the user's real and virtual position. However, between the shape of the curve, the gain value, the input value, and starting and stopping conditions, the design space is extensive [71]: It is unclear how different configurations lead to different experiences. In particular, two things need to be included: methods to design transfer functions for walking in complex design spaces and an account of the qualities of walking in order to evaluate how a proposed function affects the virtual experience. This section discusses how the paper "Step On It" addresses this problem. The paper can be found in chapter 9.

The paper addresses these problems by combining Bayesian optimization to optimize transfer function design and semi-structured interviews to study the qualities of walking. First, the paper describes a way to design transfer functions using a cubic Hermite spline between a start and end position. Two parameters of this spline can be adjusted separately to control the degree of acceleration when starting and stopping to walk. The inspiration for this approach is that when walking normally in the real world, people's gait and body movement are not symmetric when starting and stopping to walk. The proposed design space enables the transfer function to leverage this by applying a different gain to different walk phases. Through heuristics and a couple of assumptions to limit the scope, the design space is left with the two Start and Stop parameters. However, many possible configurations remain. Exhaustively evaluating all options is not feasible, and educated guesses are ineffective in finding the best results. Instead, we opted for a Bayesian optimization approach to optimize the Start and Stop parameter values for each user. In a user study, an algorithm samples a pair of parameter values to try, after which the user evaluates these after walking on perceived usability (UMUX-Lite in-VR questionnaire) and gait quality (walking speed measured from the headset tracking). The algorithm determined an optimal transfer function for that user after ten trials based on a goodness function that combined these quality metrics. After the user study, we conducted a 20-minute semi-structured interview to inquire about the perceived qualities of walking.

**Significance.** The paper considers a constructive problem (current transfer function designs are unsatisfactory) and an empirical problem (it is unknown what qualities of walking matter to users when walking in VR). In particular, the paper focuses on transfer functions for repositioning techniques, or *non-isometric* walking with high gain [71, 292]. Designing good walking-based locomotion techniques for virtual reality is a significant, unsolved problem. Although several solutions have been proposed, each has significant downsides, ranging from the risk of VR sickness and physical space requirements to implementation difficulties. The problem is exacerbated by the lack of methods to evaluate walking-based locomotion techniques subjectively. Although test-beds have been proposed (e.g., [34, 24]), they are rarely used, and in general, evaluation defaults to performance metrics and singular measures of workload and presence. It is unclear how walking-based locomotion affects the overall experience or what meaningful qualities of walking are present in virtual reality.

**Implications.** After coding the transcribed interviews and analyzing them using affinity diagramming, we found six qualities of walking: naturalness, enjoyment, comfort, control, (physical) effort, and difficulty. These results provide implications for methodology, as they inform how future research can subjectively study the quality of walking-based locomotion techniques. Effort and difficulty are partially captured by standard questionnaires such as the NASA-TLX, which is already commonly applied in VR, but the others require further investigation. More importantly, the paper demonstrates how to efficiently apply a human-in-the-loop optimization approach to design transfer functions and evaluate the quality of proposed solutions. This, too, has implications for methodology. There are several such problems in HCI, and applying optimization methods to user studies is uncommon but can be successful, as demonstrated in this paper. Finally, there are implications for design in that designers can use the proposed methodology to create and evaluate new transfer functions.

**Effectiveness.** The results from the user study show that the optimized transfer functions were highly successful, with some participants commenting that walking at 40 km/h felt like normal walking [71]. This shows that the design and optimization approach successfully created a good experience through walking in virtual reality. The qualitative evaluation adds a broader context to the problem of designing good locomotion for virtual reality by reporting six relevant qualities of walking. In doing so, the paper also directly addresses the thesis: The methods investigate quality aspects of the virtual experience and provide means to effectively sample and evaluate different configurations to create an optimal experience. Furthermore, using optimization methods allows researchers and designers to determine a personally optimal profile for participants, which dovetails with the goal of investigating subjective qualities.

A potential limitation lies in the goodness function of walking speed as a gait quality indicator and the UMUX-Lite questionnaire as a measure of perceived usability: Despite previous work showing degraded walking speed when walking with gains in virtual reality, we found no such variation in this work. Instead, we found that users, on average, walked at the same speed as in real life. Although this is a positive result, it was also unexpected, and more work is needed to determine how gait is affected when moving in virtual reality. However, since this lack of effect was uniform across conditions, it had little impact on the final results. More importantly, using UMUX-Lite questionnaire was successful: The results showed meaningful variation between configurations, and with only two questions, the questionnaire is particularly suitable for swift evaluation in an online optimization protocol.

**Efficiency.** The Bayesian optimization is a particularly efficient method to apply to this sort of problem: It is easy to implement, and although the choices of goodness function and prior are not trivial, the method is robust and will often produce good results after only a few trials. In the case of this paper, efficiency could have been further improved by re-using priors and providing a more sensitive goodness function. Still, after only ten trials, the results were promising: Nearly all participants showed clear preferences in their data. The method to study the qualities of walking could have been more efficient: semi-structured interviews are a relatively time-consuming method requiring significant effort in data analysis. The resulting qualities are insightful, but future research should attempt to quantify these more precisely.

**Transfer.** The design and optimization methods presented in the paper can be used to address neighboring problems: essentially, it is a procedure of identifying relevant parameters, fixing some to sensible values through testing, and setting the most relevant ones in a user optimization protocol where each configuration is evaluated swiftly. This can be applied to the design of other locomotion techniques if there are parameters to optimize towards some measurable quality goal. The critical challenges are the goodness function (what should the technique optimize for?) and the evaluation method: Although Bayesian optimization's robustness against noisy samples makes it particularly suitable for application in user studies, care should be taken that the measure provides meaningful variation between trials. The transfer of the semi-structured interview method has been discussed above and remains the same. The transferability of the results themselves is two-sided: the qualities of walking represent higher-level insights that transfer to walking in VR in general, but the optimization study results are restricted by design to that particular context. An interesting challenge for future work is to adapt the proposed methodology to design techniques that work well on multiple travel tasks.

**Confidence.** The methods in the study are explained in detail, and supplementary material, data, and source code are available. Due to the nature of the optimization protocol, the resulting transfer functions will differ upon replication and reproduction. However, conceptually, the results will be the same (e.g., the overall preference for a slow stop). External validity could be improved: within the scope of this paper, there was only space to evaluate one gain value on one distance. Although we could derive some generalizable conclusions, the overall generalizability of the results could be improved. This bears no mark on the methodological contributions, which are primary. However, future work is needed to study how to design such transfer functions for short-range (maneuvering) and more dynamic travel tasks. The internal validity was high overall, although the lack of variation in gait poses a potential threat, as discussed above. In the qualitative evaluation, it is difficult to determine whether we found *all* relevant qualities and whether our classification of *relevance* is correct. Part of this could be addressed in future work, and part of this I addressed in my later research by using semi-structured interviews with better, theory-informed questions [293].

## 2.5 Doorways Do Not Always Cause Forgetting

Because movement in virtual reality is different from real life, it may affect our memory and cognition in unforeseen ways. For example, distance and self-velocity perception in virtual reality is incorrect [229, 96, 141], we can imperceptibly rotate the world to redirect users [211, 186], and spatial orienting performance depends on how we move through the virtual environment [145, 108, 25]. Similarly, it is vital to explore how real-world effects occur in virtual reality, particularly when those have the potential to be (more) detrimental in VR. One such phenomenon is the "doorway effect," or "location updating effect" [206, 207] that describes how crossing an environmental boundary can cause forgetting of items in short-term memory. In virtual reality, crossing environmental boundaries can be done with different travel techniques, and the boundaries can be visualized in different ways. However, it is unclear whether the doorway effect occurs in virtual reality and how different travel techniques and boundary visualizations affect it. This section discusses how the paper "Doorways Do Not Always Cause Forgetting" addresses these problems. The paper can be found in chapter 10.

The paper addresses these problems by conducting two lab experiments. The first is a conceptual replication of previous studies where we aim to determine the presence of a doorway effect when using real walking in virtual reality. In addition, we evaluate the effect of teleportation, a common locomotion technique in contemporary VR applications. The study asked participants to put six objects in a box, close the box, and walk to the other side of a room, either passing through a door or not. In the other half of the room, a series of memory recognition probes would query whether a particular object was in the box. After several trials, we calculated the hit rate (answering "yes" to an object that was indeed in the box) and correct rejection rate (answering "no" to an object not in the box) for the conditions where there was a door and not, for both locomotion techniques (between subjects). The second study was similar but only used real walking and instead varied the visualization of the door over five levels: no door, classic door, sliding (transparent) door, sliding door, and portal. For either study, the outcome variables were modeled using Bayesian modeling similar to [290] and frequentist inferential statistics. The results show no difference between door and no-door conditions in the first study, a slight, non-significant difference between walking and teleportation, and no significant differences between visualizations in the second study. This means that we found no evidence of a doorway effect occurring in virtual reality using these locomotion techniques and various boundary visualizations. The paper discusses some possible explanations for our unexpected and divergent results.

**Significance.** The paper considers two empirical problems of unknown effects of locomotion technique and doorway visualization on memory retrieval performance. The "doorway effect" studies originate in psychology, where desktop-based virtual environments were used to study the effect. More recently, immersive virtual reality was used to try and replicate the effect, but this produced mixed results [161, 86]. It is not clear whether the doorway effect occurs in virtual reality and how it is affected by the locomotion technique used or the virtual environment. The paper argues that contemporary VR systems may use relatively more environmental boundaries to improve performance or redirect the user (e.g., scene manipulation, see [292]). If environmental boundaries in VR cause forgetting, many application scenarios may be negatively affected. Similarly, while previous experiments have used realistic doorways, VR may visualize environmental boundaries in implausible or unrealistic ways. To design good virtual experiences, we need to know how the design of the virtual environment affects memory. Finally, the paper investigates explicitly the effect of walking, thus evaluating the problem in the context of whole-body movement.

**Implications.** The results from the two studies in the paper lead to implications for theory and methodology. Implications for theory "improve our ability to understand and predict phenomena in interactive computing" [11]. The premise of the studies is based on a theory of event-based memory [206, 209] that predicts the doorway effect. By not being able to replicate the effect, the paper brings into question the prerequisites for the effect and the mechanisms of event-based memory. Our work shows that the effect is not as robust as suggested in previous work. Two of three papers investigating the doorway effect using immersive virtual reality, representing both a strictly controlled experiment [161] and a more ecologically valid environment [291] were not able to find the effect. It seems unlikely that the doorway effect will noticeably impact typical VR use. However, more work is needed to determine how VR can replicate these effects and provide additional replications in new contexts (as this paper did).

The implications for methodology stem from using Bayesian modeling, a replication study, and pre-registration in the paper. The paper comprises an example of how these approaches can be used to replicate previous work in a different field and apply it to HCI. In addition, the paper makes an important point about the reporting and publication of null results: Despite being unable to reject the null hypotheses, insights and implications for theory could be derived. It is important to publish these insights alongside positive results to improve the field's problem-solving capacity.

**Effectiveness.** Lab experiments are a good choice to investigate object recognition performance effects, as they allow the experimenter to control the influence of many confounding influences. Such effects are typically shown through patterns in the data after many repetitions instead of subjective evaluation or choice. The study design closely matches previous studies, allowing for precise and direct comparisons. The studies in the paper are not a direct replication, as that would have been less informative; the study design in the paper was arguably more ecologically valid by using realistic rooms and boundaries and standard travel techniques. The paper also evaluated non-real aspects through teleportation as a travel technique and portals as an environmental boundary to cross. This allows the paper to effectively address the problem in the context of virtual reality, in addition to evaluating whole-body movement through walking.

**Efficiency.** The methods, a lab experiment using a memory probe in a virtual environment, are inexpensive to apply and generally lead to reliable results. In particular, replicating previous work in a new context is an efficient way to increase the problem-solving capacity of the field by providing additional credibility and new insights. The efficiency of the solution for investigating the effect of whole-body movement on virtual experiences is somewhat lower: The experiments did not focus on whole-body movement *per sé* and investigated a relatively minor factor in the virtual experience, especially given the unclear effects. However, the relative importance of this aspect only became apparent after experiments. Although the paper represents significant problems, as discussed above, its methods excel at studying well-defined, readily measurable effects; they are less efficient at investigating virtual experiences at a broader level, which are often subjective and ill-defined.

**Transfer.** This paper and its previous work use the same methods to measure the doorway effect, a testament to the fact that the methods transfer to other contexts for the same problem. At the same time, however, slight differences between experiment designs may prevent a successful replication, as discussed in this paper and [161]. More generally, constructing a virtual environment to enable a user to perform a task in a controlled environment is relatively common and transfers to various problems. A particular challenge in these cases is using measures that require user input, primarily questionnaires, since they may distract from the task or the environment. Given the apparent robustness of the effect in non-immersive environments, we expected their results to transfer to the current problem. This was not the case, and it makes me skeptical whether the results in this paper transfer to other contexts.

**Confidence.** The reliability of the results and the methods is high: the methods are reported in detail, and one study was pre-registered (and conducted with minor alterations that do not affect the inferences). Both studies' data, additional materials, and data analysis code are available to support future reproductions and replications. For the statistical analysis, we used both Bayesian and frequentist methods. Their results were consistent, which lends additional credibility to the results. The analysis was based on a correctly adjusted causal model, and we controlled for several potential confounds (e.g., travel time). In terms of external validity, some potential limitations are discussed in the paper, and some limitations regarding the transfer of the results are discussed above. As the paper suggests, it may be worthwhile to consider the prerequisites for the doorway effect more carefully in future work.

# 3 General Discussion

In the previous chapter, I discussed how the papers in this thesis increase our problem-solving capacity. The current chapter aims to tie the papers together on a different level, while the next chapter provides additional directions for future research.

The questions I asked in the papers and the experience-centric methods to investigate those provided a unique insight that goes beyond the individual contributions: They draw into question how we consider well-known effects, such as VR sickness or presence, or the role of previously overlooked factors such as maneuvering, event-based memory, or qualities of walking. By being able to study the role of whole-body movement in virtual experiences, we find that previous assumptions and overlooked effects—"underdog factors," if you will—play a crucial role in creating good virtual reality (VR) experiences.

Some examples will clarify: In "Sicknificant Steps," we found that the common assumption that normal walking as a locomotion technique does *not* cause VR sickness does not hold. More importantly, we found severe problems with the measurement and reporting of VR sickness, mainly centered around the (mis)use of the SSQ as a measure of general discomfort or VR sickness. Many of these problems have been known for a while but are often overlooked and repeated in new research.

In "Towards a Bedder Future," we found that maneuvering is assumed to "just work" because most users use VR while standing. However, when the user is sitting or lying down, maneuvering is not supported by the interaction techniques. This has implications for standing VR as well, where maneuvering is typically a simplified version of how we move in real life: a better understanding of the role of maneuvering and interaction techniques to support this specifically will result in better virtual experiences. In general, the use of VR in atypical contexts is overlooked, but investigating this can be illuminating to explore particular effects. For example, sense of embodiment with mismatching gravity perception and haptic feedback, in this case.

In "Step On It," some users commented that walking at 40 km/h felt as natural as normal walking. These positive results were possible due to carefully considering how people walk, what qualities of walking are important, and using clever methodology to optimize the design space per participant. This represents a different perspective on the design process that draws attention away from comparative evaluations between generations of a technique. Instead, regardless of whether the technique is faster than the state-of-the-art, it provided a *good experience*, and the methods can be applied to other techniques to the same end.

"Doorways Do Not Always Cause Forgetting" argues that because movement in virtual reality is different from real life, its effects on memory and cognition may also be different: this could lead to a detrimental experience in virtual reality, and the potential factors have been overlooked. Even when considering well-known effects such as presence, we found that it is worthwhile to question the status quo: "How You Physical Environment Affects Spatial Presence" shows that gaps in existing theories and phenomena of VR use have been overlooked because the whole context of the experience, including the physical environment, had not yet been considered.

By continuing to (only) use traditional measures of performance or applying standard questionnaires to VR use, we do not learn how to create good virtual experiences. Of course, there is a time and place in research and usability evaluation for performance metrics and questionnaires. In section 1.2, I discussed how some authors have argued that up until recently, more important limitations in VR systems prevented a comprehensive study of experiences: evaluations of functionality and usability were needed first. But now, many of those barriers have been removed. As user experience research is evolving towards a less usability-centric paradigm, virtual reality, too, has an opportunity to start focusing on creating better *experiences* in VR. It is clear now that more is needed in order to deliver VR to the next level. By presenting several new ways to study the experience of movement in virtual reality, my thesis has laid the foundation to make that happen.

McGrath [162] discusses the role of methods in the research process, noting that each method in itself is flawed but may have advantages. When carefully combined, multiple methods have the potential to offset each other's weaknesses and improve the credibility of the solution. Conversely, instead of evaluating whether a method is flawed, we should evaluate whether its outcomes are consistent with the outcomes of other methods that address the same problem. In this thesis, multiple methods are used at two levels. At the paper level, four of the five papers use more than one method to address their research question, and the increase in problem-solving capacity was discussed in section 1.2. At the thesis level, all papers contribute different methods that are used to address the overarching problem. Overall, the papers are consistent in that they show that *subjective* qualities of virtual experiences can and should be improved. This is also consistent with the discussion above.

A potential limitation of this thesis is that all research works (except "Sicknificant Steps") employed lab experiments as a research strategy. Similar to methods, each research strategy has advantages and limitations. In the case of lab experiments, they are powerful tools to investigate specific phenomena without the influence of confounding factors. However, the particular scenario or context would not exist without the researcher's motivation (i.e., the ecological validity is relatively low) [162]. Despite this, the thesis comprises an amount of variation: while the "Doorways" and "Spatial Presence" papers used strictly controlled lab experiments, the "Bedder Future" and "Step On It" papers purposefully allowed influences of the participants' experience and preferences. The "Bedder Future" study, in particular, was quite close to how I imagine users would use VR while lying down at home. In sum, the employed strategies comprise a balance between strictly controlling for confounding factors and enabling a broad perception of the user's experience.

Finally, a shared strong point of all papers in the thesis is that they are (or will be) published with open access: This enables researchers and practitioners anywhere to benefit from and build upon this work. The papers also make available data, additional materials, source code, and data analysis code. Replications, reproductions, or open science, in general, are rare in HCI [92, 60]. By publishing these materials and including preregistration and replications in some work, this thesis takes steps in the right direction.

# 4 Future Perspectives

In the previous chapters, I have discussed several quality aspects of the virtual experience and how they are affected by whole-body movement. However, many more remain. There are three open questions related to this topic that deserve future attention: Does it matter whether a travel technique is plausible within the virtual story? How does expertise with a technique or movement change the experience? How can we move better than real life?

**One.** In recent years, several travel techniques have been proposed that noticeably change something about the virtual environment to enable users to travel better: Han, Moere, and Simeone [79] used folding walls and floors, Cmentowski, Kievelitz, and Krueger [43] used non-Euclidian tunnels, and Abtahi et al. [3] turned users into giants. Notably, these techniques were evaluated in realistic environments that conceptually represent our real world. This raises a question: Does folding your room in half, seeing a tunnel cross the market square over-land, or being the only giant in an otherwise normal city *make sense*?

Slater [251] introduced "plausibility illusion" (PSi) as one of two dimensions of sense of presence in virtual reality.[1] It is the illusion that what you see is really happening. In this context, the questions above ask whether the observable characteristics of a travel technique in a particular virtual environment support or distract from the plausibility of the virtual environment. In other words, whether they support or hinder the user's sense of presence.

One example of a technique that gets this right is the "gravity glove" concept in the VR game Half-Life: Alyx.[2] This virtual hand-worn device enables long-distance object selection and manipulation, thus solving a critical usability issue. More importantly, the glove and its functionality make sense within the universe and story of the game: Despite it being a futuristic and unique device, it is plausible that such a device exists and that the protagonist would have access to it based on what we know about the virtual world and the story.

How does this degree of consistency between the technique and the virtual story affect the overall experience? Is it practically relevant? On the one hand, it could affect presence through the plausibility illusion. There may be other qualities that are affected. On the other hand, I cannot remember the last time a participant complained that teleporting within a contemporary environment, using an oversized laser pointer to select objects, or walking at 40 km/h in a hotel hallway ([71]) did not make sense, even if it seems implausible upon reflection. Suppose the plausibility of an interaction technique within a virtual environment does affect the experience. In that case, this effect may be more akin to what Jordan [103] calls a *need of appreciation* or what Hassenzahl and Roto [84] call a *be-goal*: something that is not a necessary prerequisite for a good experience but can improve upon the experience further by fulfilling hedonic needs.

[1] The other being "place illusion" (PI), similar to spatial presence in [290].

[2] Steam ID: 546560

**Two.** Five of the six user studies in this thesis used a convenience sample that mainly consisted of inexperienced VR users or even complete novices. The only exception is the user study in "Towards a Bedder Future," where we purposefully selected experienced participants to control for the confounding effect of "struggling to use the VR system." Inexperienced participant samples are typical in virtual reality research. For example, a large majority of walking-based locomotion studies in "Sicknificant Steps" (see supplementary materials) had inexperienced participant samples [292]. However, even when using expert VR users, they will likely not have expertise in the new technique you are evaluating. This raises a general question for VR research: How does the virtual experience change when users become proficient with the travel technique?

The abundance of inexperienced evaluations presents an unfair advantage for techniques that are immediately easy to use but lack the functionality to complete complex travel tasks. It also overlooks the potential of travel techniques that are complex and require training but that can be highly effective in multiple environments and scenarios. "Complex" is used loosely here: Even walking-in-place techniques require some training to be used effectively. If we compare how we travel in real life and virtual reality, virtual reality travel techniques seem oddly self-restricting. Consider, for example, riding a bike or driving a car: Both require extensive training to be used effectively and efficiently, yet their usefulness is unquestionably worth the effort. When evaluating a new in-car entertainment system while driving, we would not select participants who do not know how to drive. In a typical virtual reality evaluation, however, a participant may be given fifteen minutes to become familiar with the controls of a travel technique and is then left to muddle through the task.

We know very little about how whole-body movement affects the virtual experience for expert users. There is limited work on adaptation to various factors in virtual reality, such as redirection gains [18, 221], habituation and VR sickness [221, 213], and gait changes when walking in VR [179, 99], but more work is needed. The question of expertise also relates to how we can leverage the transfer of motor learning to improve the virtual experience when using an unknown technique: It is unlikely that there will ever be a one-size-fits-all technique for movement in virtual reality, requiring a significant amount of learning and re-learning. Similar to how we learn new skills in real life, the transfer of motor learning dramatically improves the effectiveness and efficiency of learning a new motor skill, by applying and adapting existing skills to a new context.

**Three.** In the introduction to this thesis, I asserted that people love to move. A cheeky statement, considering that one could easily argue that people, in fact, *hate* moving and only do it when absolutely necessary. Affect notwithstanding, the bottom line remains that movement is ubiquitous. Going one step further, psychologist Barbara Tversky argues that movement controls the way we think, not the other way around: It is through movement that we form perceptions, understanding, and action upon the world around us; the brain structures underpinning spatial relations and way-finding form the foundation for abstract thought [284]. Thus, regardless of whether walking will be the locomotion technique of choice in twenty years, it seems reasonable to assume that whole-body movement is here to stay. This entails that research needs to focus on enabling whole-body movement in virtual reality—for example, through maneuvering—to create good future experiences.

Virtual reality has the fascinating potential to allow us to travel better than in the real world. I do not mean better in the sense of going faster, making fewer errors, or perceiving less redirection; I mean that movement in virtual reality could circumvent the reasons we would not want to travel: effort, time, funds, motion sickness, etc. Earlier in this dissertation, I gave the example of previous work showing that people do not actually want to sneak, likely because they are bad at it and it requires much effort. They want to feel like they are sneaking. The paper showed that the way you move your body significantly impacts this feeling but does not necessarily have to mimic reality [44].

Similarly, people dream of flying like a bird. However, few would actually want to: It is cold, effortful, and the rather impractical position of our eyes entails either neck pain or great difficulty navigating. Instead, we want to *feel* as if we are flying like a bird. Alternatively, imagine the potential of movement in completely unrealistic spaces (e.g., science-fiction, non-Euclidian, or psychedelic environments) where real-world expectations are diminished. In this lies the future potential of virtual reality: to provide a better-than-real experience.

This thesis has argued that this future cannot be achieved by conducting evaluations of the kind that question whether one technique is faster than another. Instead, we need a hedonic evaluation of multiple aspects that describe the experience as a whole. This thesis has taken the first steps towards such evaluations in the hopes that we may now create better virtual experiences.

# 5 Conclusions

In this dissertation, I have introduced the goal of my thesis: to improve our understanding of how we can leverage whole-body movement—particularly walking and maneuvering—to create better virtual reality experiences. To accomplish this, I have presented five papers that use whole-body movement to study virtual experiences from various perspectives. In particular, I have introduced new ways to apply existing methods for this purpose and applied these methods in user studies to quantify virtual experiences.

“Towards a Bedder Future” used a think-aloud protocol and semi-structured interviews to reveal the importance of maneuvering in virtual reality (VR). “How Your Physical Environment Affects Spatial Presence” conducted two lab experiments to model the effect of the physical environment on spatial presence when you move around in VR. ”Sicknificant Steps” conducted a comprehensive systematic review and meta-analysis of VR sickness effects in walking-based locomotion techniques. “Step On It” investigated the qualities of walking in VR and used Bayesian optimization in a user study to design fast-walking techniques that felt like “normal walking, but fast” to their users. Finally, “Doorways Do Not Always Cause Forgetting” conducted a conceptual replication study and additional lab experiments to investigate whether walking or teleporting through environmental boundaries can cause forgetting in VR.

In section 1.2, I have discussed the quality of the proposed solutions with respect to six quality heuristics: significance, implications, effectiveness, efficiency, transfer, and confidence. In chapter 3, I have discussed how the papers come together to question current assumptions about virtual experience qualities and investigate previously overlooked factors. Finally, in chapter 4 I present three ideas to complement the thesis in the future.

In conclusion, my thesis represents high-quality research that illuminates how we can study how movement affects virtual experiences and the critical quality aspects. All papers are or will be published as open access, and all data, materials, and source code are available: future researchers and designers can quickly and confidently build upon my work. The contributions in this thesis enable us, as researchers and designers, to create better virtual experiences in the future. I will present the complete papers in the next part of this dissertation.

# Part II

# Papers

# 6 Towards a Bedder Future

This chapter presents the paper “Towards a Bedder Future: A Study of Using Virtual Reality while Lying Down” [293] that is published as an open-access, peer-reviewed conference paper in CHI ’23. The content in this chapter is predominantly similar to the published version-of-record, except for minor spelling, stylistic, and typographic improvements.


## Abstract

Most contemporary virtual reality (VR) experiences are made for standing users. However, when a user is lying down—either by choice or necessity—it is unclear how they can walk around, dodge obstacles, or grab distant objects. We rotate the virtual coordinate space to study the movement requirements and user experience of using VR while lying down. Fourteen experienced VR users engaged with various popular VR applications for 40 minutes in a study using a think-aloud protocol and semi-structured interviews. Thematic analysis of captured videos and interviews reveals that using VR while lying down is comfortable and usable and that the virtual perspective produces a potent illusion of standing up. However, commonplace movements in VR are surprisingly difficult when lying down, and using alternative interactions is fatiguing and hampers performance. To conclude, we discuss design opportunities to tackle the most significant challenges and to create new experiences.

**Title:**
Towards a Bedder Future: A Study of Using Virtual Reality while Lying Down.

**Authors:**
*Thomas van Gemert*, Kasper Hornbæk, Jarrod Knibbe, and Joanna Bergström.

**DOI:**
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**What was the role of the PhD student in designing the study?**
The student designed and carried out the study.

**How did the PhD student participate in data collection and/or theory development?**
The student carried out the data collection and analysis.

**Which part of the manuscript did the PhD student write or contribute to?**
The student wrote and contributed to the entire manuscript.

**Did the PhD student read and comment on the final manuscript?**
Yes.

Figure 6.1: Three examples of participants using Virtual Reality (VR) while lying down: The top row shows their VR view and the bottom row their movement in the moment. On the left, a participant relaxes in bed while traveling through the mountains. In the middle, another is sitting up to dodge a wall in a rhythm game. On the right, a participant is leaning to aim a catapult.

## 6.1 Introduction

In the majority of virtual reality (VR) applications, the user is in either a standing or seated position. More often than not, the user is not just standing still but is using natural movement to move through the virtual environment. In fact, eight of the top ten best-selling VR titles on Steam[1] allow the user to interact by ducking under an obstacle, stepping around a corner, leaning to aim a weapon, or reaching for and grabbing an object. In research, too, there is an increasing interest in how we move through the physical space while in VR, for example, by dancing in VR [203], using walking-based locomotion (e.g., [71, 187]), or accidentally moving out of the tracking space [49]. Even when sitting, users can still leverage their torso and arms to lean, reach for buttons, or grab things off the ground. However, it is unclear how we can use VR while lying down.

We spend much of our time lying in bed or on the sofa, using up to four hours a day for entertainment [232, 75]. While lying down, VR can be used to watch movies on a virtual ceiling (e.g., through Netflix VR or Bigscreen VR), enjoy guided relaxation or meditation (e.g., [64, 137]), watch 360-degree videos, or even sleep (e.g., [318, 277]). Outside of popular use, VR is gaining traction in areas where a user typically lies down. In medicine and rehabilitation, VR improves therapy [17] and offers pain relief [172, 256]. In neuroscience, VR has been used in studies using MRI or EEG [138]. However, these virtual reality experiences are often limited by rotation-only tracking, design for stationary use, or a constraining environment.

Simply donning a VR headset and getting into bed or lying on the sofa presents numerous challenges. First, when a user lies down, they will be staring at the ceiling or sky—typically not the most exciting part of the environment. Second, the virtual perspective can be rotated to let the user look forward virtually, but this breaks the mapping between

[1]The largest video game digital distribution platform for PC; `https://store.steampowered.com`

their body's pose in the real and virtual worlds. Third, the surface the user lies on likely imposes significant movement restrictions compared to standing freely. These are some of the open questions we address: How do users move around? How do they want to interact? How do they feel when using virtual reality while lying down?

We investigate the user experience and movement requirements of popular VR applications when lying down. We developed a custom driver for SteamVR to transform the virtual coordinate space; this allows the user to look virtually forward while physically lying down. We then conducted a qualitative study using a relaxed think-aloud protocol with 14 experienced VR users. The participants used six of the most popular VR applications on Steam, selected for a variety of genres and movement requirements, for approximately 40 minutes. Finally, we conducted a semi-structured interview to address more general questions related to pragmatic and hedonic qualities.

Using thematic analysis, we identified three themes related to using VR in bed. First, we describe how everyday movements become tricky when lying down; this requires users to devise new ways to move and interact, which are strenuous and uncomfortable. Second, despite the additional strain, users can use the applications while lying down comfortably. Third, we discuss how the illusion of virtually standing up can lead to embodiment—when the virtual torso is aligned with respect to the physical head—and disorientation—when the virtual horizon is misaligned with respect to the physical body. We conclude this work by suggesting design opportunities to create new experiences and future directions to tackle the current challenges of using VR while lying down.

## 6.2 Background

(a) Using VRChat with the Diver-X HalfDive VR system

(b) A patient using a SyncVR system at the dentist

Figure 6.2: Two real-world examples of using VR while lying down: (a) Diver-X's hardware system for using VR in bed [55, 56] and (b) a patient using a commercial (SyncVR Medical) product at the dentist [163].

In this section, we show that a need for using VR while lying down exists and that many applications demonstrate that VR is useful while lying down. However, we know remarkably little about the challenges of using VR in bed or designing VR experiences for use in bed. To conclude, we present an overview of applications and research related to using VR while lying down, and we discuss previous efforts to understand the experience and tackle the obstacles of using VR in bed.

**Why Should VR Be Used While Lying Down?** People may want to use VR while lying down out of necessity or by choice. The W3C's XR Accessibility User Requirements state that "the user should not have to be in a particular physical position such as standing or sitting to play a game or perform some action" [104]. This suggests that VR should be usable while lying down, but in practice, this is not yet the case: Amongst recent discussions of accessibility of VR, Gerling and Spiel [73] argue that current VR systems and software are an "inherently ableist" technology that requires a whole, average body to use: Many applications require bodily motion controls without providing alternatives. HCI researchers have echoed the need for accessible VR in the context of wheelchair users [74], system use [173], and software (e.g., WalkinVR[2]). Some recent forum posts show that bed-bound users want to use VR while lying down in bed (e.g., [280, 102]) and that this need has not yet been satisfied.

Outside of VR, people spend about 4 hours a week watching TV in bed [232]. The idea of using virtual reality in bed appears to be well-established in popular culture: A Google Images search for "virtual reality in bed" produces a plethora of stock images and videos of people wearing VR headsets in bed—sleeping, relaxing, or excitedly reaching out to something in the virtual environment. Other examples come from fiction, such as the anime series "Sword Art Online" or the movies "The Incredible Doctor" and "The Matrix," in which people are completely immobile in the physical world.

Together, these works suggest that 1) there is an imminent need for using VR in bed, 2) current work on accessibility in VR does not cover the use of VR while lying down in bed, and 3) there is an imagined future where VR can be used in bed when desired.

**Why Has VR Been Used While Lying Down?** VR has been applied in contexts where the user already needs to lie down, such as pain relief for bed-bound patients (e.g., [172, 189] and Figure 6.2b), VR-augmented therapy (e.g., [138, 17, 140]), and creating conditions for magnetic resonance imaging (MRI) or other neuropsychological assessments (e.g., [138, 244, 76]).

When lying down by choice, VR has been used to improve sleep quality (e.g., [318, 238, 137]) or to provide guided meditation (e.g., [64]). When consuming entertainment, VR users may want to lie down for comfort. For example, apps like Netflix for VR and Bigscreen VR already allow users to watch movies in a virtual environment by placing the TV on a virtual ceiling. Research papers have discussed the potential of immersive applications for VR pornography [312, 61]. Some users of the popular VR app "VRChat" are already sleeping in virtual environments. YouTube creator "The Virtual Reality Show" presents an interview with such users [277]: The mentioned benefits include the ability to sleep in wondrous, often natural, locations (e.g., camping in the mountains) or social sleeping with physically distant friends or family. These examples show that VR can benefit many applications where people need or want to lie down. However, they reveal little about the challenges in doing so.

[2] https://www.walkinvrdriver.com

**What Are the Obstacles for Using VR While Lying Down?** Both academic and commercial works have designed hardware systems to enable VR while lying down. One of the first examples of using an immersive system for pain relief and entertainment in bed was published in 1998 by Ohsuga et al. [189]. Their "Bedside Wellness System" used a large mechanical arm to hold displays above the user's head and foot pedals to allow the user to locomote through a virtual environment. More recently, Kwon et al. [120] presented a VR system for viewing immersive bedtime stories in bed while minimizing movements. They present a custom pillow with lenses wherein a smartphone can be embedded and a back-of-the-head pressure sensing system to provide interface control through head rotations. The ergonomics of virtual reality use have been investigated (e.g., [309, 41, 67]), and interaction techniques have been proposed to improve standing and sitting VR use (e.g., [303, 170]). However, apart from anecdotal reports regarding the comfort of the hardware while lying down (e.g., [238]), the ergonomics of using VR while lying down remain unclear.

On the commercial side, Figure 6.2a shows the proposed HalfDive VR system that was designed specifically for use in bed [55, 56]. The system comprises a platform under the head and an HMD that surrounds the user's head. The hardware platform supports head rotations, input through foot controllers, and force feedback on the hand controllers. The Kickstarter page says the HalfDive aims to "complete life in-bed" for working and playing in bed. However, the project was canceled in 2022. The creators noted that contrary to the project's direction, their potential users were more interested in interaction techniques for working in bed than the video system. Figure 6.2b shows a different VR system that relies on specialized software to allow its use while lying down. Due to the lack of positional tracking and its proprietary nature, it is unclear a user's movement in VR is supported.

These works suggest that enabling the user's movement for interactive VR while lying down is important, but the possible challenges of moving while using VR in bed remain uncharted.

**How Do People Experience VR While Lying Down?** Since lying down physically and looking forward virtually creates a mismatch between the perceived virtual and physical direction of gravity, some authors have hypothesized that this can induce VR sickness. Marengo, Lopes, and Boulic [150] created a custom "Pac-Man" game with a rotated coordinate space and joystick locomotion and measured VR sickness between seated and lying-down users. Their 25% drop-out rate and high reported SSQ scores suggest that supine users are more susceptible to VR sickness. Another study by Tian et al. [279] compared supine users between a Body-Vertical / Real Vertical and Static / Dynamic game. The study does not report a significant difference in SSQ scores. However, the SSQ-Disorientation score was always higher when the direction of gravity was body-aligned (i.e., using a rotated virtual coordinate space). Although the assumption in these studies was that the source of the sickness was the mismatch in the perceived direction of "up," they did not measure how participants perceived the direction of gravity. Kawai, Hara, and Yanagida [106] studied this perception and found that the perceived horizontal plane depends mainly on the proprioceptive sensation of the upper body angle, not on the physical direction of gravity.

These studies suggest that the experience of using VR while lying down differs from that of standing, at least in the discomfort of VR sickness. However, the overall experience, including a positive aspect that could inform the design of VR while lying down, remains unclear.

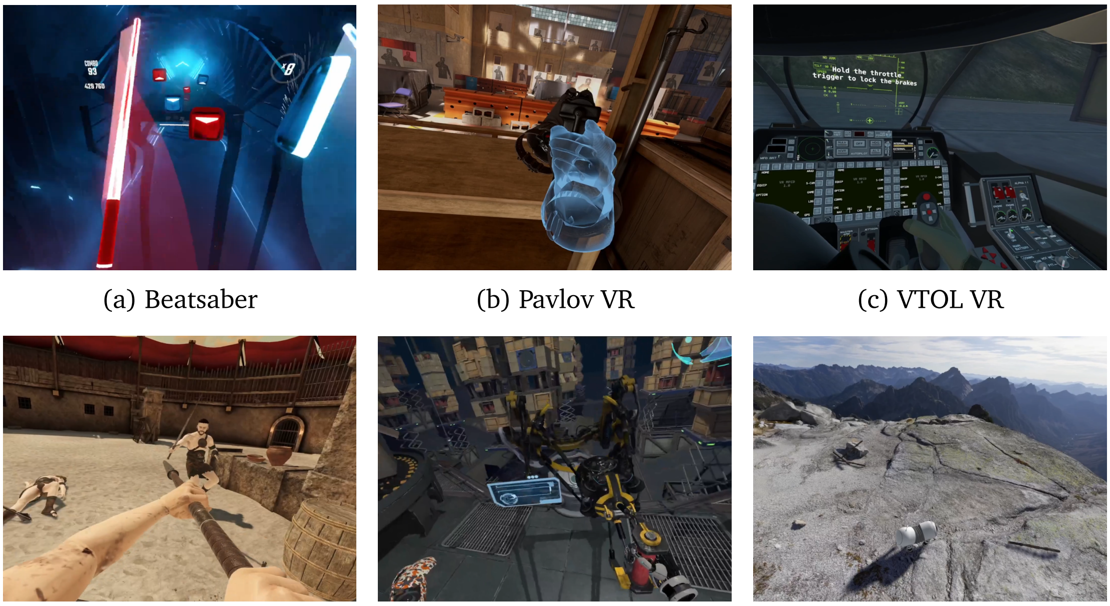
## 6.3 Study

This study aims to identify the movement requirements and user experience of VR while lying in bed. To do so, we develop a custom driver for SteamVR to transform the virtual coordinate space and select six applications to represent contemporary VR. We use a relaxed think-aloud protocol and semi-structured interview for data collection and conduct a thematic analysis on video and audio recordings of those. In the following, we describe the study.

**Method.** In the first part of the study, participants used three of the selected six applications (see item 6.3) for a maximum of 45 minutes in total. In this part, we used a relaxed think-aloud protocol (RTA) [89, 88] to collect rich verbalization of the participant's experience as they were engaging with the applications. We used a relaxed think-aloud protocol because it allows us to prompt the participant to elaborate when they move or interact in an interesting way but do not verbalize why they do so. Furthermore, it allows us to communicate with the participant and provide instructions where needed to limit the influence of unfamiliarity with the application or the controls themselves. We recorded a video of the participant lying in bed and captured a video of their application view. We simultaneously recorded audio from the participant, observer, and application. The observer was positioned so that they could observe the participant and the application view simultaneously, take notes, and communicate with the participant.

After the RTA part, we conducted a semi-structured interview (SSI) outside of VR to ask more general questions about the experience of using VR while lying in bed. The SSI focused on three topics. First, the quality of the interaction with the virtual environment (Gameplay), which is characterized by usability, utility, and emotional impact. Second, the context of the user (Context), which is characterized by the user's previous experience, physical position, and physical abilities. Third, a higher-level reflection (Reflection) on the utility and appeal of the VR experience when lying down. For each of these topics, we constructed a starting question that focused on how participants *use* the system (pragmatic quality, P) and how participants *feel* while using the system (hedonic quality, H) [84]:

1. How did it feel to use these VR applications in bed? (Gameplay, H)
2. Were you able to do what you wanted to do in the application? (Gameplay, P)
3. How does the experience compare to other times you've used VR? (Context, H)
4. How does lying down influence the way you move? (Context, P)
5. Why do you think people would want to use VR while lying down? (Reflection, H)
6. What would you want to be improved about the system to make it perfect? (Reflection, P)



(a) Beatsaber (b) Pavlov VR (c) VTOL VR

(d) Blade and Sorcery (e) The Lab: Slingshot (f) The Lab: Postcards

Figure 6.3: Screenshots of the six applications in the study.

**Applications.** VR games represent one of the most popular forms of VR applications for consumers. To have a representative sample of contemporary VR experiences, we selected the six games from the "Top Seller" list of VR titles on Steam. Within the most popular titles, we selected different movement requirements, locomotion techniques, and genres. Each application could be played for a maximum of 15 minutes or less if the participant finished the task early.

In the study, each participant was assigned a unique order of applications, and each application was played at least six times in total. Based on a pilot study, the nature of the applications, and the physical setting, we expected some issues to be similar across games and participants. So, a relatively small number of participants will suffice to identify the most prominent challenges and benefits. Simultaneously, we wanted to consider individual preferences, experiences, and differences between the applications, so we opted for at least six samples per application.

Figure 6.3 shows a screenshot of typical gameplay for each of the six applications. Below, we describe the type of application and their typical movement and interaction requirements. All of the applications, except for VTOL VR, support a room-scale play area, which means the user can move around in-game by physically moving. We describe the selected applications and their different genres ([66, 1]) below. We also describe typical movements in these applications in standing or seated VR.

*Beatsaber* (Figure 6.3a): A *Music/Rhythm* application (Steam ID: 620980) that requires the participant to hit oncoming blocks using two light sabers. The participant plays the first three songs—"$100 Bills," "Balearic Pumping," and "Beat Saber"—at a self-selected difficulty. The walls are enabled by default but may be disabled if the participant fails to dodge them. The interaction area is primarily in front of the participant. The participant uses their arms and hands to swing the sabers in time, either in front of them or to the sides. Furthermore, they use their whole body to lean left and right and duck to dodge oncoming walls.

*Pavlov VR* (Figure 6.3b): A *Shooter* application (Steam ID: 555160) with a wide variety of guns and a full-body avatar with inverse kinematics. The participant plays the tutorial. The interaction area is all-around (shooting targets) but primarily on/near the body (weapon handling). The application features a lot of object manipulation in handling, customizing, and aiming the weapons. Navigation is done through natural motion (walking) or joystick locomotion and snap-turning.

*VTOL VR* (Figure 6.3c): A *Flight* application (Steam ID: 667970) where the user controls a military aircraft with a high degree of realism. The participant plays the first two tutorial missions that teach them how to operate the aircraft, take off, and land. The participant is virtually seated in the aircraft, and the interaction area is in front of the participant and at waist height (controls). The application requires precise hand-eye coordination to control the various switches, buttons, and joysticks.

*Blade and Sorcery* (Figure 6.3d): A medieval-style *Fighter* application (Steam ID: 629730) with realistic physics, various melee weapons, and a full-body avatar with inverse kinematics. The participant's task is to play "Recruit" training in the "Arena" map and kill ten enemies. The interaction area is all-around. The participant can navigate through natural motion or joystick locomotion and snap-turning. Dueling the enemies requires full-body maneuvering and fast and precise arm movements to handle the weapon with one or two controllers.

*The Lab: Slingshot* (Figure 6.3e): A *Puzzle/Action* application that is part of The Lab (Steam ID: 450390). The user needs to shoot a ball at towers of stacked boxes using a large slingshot. The task is to play the application for three rounds. The interaction area is primarily in front of the participant (the slingshot). Due to the size of the slingshot, the participant needs to maneuver around in a 3x3m virtual space to aim the slingshot using precise hand-eye coordination. Locomotion is also supported through teleportation and snap-turning.

*The Lab: Postcards* (Figure 6.3f): A *Simulation* application that is part of The Lab (Steam ID: 450390). In Postcards, the participant explores four real environments that have been photo-realistically re-created. The majority of interaction is active viewing. The participant can use natural motion to navigate or teleport between fixed locations and rotate using snap-turning. The participant can also pick up sticks off the ground to play fetch with the robodog.

**Participants.** We invited 14 experienced VR users to participate in the study. We selected experienced participants because participants with little to no experience may be distracted by the new experience of VR itself and its controls instead of the experience of using VR in bed. We recruited participants in the local area through an internal mailing list, word-of-mouth advertisement, social media posts, and by reaching out to VR companies and research groups. Overall, our participants were very experienced: eight participants regularly use VR in a professional setting; the other six regularly use VR for games or entertainment. Most participants had played Beatsaber before, and two could comfortably play at the highest "Expert+" level. The participants had little

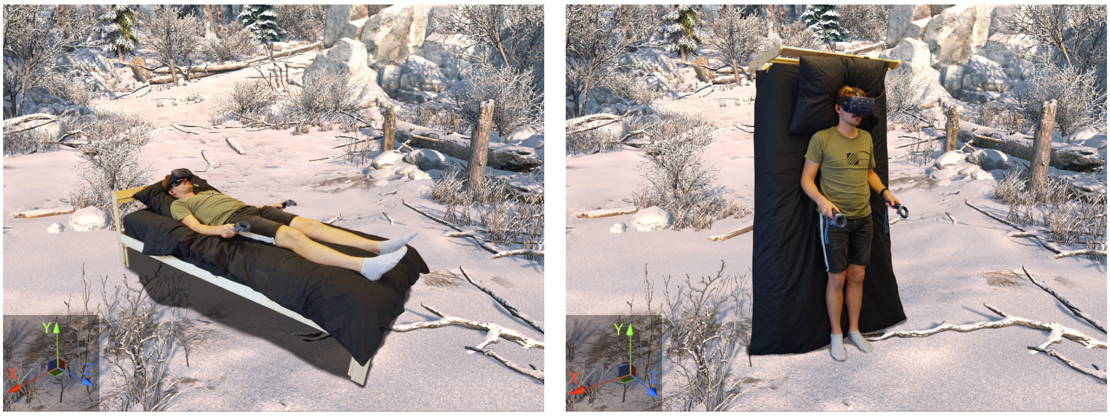


Figure 6.4: This figure shows the effect of lying down in VR and rotating the virtual coordinate space to compensate. On the left: while physically lying down, a VR user will be facing the sky. On the right: by transforming the virtual coordinate space, the physically lying user will be virtually standing in the virtual environment. The gizmos in the figures indicate the world coordinate system for the virtual environment.

experience with the other games in our repertoire, but most participants had at least heard of them and had played similar games. The participants were eleven males and three females. The mean age was $31.8 \pm 5.9$ years old. The mean time participants spent in VR in this study was 00:37:56 ± 00:03:46.

**Rotating the Virtual Coordinate Space.** To enable users to use existing VR applications while lying down, we need to rotate the standing forward direction (by approximately 90°) so that the participant looks forward in the virtual world while physically lying down. The desired effect is illustrated in Figure 6.4. To accomplish this, we modified OpenVR Motion Compensation[3] (OVRMC), a custom piece of software for SteamVR that hooks into the OpenVR drivers to modify the pose of a tracked device. Our version of OVRMC tracks the pose of a reference device (e.g., an HTC Vive tracker) and applies the inverse pose to both the HMD and controllers. This means that the virtual environment moves with the tracked device. We use this to rotate the virtual environment by rotating the reference device while the HMD and controllers maintain their true pose with respect to the user's body. Furthermore, we implemented software offsets to align the center of the tracking space with the participant's feet. Because this approach works at the driver level, it allows us to transform the virtual coordinate space for any SteamVR title. The code is available in the supplementary material[4].

Figure 6.5 shows the rotation between the physical and virtual coordinate spaces. The procedure to rotate the virtual coordinate space is as follows: We ensure that the bed is aligned parallel to the virtual forward direction (perpendicular to the solid green line in Figure 6.5), so we can rotate the tracker 80–90° around the world lateral axis, changing $alpha$. The virtual forward direction is now aligned with the physical up direction. We then translate the center of the tracking space to align it with the user's feet so that they are virtually standing in the center of the tracking space, looking forward. When the

[3] `https://ovrmc.dschadu.de/`

[4] `https://github.com/tvangemert/OVRMC-BedderFuture`

user rests their head on a pillow, $\beta$ indicates the angle between the head-forward and virtual vertical axis. We used a simple Unity application to manually check and calibrate $\alpha$ and $\beta$; the code is provided in the supplementary material.

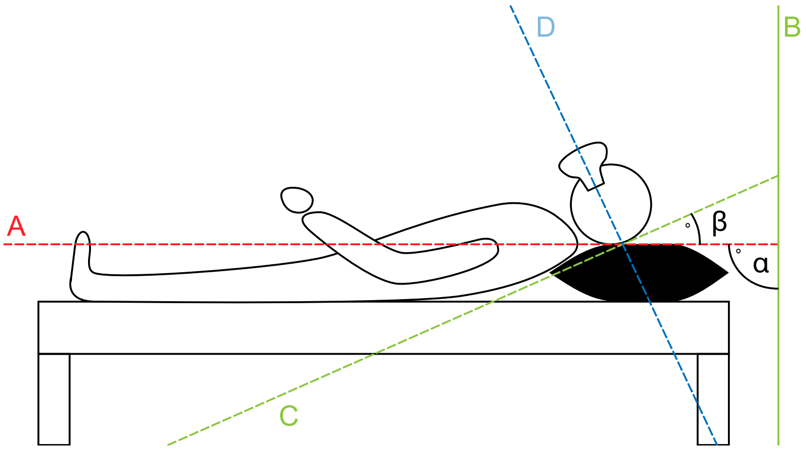



Figure 6.5: We have rotated the virtual coordinate space so that line (A) is the virtual vertical axis. Angle $\alpha$ is the degree of rotation between the physical vertical axis (B) and the virtual vertical axis (A). $\alpha$ is controlled by physically rotating the HTC Vive tracker. Angle $\beta$ between the head vertical axis (C) and the virtual vertical axis (A) is controlled by the user's position in the bed and the pillow ($\beta$ is exaggerated in the figure for illustrative purposes). Line (D) is the virtual head-forward axis.

**Apparatus.** Figure 6.6 shows the physical setup of the study. The bed is an Ikea Neiden (90x200cm) with an Ikea Vestmarka mattress and Ikea Sköldblad pillow. Perpendicular to the bed was a desk with a laptop for note-taking and three monitors to display the in-game view, an on-screen clock, and the OBS recording window. The laptop was positioned so that the observer was facing the participant as well as the in-game view and clock.

The VR system comprised an HTC Vive Pro headset with a modified head-strap (see Figure 6.6), two HTC Vive Pro controllers, and four SteamVR 2.0 lighthouses. The reference tracker was an HTC Vive Tracker mounted on a tripod and connected via an additional HTC USB radio. The headset cable was suspended from the ceiling above the participant's head. The HTC Vive Pro, by default, has a rigid head-strap with a buckle at the back of the head. To improve comfort while lying down, we created custom mounting hardware to attach an HTC Vive (original) head strap to the HTC Vive Pro (see Figure 6.6). The head-strap for the original Vive is flat and does not impair the head while lying down. The models for 3D printing and instructions for the conversion are available in the supplementary material.

We used SteamVR version 1.23.7 on Windows 10. To rotate the tracking space, we used our modified version of OVRMC (see Figure 6.3) which was based on version 3.6.0. The tracking space was set up to be approximately 2.5 by 2.5 meters. We rotated the virtual coordinate space to $\alpha = 86.06 \pm 1.42°$ on average. With the pillow, $\beta = 14.64 \pm 7.93°$ on average. The latter varied based on the participant's preference and pose in the bed; some participants removed the pillow during the study, and several re-adjusted their head position during the study by moving around in bed.

A video camera was pointed at the bed. We used OBS Studio to record the in-game footage from both eyes using SteamVR's built-in "VR View." An on-screen clock was included in the PC recording and video camera recording to synchronize the videos in post-production. The computer to drive the VR system was a powerful workstation with an AMD Ryzen 7 5800X CPU and an Nvidia GeForce RTX 3080 GPU. We used the HTC Vive Pro's built-in microphone to record the participant audio and a Blue Yeti microphone to communicate with the participant during the study and to record the interview. MaxQDA 2022 was used for coding and analysis.


Figure 6.6: On the left: an overview of the study setup and apparatus. (1) One of four lighthouses for tracking, placed in each corner of the space. (2) A tripod where the camera would be mounted and pointed at the bed. (3) The HTC Vive tracker that is mounted on a tripod and rotated ~90°. (4) An additional screen that displays a clock for synchronizing the camera and in-game video footage. (5) The observer's desk with two screens with controls, recording, the VR view, and a laptop for note-taking. (6) The bed with the HTC Vive Pro headset resting on the pillow, with the cable suspended from the ceiling. On the right: the HTC Vive Pro HMD with modified mounting brackets to mount an original HTC Vive head strap. For audio, we used JBL in-ear earphones using a 3.5mm to USB-C adapter.

**Procedure.** Before the study, the observer set up the bed, VR hardware, computers, and peripherals. They then rotated the virtual coordinate space and aligned the tracking space origin with the observer's feet as they were lying in bed. At the start of the study, the observer welcomed the participant and explained the purpose and procedure of the study: that we are interested in the user experience of using VR while lying down with a "rotated world, so you will be looking forward in VR" and that we wanted to know "what works well and what does not." Within that context, the participant was free to comment on anything, from feelings to usability issues. After obtaining informed consent (and optionally, permission to use their images in the figures), the participants conducted two warming-up exercises for the think-aloud protocol: verbally solving a math problem and brainstorming improvements for a household device.

When the participant was confident they understood the protocol, the VR system, and the procedure, the observer asked them to lie down and put on the headset. OVRMC and the calibration application were already running, so the participants would immediately be in the transformed coordinate space. We provided a pillow and used the application to set the floor-HMD height and record $\alpha$ and $\beta$. Then, the observer asked the participant to put in the earpieces, started SteamVR Home, started the video and audio recordings, and instructed the participant to start thinking out loud.

When the participant acknowledged that they were ready and had no further questions, the observer asked them to start the first application from the SteamVR Home menu. Once the game had started, the observer gave the participant instructions on the controls for the game and the task they were to complete. If the participant got stuck in the application and could not figure out how to proceed, the observer provided additional instructions. In some games, the observer provided tips to ensure that all participants used the games in roughly the same way (e.g., trying to use a sword in Blade and Sorcery). When the task was completed or the time limit was up, the participant was instructed to return to SteamVR Home and start the next game.

During the entire VR session, from calibration up to the interview, the participant was in VR. After the last application had finished, the observer instructed the participant to take off the headset and take a seat on the bed next to the desk. The observer then proceeded with the semi-structured interview for approximately 10 minutes. Afterward, the study ended, and the participant was thanked with a gift worth $20.

**Analysis.** To analyze our data, we drew upon the thematic analysis framework as explained by Braun and Clarke [28]. We use a primarily inductive approach: this allows us to stay close to the participant's experience of using VR applications in bed. This experience was expressed through their utterances during the think-aloud study and interview, as well as their movements and interactions that were recorded on video. We have no existing frameworks or guidelines to analyze the user experience, movements, or interactions of using VR while lying down, so a bottom-up approach is the most appropriate.

The first two phases of thematic analysis are data familiarization and initial coding. One of the authors was also the observer during the studies and was thus intimately familiar with the data. To streamline the first two phases with multiple coders, we coded the first two participants together in a simultaneous session where interesting segments and codes were determined collectively through discussion and analysis of the data.

What to code was determined by what the authors agreed to be interesting with respect to how the participants used VR while lying down: This could be a movement, an utterance, a design limitation, or a way to interact with the virtual environment. We used descriptive codes and memos to detail interpretation, context information, or assumptions. Following Braun and Clarke [28]'s recommendation, we erred on the side of inclusion during initial coding. Irrelevant codes were dropped during theme construction. We used the following research questions to guide our analysis:

1. What is the user experience of using VR while lying in bed?
2. How do users move, or want to move, when using VR in bed?
3. How can users interact with the virtual environment?
(e.g., locomotion, object manipulation)

After the two simultaneous coding sessions, we created an initial loose grouping of codes to serve as an initial code system for coding the rest of the participants. In further sessions, authors individually coded three participants each by adding their codes to the existing code system. Finally, we held three 2-hour collective sessions to search for, construct, and review potential themes. During these sessions, we created a more detailed grouping and hierarchy of the codes and then merged and split codes as needed into the constructed themes. The themes were further refined during writing. Both the detailed grouping and the final themes with their codes are available in the supplementary material.

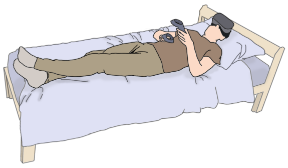
## 6.4 Results

During the study, we observed how participants experienced VR while lying down for the first time: some were highly active and engaged, whereas others preferred to lie mostly still and relax. At the start of the in-VR session, most participants remarked something about the strange virtual perspective that resulted from transforming the virtual coordinate space. While performing the task, the participants spoke about what they were doing, how it felt to do things in VR while lying down, or about the implications of lying down for their behavior. In moments of high concentration (e.g., a fast section in Beatsaber or landing the airplane in VTOL VR), it was difficult for the participants to think aloud and play at the same time. Sometimes, we reminded them to "keep talking." Other times, we asked them about an unfinished thought they had spoken about or something they were doing without commenting on it.

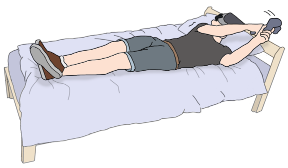
The participant's speech and movements in bed provided rich data about how they could and wanted to move while lying down and how it felt to use VR while lying down. We provide a 5-minute video in the supplementary material that summarizes the results and shows footage from the study. In the following, we present the results from our thematic analysis of this varied and fascinating data set.

**"It's just a lot of ab work!"—Common Movements are Surprisingly Hard in Bed.** Many VR applications require relatively small, precise, and localized full-body movements that we call "maneuvering" [131]. In standing VR, interactions like grabbing a cup from the other end of the table, looking around a corner, or ducking under an obstacle are straightforward and effortless. However, using VR while lying down highlights how frequently maneuvering is needed and yet how hard it is to do.

*Leaning:* While P12 is playing Beatsaber, they describe a lack of maneuverability: "I can't really move to the sides that much. I'm supposed to move to either left or right when there's a wall coming towards me, but that is difficult when you're lying in bed." The participants also lean to aim (Figure 6.7j and Figure 6.7b), which is slow and difficult:



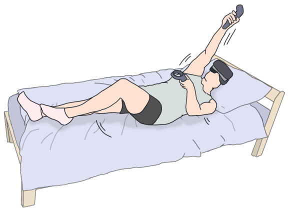
(a) Relaxing



(b) Aiming with torso

(c) Looking around

(d) Looking over shoulder



(e) Reaching forward

(f) Reaching with elbow support

(g) Aiming with the arms

(h) Sit-up to duck

(i) Sit-up to crouch

(j) Leaning sideways

(k) Straddling the bed

(l) Looking through body

Figure 6.7: This figure shows a selection of movements that the participants in the study performed while using VR applications in bed. The figures are directly based on the video data and thus accurately represent the participant's pose mid-action.

“Ok, so I’m trying to aim at the hidden barrels there, but this is very awkward for me here” (P2).

A user can lean in bed by engaging the abdominal muscles to lift the torso slightly off the bed to get enough clearance to tilt the torso left or right. The required ab crunch demands significant physical effort, which was highlighted by P8’s already sore muscles: “Leaning to the side is quite uncomfortable. But again, I already [had] a bit of an ab workout … yesterday.” Some participants used their legs as a counterweight or as an anchor for additional balance and support: For example, P1 straddled the bed to improve their “ability to dance [in Beatsaber]” (see Figure 6.7k).

*Reaching:* When lying down, reaching (Figure 6.7e) for something “[is] a workout when things are not right in front of you” (P9); due to the rotated coordinate space, users also need to pitch their head backwards to maintain a forward perspective. This movement was “weird” (P6), or as P9 put it: “Just not natural, at least. But it was doable. … I could still play the game.”

Compared to leaning, reaching forward is more strenuous if the user has to hold the position for a moment. While P2 is controlling a switchboard in front of them, they do an ab crunch to reach forward and remark: “Especially these kinds of interactions where you lean in, and you have to do multiple things while holding your abs, is pretty tiring.” Two participants figured out a solution by supporting themselves on one elbow while reaching forward (Figure 6.7f).

*Crouching:* The participants often found their object of interest to be lying on the ground (due to game design or after being dropped). This required them to crouch down virtually and grab the object. In Beatsaber, two of the songs included an overhead wall that needed to be dodged by moving down and under it. The applications in the study did not have the option to move down vertically other than through physical movement.[5] So, the participants used a sit-up (i.e., the fitness exercise) to virtually move down to duck (“ducking,” see Figure 6.7h) or to reach the ground to manipulate objects (“crouching,” see Figure 6.7i and Figure 6.9). Like reaching forward, ducking requires the participant to maintain sight of the target by pitching their head back, which does not feel natural.

Most participants were acutely aware of the need to crouch, but it took them a while to figure out that they could use a sit-up. For ducking, as in Beatsaber, the time pressure showed how a sit-up is not intuitive even if the participant had used crouching before: “Heading head-first into a barrier … Aaand I failed. Because I cannot duck, in a bed” (P14). Other unsuccessful responses were leaning hard to a side (P14), dragging themselves lower in the bed (P1), or leaning back into the bed, pressing their head into the pillow (P6). On the other hand, P10 had used a sit-up to crouch before and managed to duck just in time:

> Oh no! You have to duck for this?! [*Does a sit-up to dodge, lies back down.*] Oh, we’re bringing sit-ups into this. … Kind of counter-intuitive to have to sit up to duck. It’s interesting.

[5] Some applications, such as Afterlife VR, allow crouching by button press when playing in “Seated VR” mode.

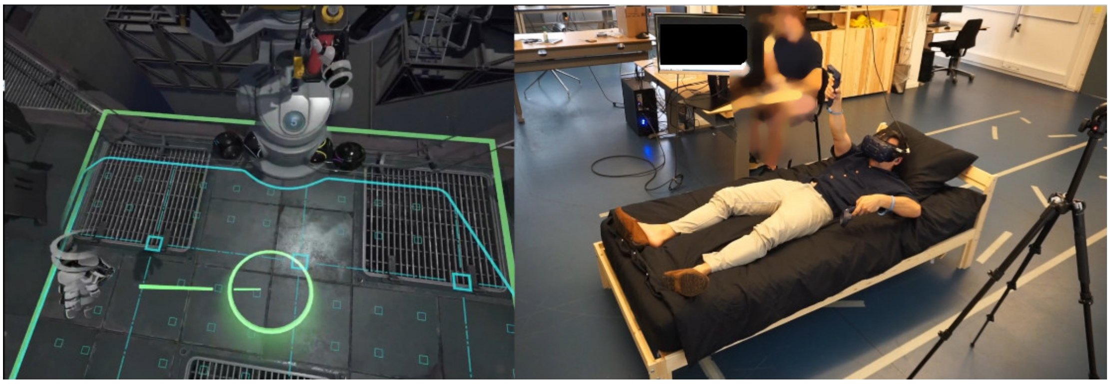


Figure 6.8: P2 (right) is trying to teleport backwards in The Lab: Slingshot (left). They are looking down to aim the teleport behind their feet by pitching their head down physically and angling their left hand to control the marker. Their right hand is still holding the catapult.

Most sit-ups were paired with grunting and comments on it being an "ab workout." P5 describes it as "grabbing something off the floor is [not exhausting, but] obviously way harder" (P5). P4 figured out an alternative to sitting up: they preferred "being lazy" in bed, and so when they see their weapon lying on the ground in Blade and Sorcery, they decide that "[it] is unreachable" and instead use the kicking mechanic to attack the enemy.

However, a sit-up can be less strenuous compared to leaning and reaching because the physical effort is minimal once sitting up. We regularly saw participants sit up for a moment before lying back down. Some participants enjoyed the physical effort required by ducking: "The walls are really fun! ... There's something really satisfying about having to account for that" (P3). Although sit-ups can "[disrupt] the flow of Beatsaber," some participants enjoyed how it "brings back some of the 'physicality' you normally have in Beatsaber" (P1) and that "[it's] good exercise" (P2).

*Looking around:* Virtually looking down is a common movement that is required to observe interaction at waist-height and on-body or to aim the teleportation (see Figure 6.8). However, an ab crunch is needed to move the chin towards the chest to look down. P4 said that "looking down is *so* fatiguing" and the physical effort appears to hamper task performance: "The constant neck strain from looking at the controls makes it hard to follow [the instructions]" (P5, VTOL VR). However, the participants were *able* to virtually look down, contrary to looking up, which was physically blocked by the bed.

Ironically, the limited field-of-view (FoV) of the headset means that more head rotations are needed: When standing, eye movements that are used to look around can be substituted for head movements with relative ease to account for the limited FoV. The headset is also specifically designed to maintain the "clear spot" of the lenses in an upright pose. When using VR lying down, the sub-optimal headset design and the pillow cause the headset to move around on the user's head, making it difficult to maintain a clear image. At the same time, because of the difficulty of moving the head when lying down, it is difficult to look around outside of the limited FoV.

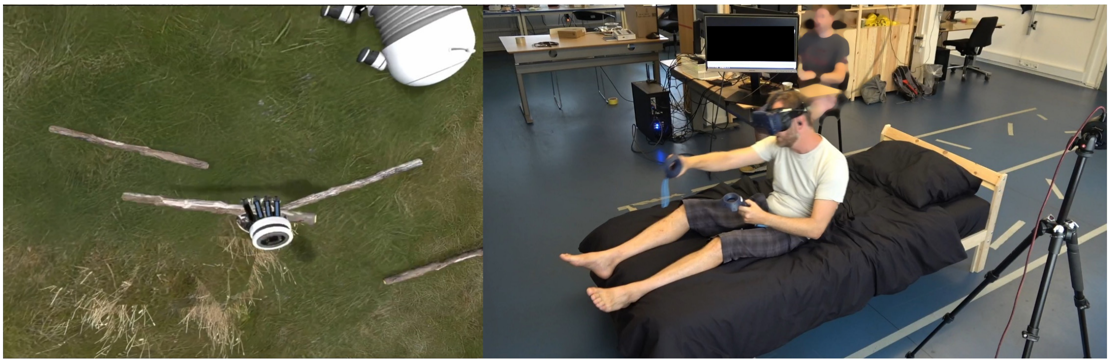


Figure 6.9: P12 (right) is trying to pick up the stick off the virtual ground in The Lab: Postcards (left) with their right hand, but in order to do so they physically need to do a sit-up to get close enough.

In order to look around, most participants lifted their head or torso off the pillow (see Figure 6.7c and Figure 6.7d) to enable a greater range of head movement at the cost of physical effort. This makes looking around take more time and require more energy than when standing, which affects task performance and enjoyment. Participants were comfortable lying down and did not *want* to move their heads (P3, VTOL VR):

> … because your head is so comfy in the pillow, you don't look around as much. And so I'm assuming [that] if I was sitting or standing … I would have looked over my shoulders a lot more.

*Translating:* The locomotion techniques in the applications, like joystick locomotion, teleportation, and snap-turning, were not precise enough to be used as an alternative for taking a physical step. All of these were difficult to control to move small distances, especially while simultaneously using the controllers to aim (Pavlov VR and Slingshot) or swing a weapon (Blade and Sorcery). P5 commented that "It put a lot more cognitive stress on me in a certain way, because I had to map the navigation to my hands. And at the same time … the games also put a lot of different actions on different hands."

However, when participants got used to the combination of controller-based locomotion and arm interaction while lying down, even the intense applications became usable: "Pavlov was okay, you could move around. And then [Blade and Sorcery], I think, was completely fine. I don't know if I adjusted to it maybe, but I didn't feel the difference so much" (P11).

Even when successful, using the locomotion techniques did not completely relieve the need for ab work: Turning around by button press (snap-turning) typically rotates the virtual view $\sim$45°, which then requires additional head rotations to get the desired perspective, and aiming to teleport requires an ab crunch to look down or to the sides. Teleporting backward is particularly difficult. P11 preferred an ab crunch in Slingshot over the awkward aiming of the teleportation: "I'm too lazy to teleport, so I have to reach out."

**"If you're moving so much, why not get up?"—The Challenge of Benefiting from Lying Down.** Intense applications, such as Blade and Sorcery, and applications that require crouching, were overall regarded as being uncomfortable and difficult. When asked about their ability to play the games, P13 responded: "I could do the mechanics, but I was like, if I'm rolling around in bed, why am I not getting up?"

However, when you can take a breath, lie back, and just use the controllers, then VR while lying down is very comfortable. Slower applications, such as Slingshot, Postcards, or VTOL VR worked well for this. Moreover, despite the additional physical effort, participants were surprisingly capable of using the applications.

*Relaxing and being comfortable:* Being comfortable or being able to relax were the most common positive experiences mentioned for VR while lying down. For example, P1 summarizes his experience as "surprisingly not weird. I was gonna say surprisingly comfortable." Figure 6.7a shows P13 relaxing and taking in the scenery in Postcards. When the movement requirements are low and the participant can relax, "it's so chill, doing something like this lying down" (P3, VTOL VR). P8 explains this nicely:

> I think for the most part, it felt good. But as soon as I had to perform … movements that are unnatural in bed like sitting up or, especially in Beatsaber in the end with leaning to the side, it got quite uncomfortable. But … when I was able to do the interactions, where I was lying and resting my elbows, and … the movement was constrained within that space, it actually felt totally fine and all.

Some participants were eager to put in a lot of physical effort, but others considered a trade-off between staying comfortable (lying down) and having to move to interact: "It's like nah, now, I'm lying in bed, I don't want to do some exercises. … But yeah, it's comfortable" (P4).

Among the more intense experiences, participants returned to a comfortable pose whenever possible. While lying down, P3 in Beatsaber "[puts their arms] down on the bed as soon as [they] get a chance." Similarly, participants enjoyed playing with the elbows on the bed. P14 exclaims in Beatsaber: "Ah, nice blocks! Now I can just stay in the middle, which is relaxing" and P10 "… realized that I can rest my arms, I don't have to hold them up all the time."

*Using the arms to interact:* Overall, interacting within arm's reach "without having to get up" (P8) worked well: "Everything that is really close, in this area [*signals area in front of torso*], is comfortable" (P4).

The participants also held their arms up in the air regularly for improved freedom of movement (e.g., Figure 6.7g or Figure 6.7k). For example, in Beatsaber for faster or wider movements, or in VTOL VR during moments that require high concentration (e.g., landing the airplane). Keeping the arms up for a prolonged duration is fatiguing, as explained by P10: "Well, I guess it's more tiring. Because you're fighting gravity with your arms." Fast arm movements were difficult because the bed was too "bouncy." P14 explains this nicely:

> … When doing the rapid movements, everything felt sort of laggy and oscil-

> lating. … My response time has gone down significantly when lying down, and I feel the bed shaking when I move too fast.

Despite the arms having relatively much freedom of movement while lying down, some movements remain challenging: The bed blocks the elbows (P3), which hampers performance in Beatsaber and Blade and Sorcery, where you need to swing your arms: "I miss the ability to do proper swings [*demonstrates elbows hitting bed*]" (P8). In Slingshot, many participants wanted to pull the catapult backward, which was blocked an elbow or controller hitting the bed or their own body. "I'm a little annoyed that my arm movement is restricted and [that] I have to use teleportation and look around a lot" (P6).

*Expectations of movement:* The participants associated a bed with comfort, relaxation, and rest. Sometimes they did not think about moving or did not want to move because of these assumptions of what a bed does: "When I'm lying down, I feel like I should not sit up" (P8). P1 explains how being aware of the fact that you're lying in bed can control your movement:

> I mean, you know, the first impulse is to step. You don't actually physically step and then realize, oh, no, I can't do that. You kind of stop yourself before you make the movement.

For many participants, the bed implied a certain level of comfort or relaxation. This study challenges this implication because the applications often required physical effort to be used. However, this was not always a bad thing: It "brings back some of the physicality … that you normally get while playing Beatsaber" (P1). Once you learn that you *can* move in bed it makes a large difference, which is explained well by P3:

> But then later on, … I just kind of realized that well, actually, you can just move around quite a lot more. Which is weird for a bed. But it's not weird for a game.

*Avoiding VR sickness:* The bed may relieve VR sickness by providing physical support. P11 explains this as a benefit similar to sitting down for VR: "I have quite strong nausea from moving games: Sometimes it helps when I sit down for games like this."

P2 and P3 expected the experience to cause VR sickness, but neither experienced it after using joystick locomotion and purposefully performing crazy flying maneuvers: "Surprisingly, not nauseating!" (P3). Similarly, P10 experienced less vertigo than normal:

> Because of being confined to a certain space, being locked into a bed, so to speak, I didn't have the fear of falling. I find often when flying, if I'm standing up, I will tilt my body … and I might almost fall over. … That doesn't happen when you're lying down. So it's sort of more comforting, in a way, though also more difficult in a different way.

Two participants did report significant VR sickness, but it is unclear what the cause was: P13 exposed themselves to a lot of mismatching visual motion by maintaining

Figure 6.10: P13 (right) is testing the limits in The Lab: Postcards (left). After looking over their shoulder, they wanted to turn around. Now they are lying prone and enjoying the view while looking around.

odd physical poses in bed (e.g., lying diagonally, looking upside-down). P12 appears to have been exceptionally sensitive to the mismatching virtual perspective because they complained about it more often and more strongly than other participants. Both had to use joystick-based locomotion as well. P13 thinks the bed contributed to their VR sickness: "Because this is a very springy bed it's creating a wobbly sensation, which I couldn't deal with very well."

**"I forgot that I'm lying down"—Embodiment and the Illusion of Standing Up.** Surprisingly, the illusion of standing up in VR works, even when in reality the user is lying down. Regardless of the haptic feedback of the bed pressing against the back instead of having the feet on the ground, and despite gravity informing the vestibular and proprioceptive senses of the orientation of the body in the world, it works. As P3 put it: "You do forget that you're … lying down. And it just feels like you're playing … kind of up against a wall in a weirdly constrained way."

One illusion of standing up is about the alignment between the physical and virtual body (e.g., legs straight or bent for sitting), and another is about the alignment between head movements and the view of the horizon (e.g., rotating the head rotates the view in unexpected ways).

*Embodiment:* Some participants mentioned embodiment and other body-based illusions. P13 commented that "I don't care about body orientations, it kind of just works" and that "I don't feel I'm in a wrong orientation ever, I feel like I'm just playing a game." However, the lack of movement can limit embodiment. For example, one of the most active players, P10, mentioned that the experience "is less immersive because I wasn't able to move like in real life." P3 said it's a "less embodied experience because the head is anchored."

Yet, the embodiment seems to work even if only the torso and hands are aligned with respect to the head. For example: in VTOL VR P7 and P14 looked down at the virtual chair and without a pause or prompt agreed that they are indeed sitting in a chair. P1 tested how they might feel about such a (mis)alignment in the body by pulling their legs up into a 90-degree angle, like sitting on a chair, and added in the interview: "No, the mismatch with the body wasn't that bad. And it certainly wasn't noticeable 90% of the time." P13 in Blade and Sorcery exclaims "Oh, I have a body now!"—as they notice the virtual full-body avatar.

*Perception of the horizon:* In connection with the illusion of standing, the participants talked about the horizon in the VR scenes and about feelings of gravity. When there is a clear horizon, and the user is looking forward in VR while lying down, the illusion of standing works very well, to the point where people do not question it. P10 commented that "it's interesting that you don't think about lying down or being upright. It feels natural." When the illusion broke, the participants regained it after a moment. P10 said that "I feel like my brain naturally compensates very quickly for not having gravity in the direction that it would usually have."

The participants had differing experiences regarding the effects of sitting up on the illusion. P12 commented that "sitting up breaks the illusion" as the floor looks vertical. P2 said, "the shift in the direction of gravity kind of … reminded me that I'm not in the same orientation to the game." For some, the illusion remained when sitting up to duck, as long as they kept their head straight forward with respect to their torso. P13 thinks aloud while testing the illusion:

> It works if I'm looking down [*sits up to duck, looks at the virtual ground*]; it works when I lean back and look forward [*lays back on the bed*]; but if I look [to the side], the world is getting tilted [*demonstrates looking to the side*].

Looking to the side when sitting up or when lying down "makes the horizon seem tilted" (P12) and typically broke the illusion. But, in Postcards, when P13 is looking out over the mountains, they comment that because the world is round, they can imagine the horizon tilting when rotating to the side, so it does not ruin their illusion. P13 experimented a lot with the virtual perspective (e.g., looking upside-down, Figure 6.7l) and also managed to retain the illusion when rotating around completely on their belly to look backward (see Figure 6.10): "… Somehow having the gravity be on my chest rather than on my back matched the image better. I actually really liked that. It was a little bit like scuba diving."

The illusion of standing up is precarious when there is no clear horizon. In the cave scene in Postcards, the ground slopes up to a hole in cave ceiling with a view of the sky. P10 commented that "This whole space seems to be slanted. It's a little bit disorienting that I can feel gravitationally that I'm lying down." P13 remembered that "[In the cave scene] it was harder to rationalize my body position." In Beatsaber, P12 describes that an unrealistic scenery could actually strengthen the illusion: "It felt more natural in Beatsaber. Because I was in some kind of zero gravity space, or in space, or in some non-real location."

Table 6.1: Based on the results and the related work, we have identified several design suggestions and directions for future work. We discuss the main ones in the text, but this table provides additional concrete opportunities.

| It's just a lot of ab work!—Common Movements are Surprisingly Hard in Bed. | | |
|---|---|---|
| **Movements in VR** | **Main Finding for VR while Lying Down** | **Suggestions for Design and Future Work** |
| Leaning | Leaning is restricted by the bed. | Support physical leaning through devices. |
| | Unable to step sideways. | Replace small sideways movements with an interaction technique. |
| Reaching | Holding an ab crunch to lift torso is fatiguing. | Let user interact just outside of arm's reach without moving closer. |
| | Pitching head up during sit-up is unnatural. | Bring area of interest closer to user, instead of vice-versa. |
| Crouching | Crouching to grab requires a sit-up. | Interaction technique to look down and move down easily in VR. |
| | Ducking to dodge is not intuitive. | Replace physical ducking with an interaction technique. |
| Looking around | Head is "anchored" in the pillow. | Improve HMD ergonomics to support head rotations. |
| | Looking up/down is physically straining. | Enable dynamic head pitch angle changes. |
| Translating & Turning | Locomotion is not precise enough. | Design locomotion techniques for maneuverability. |
| | Snap-turns are slow and disorienting. | Let user turn around quickly when action is all-around. |
| **If you're moving so much, why not get up?—The Challenge of Benefiting from Lying Down.** | | |
| **Experiences in VR** | **Main Finding for VR while Lying Down** | **Suggestions for Design and Future Work** |
| Being comfortable | Movement is physically straining. | Limit full-body movements and head rotations in bed. |
| | Improper head pitch is disorienting. | Calibrate head pitch angle to provide illusion of standing up. |
| | Holding up the arms is fatiguing. | Allow user to go back to resting position (elbows on bed) often. |
| Arm interaction | Interacting within arm's reach works well. | Provide main interaction in front of the user, at chest or head height. |
| | It is difficult to "see what you're doing." | Allow for easy, small head rotations to look around. |
| | A bed is too "bouncy" for fast movements. | Explore different surfaces to lie down on for intense movement. |
| Expectations | A bed implies relaxation, lack of effort. | Avoid gross bodily movement in an app designed for use in bed. |
| | Movement is beneficial while lying down. | Manage expectations of movement and interaction in bed. |
| VR Sickness | Joystick locomotion causes VR sickness. | Avoid sickness-inducing locomotion techniques. |
| | The bed can improve balance. | Provide a stable surface to lie on or support the body on. |
| | The virtual perspective can be disorienting. | Avoid breaking the illusion of standing up. |
| **I forgot that I'm lying down—Embodiment and the Illusion of Standing Up.** | | |
| **Experiences in VR** | **Main Finding for VR while Lying Down** | **Suggestions for Design and Future Work** |
| Embodiment | Embodiment despite the rotated VE. | How does awareness of the rotated VE influence embodiment? |
| | | How does haptic feedback of lying down influence embodiment? |
| Perception of Horizon | Illusion of standing up is precarious. | Maintain illusion of standing up during head rotations. |
| | | Explore use of illusion for non-standing users. |

## 6.5 Discussion

Based on our results, we have identified a number of implications for the design and future research of VR while lying down. We discuss those here in line with the three themes of section 6.4. Finally, we discuss use cases based on a user's ability and desire to move while lying down. We show some more implications in Table 6.1.

**Implications of Movement for Research and Design.** Our results show that maneuvering is one of the most significant limitations of using VR while lying down: To maneuver, users need to exert much physical effort to use alternative movements like sitting up. Some related work exists to improve the accessibility of VR (e.g., WalkinVR) or to design VR hardware specifically for use in bed (e.g., [120, 55]). However, more work is needed in the following directions to enable movement-rich interactions while lying down.

*We need interaction techniques to replace maneuvering when lying down.* However, this is not a trivial task. Consider the difference between virtually crouching to grab or duck: The former requires physical effort, but the user can rest at the top of the sit-up, and the illusion of their position in the virtual world can remain intact. Ducking under an obstacle, however, requires fast reaction time and sight of the target (the object to be dodged). Some proposed hardware solutions enable VR use while lying down (see section 6.2), but these only allow left-right head rotations and maintain the body in a stationary supine pose (see Figure 6.2). VR applications demand more than that, so researchers and designers need to create new interaction techniques to enable maneuvering, avoid maneuvering, or make users think they are maneuvering.

*Future designs for VR while lying down should leverage the legs.* For example: by using the hips for rotation control, the feet for locomotion, or the whole legs in a walking-in-place locomotion technique. Participants complained that the existing locomotion controls were difficult to use because they were on the same controller that needed to be swung at an enemy or aimed at a target. By offloading the locomotion controls to the legs, this problem can be solved. In real life, crouching, ducking, and side-stepping rely on the legs to move the user and maintain balance. Legs were used in our study to provide additional balance and support, but not directly to interact. Although our applications did not support leg-based interaction, there is ample previous work on foot-based interaction (see [297] for an overview) to kick-start new interaction techniques for VR while lying down.

*Physical head rotations should be supported and augmented.* We need the ability to use head rotations to effectively interact with VR applications and benefit from the immersion of VR. Looking around while lying down was difficult enough, physically straining enough, that users would rather not move and stay comfortable. So, the ability to turn the head left or right and especially up or down should be better supported. Several aspects should be considered in future work to better support head rotations. First, the ergonomics of the headset: Currently, the HMD interferes with head rotations left and right and it moves too freely on the face, causing the clear view through the lenses to shift. Improvements to the field-of-view of the HMD could allow the user to more easily look around with their eyes before requiring head rotations. Second, physical head rotations could be supported by hardware solutions (e.g., [55]), but also need to consider up and down rotations. Third, novel interaction techniques should be designed to let the user vary how much they look up or down dynamically, with only minimal physical head movements.

*Strenuous physical movements can be replaced with game mechanics.* Rather than using alternative physical movements to interact while lying down, we can integrate new interaction techniques into the experience. An example of this was demonstrated by a participant, who decided at some point during the session that they did not want to do a sit-up to grab a weapon off the floor. Instead, they used an existing mechanic, kicking, to attack the enemy, which meant they could remain lying down and comfortable. A similar idea exists in the popular VR application Half Life: Alyx[6], where the protagonist can pull faraway objects closer using their "gravity gloves." Both of these techniques have the added benefit that they stay true to the application's universe while greatly

[6]https://store.steampowered.com/app/546560

improving users' ability to interact. Many techniques for object interaction at a distance exist [10] as well as for locomotion [53]. The challenge for future work is to determine which of these are most suitable for use in VR while lying down.

*We need locomotion techniques for small, not just medium, distances.* It was surprising to see how difficult popular VR applications become when maneuvering is not an option, and the only choices are typical locomotion techniques or ab crunches. At first sight, locomotion techniques are an obvious alternative to maneuvering, as they are in seated VR. However, the more restricted freedom of movement while lying down makes locomotion techniques like joystick control, teleportation, or snap-turning not precise enough for maneuvering. Normally, they do not need to be, as they are designed for use with the more common standing VR experiences. In section 6.2, we discussed how the field of accessibility of VR has some overlap with VR while lying down, and the lack of good interaction techniques for users with limited movement (by choice or necessity) is a prime example. We need locomotion techniques to allow users to maneuver while lying down. We suggest that VR designers consider how, for example, a supine user could compete for a top-3 score in Beatsaber.

**Implications of the Bed for Research and Design.** Apart from the challenges of maneuvering, we found many aspects of lying in bed to work well for VR. Being comfortable is the main benefit, and applications with low movement requirements (e.g., VTOL VR and Postcards) work quite well without additional improvements. Other low-intensity VR applications, such as watching a movie, browsing the web, or doing office work, can be readily adapted to lying-down use. However, several issues will remain, such as limited head rotation, arm fatigue after prolonged use, and limited maneuvering (e.g., when grabbing an object). Here, we discuss some opportunities to leverage the benefits of lying down.

*Manage expectation of comfort versus effort.* For most users, a bed comes with the *expectation* of being comfortable. We saw this in how users did not want to or did not know to move while lying down. Having to move to interact (e.g., the infamous ab crunch) causes discomfort and thus frustration. However, just lying in bed is very comfortable, and the participants enjoyed VR experiences with low spatial and temporal movement requirements, such as VTOL VR, Postcards without crouching, or Beatsaber at low difficulty. However, designing relaxing experiences that integrate a small amount of movement is a good opportunity to create engaging VR experiences. We expect that small maneuvers like leaning, reaching, or turning on a side are acceptable, but managing the user's expectations is crucial: a relaxing experience for use in bed should not require physical effort, but an exercise application for the sofa could.

*Expand the usable area of interaction for the arms.* The bed provides a stable basis of support, which supports comfortable interaction with the arms and relieves VR sickness. Using the arms with the elbows on the bed was considered to be very pleasant and offers an interesting design opportunity for VR when lying down. Applications like Beatsaber, VTOL VR, and Postcards could all be enjoyed while keeping the arms comfortably supported by the bed. On the other hand, the bed also blocked some arm movements at the elbow or hand. There is a relatively small space where arm interaction is easy, between the arm's reach and the "wall" of the bed. Future work should investigate how we can (virtually) extend the area where arm interaction is easy and comfortable. For example, existing work on improving the ergonomics of VR interaction through hand redirection may be extended to lying down VR [170].

*Explore the use of VR for reclining and lying on other surfaces.* In this study, the participants all used the same single bed. However, there are many more surfaces where a user could be supine: double beds, softer or harder surfaces, sofas, recliners, and even the floor. We found that the bounciness of the bed can hamper performance for expert users who need fast movements. Furthermore, the pillow did not work as well for everyone. Small differences in the results may be observed for different supine surfaces. For example: lying on the floor may improve performance at the cost of comfort.

Another obvious use case of VR for comfort would be to sit or recline on a sofa or chair. The VR hardware and the software we used to rotate the coordinate space can easily be adapted to different non-vertical poses. We speculate, however, that the experience of these different poses and surfaces will vary slightly from our observed results. For one, the illusion of standing up may be more powerful when supine, and so a different reclining angle may be less effective [106, 105]. Second, some movement restrictions will be alleviated depending on the surfaces (e.g., head rotation on a chair), but others will change or remain (e.g., the back of the sofa may prevent elbow movement when seated or whole arm movements when lying down). Third, a user may be more likely to change pose when not in bed, for example: going from lying down to leaning to sitting upright on a sofa. Currently, our system does not dynamically adapt to these changes. Exploring the impacts of updating the transformed coordinate space during changes in pose remains an exciting avenue for future work.

*Use locomotion techniques that do not cause VR sickness.* Future work should investigate the effect of lying down on VR sickness in a controlled lab study, as our work provided conflicting results. Some participants suggested that the bed may relieve VR sickness—likely by improving balance. However, previous work suggests that VR while lying down causes VR sickness [150], and two participants reported VR sickness. Considering the limitations of previous work, the exceptional movement of our participants, and participants' comments on VR sickness relief, it is impossible to conclude the effect of lying down on VR sickness.

**How Do Haptic and Vestibular Sensations Influence Embodiment?** Proprioception is known to influence embodiment [223, 78]. In our study, the visual and proprioceptive cues were congruent: when looking down or holding the hands in front of their face, the participant could see the parts of their virtual body being collocated with and moving like their physical body. However, the visual feedback of standing was incongruent with both the haptic and the vestibular sensations of lying down. The backside of the body pressing against the bed provides a haptic sensation of lying down, and gravity pulling on the horizontal body provides a vestibular sensation of lying down. Regardless of the conflict between these two sensory perceptions and visual perceptions, our participants experienced embodiment.

Vestibular and haptic information contribute to the experience of embodiment through multisensory integration: congruency increases the illusory effect of body ownership and embodiment (e.g., [148, 205]), and incongruency severely hampers it. Research in

Table 6.2: We can distinguish four types of use cases for VR when lying down, based on whether the user can move (Ability) while lying down and whether they want to (Desire). In this table, we show an example use case for each scenario. The scenarios where a user can move (italics) are the most promising.

| **Desire** | **Ability** | |
|---|---|---|
| | **Yes** | **No** |
| **Yes** | Exercise | *Bed-bound* |
| **No** | *Travel* | MRI |

neuroscience shows that without vestibular sensations (e.g., in microgravity), the sense of disembodiment is not severe. But, both the neural measures [148] and subjective perceptions [205] indicate significant reductions in body ownership when the sensations conflict.

Nevertheless, our results suggest that people experience embodiment when using VR while lying down. This has two implications for future work. First, investigating how the components of embodiment, such as body ownership and self-location are perceived while lying down could help in understanding why, and when, the illusion of standing can be created. Second, when understanding how the illusion of standing can be induced, the visual-vestibular mismatch can be employed in applications to improve body ownership or provide even stronger experiences, such as allowing bed-bound patients to experience the freedom of walking.

**Use Cases of VR when Lying Down.** "I don't want to use VR while lying down if I don't have to" summarizes what many participants felt after the study. A bed is comfortable, but much of the comfort comes from the lack of physical effort. When using VR in bed, our participants had to use a lot of physical effort to be able to interact with the applications. This negates the expected benefits of lying in bed and leads to frustration and little motivation to use VR while lying down. Based on the related work and our results, we can distinguish two high-level ways by which users may use VR while lying down: by choice or out of necessity. Based on this, Table 6.2 provides an overview of use cases for VR while lying down.

*You can, but do not want to move:* By choice, a user may lie down for comfort (e.g., on a bed or sofa) or because lying down holds a benefit. For comfort, movement should be limited and the focus should be on relaxation and immersion. Immersive animations, movies, or travel experiences are examples of suitable applications according to our participants. Still, these experiences can benefit from hand-based interaction and easy head rotations.

*You cannot move, but want to:* Out of necessity, on the other hand, a user may lie down because they cannot do otherwise (bed-bound users with chronic ailments, hospital patients, etc.) or because it is required by the application. For bed-bound users who are in hospitals, undergoing therapy or rehabilitation, or have to lie down due to chronic ailments, VR can offer a welcome distraction or improved treatment. Several recent forum posts show that bed-bound users have a need for using VR while lying down in bed (e.g., [280, 102]) that has not been satisfied yet. Furthermore, in section 6.2, we discussed the increasing popularity of VR for pain relief (e.g., [172]), which could be further improved with movement-based interaction. In these scenarios the users may not have full use of their body, so use cases in this scenario will be bound by the ability of the user and the goal of the application.

*You can and you want to move:* If the surface to lie on is not a bed, there may not be an expectation of comfort. Furthermore, different surfaces can have different benefits for applications where users can—and want to—move. For example, a military stretcher provides more freedom of movement for exercise, while lying prone in an underwater rig supports the haptic experience of being underwater in VR. Or, perhaps the bed is simply used for VR sickness relief while playing an intense game. While most users found the abdominal crunch uncomfortable and needlessly fatiguing, some users commented that it brings back some of the “physicality” of standing use of the application (e.g., Beatsaber). In any case, the user may want to move as much as possible, and the limit depends on the application.

*You cannot move and do not want to:* Finally, in some use cases, the user may be lying down and not want to move. For example, while lying in an MRI scanner or lying down in a dentist’s chair while wearing a VR headset to relieve anxiety. In some cases, the user has been sitting upright while using VR in bed (e.g., SyncVR Medical and other hospital applications), but our work shows that lying down with a transformed coordinate space is a pleasant experience. In any of these cases, an interesting direction for future work is the illusions embodiment and standing up, specifically while the user is stationary and lying down. It may be possible to design an interaction technique that makes the user believe they are moving to interact based on illusions and minimal physical input.

## 6.6 Conclusions

In this work, we conducted a study to find out how users experience virtual reality (VR) while lying down and how they move around physically and virtually. We discussed how VR has been used when users are lying down, but we found that the use of contemporary, movement-rich applications has not been considered yet. So, in a qualitative study with 14 experienced VR users and six popular VR applications, we investigated how users move, how they want to interact, and how they feel while using virtual reality in bed. Our results show that the lack of maneuvering while lying down is a significant challenge for interacting with VR applications. However, using VR in bed also has many benefits (e.g., comfort), and the transformed virtual coordinate space produces embodiment and a potent illusion of standing up in the virtual environment. We have discussed the key implications of our themes on future research and design. In addition, we have provided a discussion of use cases for VR while lying down and a table of concrete suggestions. In conclusion, our work shows that using VR while lying down has great potential, regardless of whether the user aims for comfort, exercise, new experiences, or entertainment.

# 7 How Your Physical Environment Affects Spatial Presence

This chapter presents the paper "How Your Physical Environment Affects Spatial Presence in Virtual Reality" [290]. This is a manuscript that comprises a full research paper on par with the other included papers.


## Abstract

Virtual reality (VR) is often used in small physical spaces, requiring users to remain aware of their environment to avoid injury or damage. However, this can reduce their spatial presence in VR. Previous work and theory lack an account of how the physical environment (PE) affects spatial presence. To address this gap, we investigated the effect on spatial presence of (1) the degree of spatial knowledge of the PE and (2) knowledge of and (3) collision with obstacles in the PE. Our findings suggest that limiting spatial knowledge of the PE increases spatial presence initially but amplifies the detrimental effect of obstacle collisions. Repeatedly avoiding obstacles further decreases spatial presence, but removing them from the user's path yields a partial recovery. Our work contributes empirical evidence to theories of spatial presence formation and highlights the need to consider the physical environment when designing for presence in VR.

**Title:**
How Your Physical Environment Affects Spatial Presence in Virtual Reality.

**Authors:**
*Thomas van Gemert*, Jarrod Knibbe, and Eduardo Velloso.

**Venue:**
Not applicable.

**What was the role of the PhD student in designing the study?**
The student designed and carried out the study.

**How did the PhD student participate in data collection and/or theory development?**
The student carried out theory development, data collection, and part of the analysis.

**Which part of the manuscript did the PhD student write or contribute to?**
The student wrote and contributed to the entire manuscript.

**Did the PhD student read and comment on the final manuscript?**
Yes.

Figure 7.1: A virtual reality (VR) user is charging at an enemy during a battle in VR. This person feels spatially present in the virtual environment, but how does knowing that there is a breakable vase in the room affect this sense of presence? And what if the user collides with it? Partially created with images generated by SDXL 1.0 [258].

## 7.1 Introduction

Imagine a virtual reality (VR) user who has assumed the role of a Viking fighting an enemy army (see Figure 7.1). If the user is spatially present in VR, their self-location, perceived possible actions, and mental capacities are all bound to the virtual environment (VE) [311]. The user charges at their enemy, blissfully ignoring their physical environment (PE), and consequently runs into the expensive vase in their living room. Such scenarios are common [50] and negatively affect users' health, safety, and property. In practice, users can still retain some awareness of their PE, but it is unclear how this affects their spatial presence in VR. Previous work in HCI has explored options for incorporating elements of the PE into the VE, such as visualising physical boundaries [72, 85], incorporating haptic proxies [247, 246], or designing transitional environments [262, 254]. However, it is unclear how unseen features of the PE—such as walls or obstacles—affect spatial presence in the VE.

To address this gap, it is necessary to understand how spatial presence is formed. Several theories of presence have been proposed (see [176, 80] for an overview), but we build upon Wirth et al.'s process model [311] because it (a) integrates ideas from other theories, (b) considers the "struggle" between being present in the PE or VE, and (c) provides a concrete framework of how spatial presence is formed. According to the model, spatial presence is a two-dimensional construct of "self-location"—the experience of being physically situated in the VE—and "perceived possible actions"—when the VE, instead of the PE, informs which (spatial) actions a user can take [311]. Becoming spatially present is a two-step process: first, the user constructs a cognitive representation of the spatial logic of the VE; second, they adopt this spatial mental model, instead of that of the PE, as their egocentric reference frame. At this point, we assume that if the VE allows the user to walk, we expect them to walk regardless of the boundaries of the PE.

However, previous work and theory do not sufficiently answer several questions posed by our scenario. For example, if a user enters VR and remembers, without directly perceiving it, that there is a physical obstacle in their path, do they remain spatially present in the PE to avoid a collision, or do they become spatially present in the VE regardless? Further, what happens to spatial presence upon collision with an obstacle? Does spatial presence degrade over time as the user repeatedly avoids the obstacle, or can it recover if the obstacle is no longer relevant? Finally, if a user had little knowledge of the PE around them, would this confuse them or enhance their presence in VR?

These questions inspired the creation of the current work. To answer them, we conducted two controlled lab experiments. In Study 1 (N=40), we manipulate (i) whether the user can see the physical space before entering VR (being "blindfolded") and (ii) whether there is a physical soft obstacle in the space that is not visible in VR. We model their effects on spatial presence at the beginning and at the end of the task. Study 2 (N=20) further investigates how spatial presence changes after repeatedly avoiding the obstacle and how it recovers after its removal. We model the effect of an obstacle on spatial presence over time; before encountering the obstacle, after the collision, after avoiding it, and after navigation without obstacles.

Our results suggest that participants are spatially present in VR and are unaware of the physical boundaries even if there is an obstacle. Spatial presence is even higher if the user comes into VR with little knowledge of their physical environment (blindfolded). But, collisions with the physical environment drastically lower spatial presence, more so for users who came into VR blindfolded. Repeatedly avoiding an obstacle in the physical space further reduces spatial presence, but spatial presence partially recovers when the risk of collision with the obstacle is removed from the path. To conclude, we discuss how the results answer our questions and how they fit into Wirth et al.'s model of Spatial Presence formation. We further illustrate and explain our results with qualitative data from recorded videos and interviews. Finally, we discuss how the results help design future VR experiences that require a high degree of spatial presence.

## 7.2 Background

"Presence" is a multifaceted theoretical concept with many conceptualisations, definitions, and operationalisations [176]. For example, Lee et al. distinguish between physical, social, and self-presence [136], and IJsselstein et al. distinguish between spatial, social, and co-presence [94]. Specifically, this paper focuses on *spatial presence*, which relates to the conviction of being physically located in a virtual environment (VE) [311]. In recent years, theories of spatial presence (e.g., [311, 228, 253, 236]) have started to converge, and largely agree that spatial presence is a subjective, binary experience about one's physical location being in the virtual environment, which in turn informs behavior [80]. Wirth et al. define spatial presence as follows:

> Spatial Presence is a binary experience, during which perceived self-location and, in most cases, perceived action possibilities are connected to a mediated spatial environment, and mental capacities are bound by the mediated environment instead of reality [311].

More broadly, users can be spatially present in the environment of books, movies, and other traditional media [311, 81, 235], but the immersive power of virtual reality (VR) (see [47]) has reinvigorated the discussion of what Presence is and how it is formed. In this section, we elaborate on Wirth et al.'s theory of spatial presence formation for two main reasons: for one, it provides a comparatively more detailed account of the role of the physical environment, and two, it clearly considers the role of perceived possible actions in spatial presence, which is relevant when considering the effect of an obstacle (as in our example). While a comparative discussion between different theories of presence is beyond the scope of this work, we refer the interested reader to Hartmann et al. [80], Murphy & Skarbez [176], or Skarbez et al. [249].

In the field of human-computer interaction, specifically in virtual reality research, "presence" is commonly investigated: It is used as both the goal and the quality measure of a VR simulation. Effects on presence are typically achieved through innovation in hardware, software, or interaction design. Previous work has considered the role of the physical environment (PE) in several ways, for example: George et al. [72] recognize that a visual boundary indication in VR requires shifting visual attention to the PE, which may affect presence. He et al. designed several visualisations of physical boundaries to raise VR users' situational awareness of the PE without reducing presence [85]. Tseng et al. designed an interaction technique specifically for confined spaces, recognizing the potential for breaks in presence resulting from collisions with the physical environment: They reported that participants experienced higher presence and safety, and had fewer collisions [283]. There is also ample work on the use of proxy objects in virtual reality, where physical objects or obstacles are represented in VR to improve presence, provide haptic feedback, or create ecologically valid boundaries (e.g., [247, 246, 9, 48, 185, 288]). However, in any of these cases, there is a proxy representation of the physical environment in the virtual environment that can affect presence. Tseng et al.'s work is closer to how we think about the influence of the PE on spatial presence, but their study was focused on evaluating an interaction technique. It remains unclear how awareness of, or collisions with, the physical environment (PE) can affect spatial presence, particularly when there is no representation of the PE in virtual reality.

**A Process Model for the Formation of Spatial Presence.** Wirth et al.'s model of spatial presence formation [311] comprises two critical steps: the formation of a "spatial situation model" (SSM) of the mediated space—the VE—and the acceptance of that SSM as the user's primary egocentric reference frame (PERF). Figure 7.2 shows this process in a diagram.

The first step, creating a spatial situation model, requires allocating *attention* to the mediated space and the processing of *spatial cues*. Attention allocation happens both involuntarily and voluntarily and is influenced by media factors (e.g., vividness) and user factors (e.g., interest), respectively. Attention is a necessary, but not sufficient, component of SSM construction, and thus of spatial presence formation [311, 80, 81].

Once attention is allocated to the spatial stimulus, users construct a cognitive representation of the spatial scene and its logic as provided by the medium [311, 80]. This construction is both a bottom-up—based on spatial cues—and top-down—based on spatial knowledge to "fill in the blanks"—process that allows for continuous adaptation. Spatial cues are typically visual (e.g., perspective, texture), but may also include other modalities, for example: spatial audio [87], haptic [227], or vestibular cues [216]. Throughout

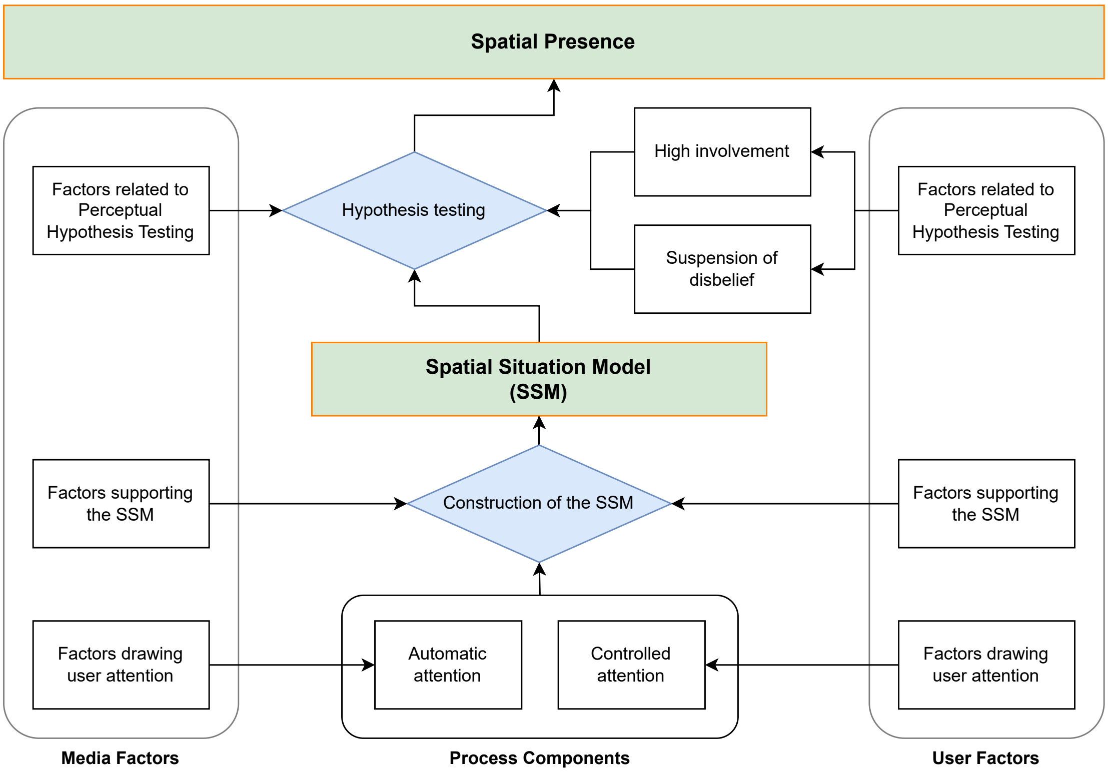



Figure 7.2: A diagram of the two-level process model of spatial presence formation. The first level comprises the construction of a spatial situation model (SSM). The second level comprises the process of perceptual hypothesis testing, after which spatial presence can emerge if the "the virtual environment is my primary egocentric reference frame"-hypothesis is accepted. Adapted from Wirth et al. [311].

the construction process, user factors (e.g., spatial imagery skill) and media factors (e.g. spatial cue modality) affect SSM construction. An SSM should be "strong" (rich and consistent) and coherent, which is achieved through "a variety of concise spatial cues (preferably within different perceptual channels), which are linked in a consistent and plausible manner" [311]. As such, virtual reality typically supports the creation of strong SSMs.

The second step consists of the user, consciously or subconsciously, deciding whether to use the SSM of the virtual or physical space as their primary egocentric reference frame. While an SSM is merely a cognitive representation of a space, an egocentric reference frame (ERF) is a first-person perspective of the user's body and immediate surroundings; it tells the user where they are in a space [216]. When constructing an SSM of a virtual space, a user may also create an ERF, and this ERF may be different from the ERF of the PE. Users can have multiple ERFs, which leads to uncertainty as to which one is "active" (the *primary* egocentric reference frame (PERF)) [216]. If, and only if, a user accepts their spatial model of the VE as their PERF, they become spatially present. At that point, the user's "perceived self-location, perceived possible actions and mental capacities are all bound to the mediated space" [311].

This crucial decision is made according to the theory of perceptual hypothesis testing [30]. When presented with uncertainty around which space is the PERF, a user may form two competing hypotheses: that the PE is the PERF and that the VE is the PERF (dubbed the "Medium-as-PERF" hypothesis in [311]). Through perception of the environment, either hypothesis receives more support and stabilises over time; when enough perceptual evidence exists, the hypothesis and related PERF are accepted. A richer, more internally consistent SSM contributes to a strong hypothesis that needs less evidence to be confirmed.

Virtual reality blocks most perception of the physical environment. So, as the user interacts with the virtual environment (VE), their perceptions strongly favour the "Virtual-as-PERF" hypothesis, leading to spatial presence arising quickly and strongly. However, it is clear that being spatially present in the VE relies on many things "going right." This is not always the case, and so we discuss how to answer the questions posed in the introduction according to this model.

**Spatial Presence and the Physical Environment.** In the introduction, we raised the question of whether the user would remain aware of obstacles in their physical environment by choice. In Wirth et al.'s model, many user factors, not in the least controlled attention, can be used to disregard evidence for the "Virtual-as-PERF" hypothesis and "choose" to be spatially present in the physical environment. However, given the likely strength of the virtual hypothesis due to VR's immersive power and user interaction with the VE, we expect this to be exceptional. Hartmann et al. report that the process model theory remains unclear about the role of emotions or "hot mechanisms" on spatial presence [80]. So, fear, apprehension, or emotional responses resulting from knowledge of an obstacle—for example, if the user has negative previous experiences—could affect spatial presence. As such, *it is still unclear whether knowing that an obstacle is present in the PE before entering VR could hinder the formation of spatial presence in the VE* (**RQ1**).

The process model acknowledges that users have a "Real world-as-PERF" alternative hypothesis, and we can reasonably assume that users will typically have a strong SSM of the physical environment (PE). However, *it is not clear what happens when the user does* not *have a (strong) SSM of the physical environment* (**RQ3**). Wirth et al. [311] build upon Lilli and Frey, who suggest that the strength of a perceptual hypothesis determines the probability that the hypothesis will be activated, the amount of information required to confirm it, and the amount of contradictory information necessary to disprove it [144]. As such, if a user were to come into an unknown physical environment with most of their perceptions of the PE blocked ("blindfolded," as it were) and entered VR, their physical SSM would be weak (following Wirth et al.'s discussion of what makes an SSM strong), and so by extension their "PE-as-PERF" hypothesis would be weak compared to the virtual hypothesis. This entails that the user should become spatially present by default, requiring minimal perceptual evidence. Alternatively, we consider the possibility that the weak physical SSM may include some assumptions (through the top-down construction path) about the physical environment. For example, a user may assume there are boundaries *somewhere*, and they will refuse to become spatially present in the VE according to our hypothesis in the previous paragraph.

If a spatially present user collides with an obstacle in the physical environment (PE), we expect a *break in spatial presence, as the collision diverts attention away from the virtual scene, and the perception is inconsistent with the user's current mental models* (**RQ2**). Then, one of two things can happen: One, if there are major discrepancies between the spatial cues and an SSM, it may be extended or replaced [311]. So, the invisible obstacle may be integrated into the virtual SSM and the user will quickly regain spatial presence using the now consistent virtual SSM. Two, the invisible obstacle is in-congruent with the virtual SSM, leading to a weak virtual hypothesis. Further, contact with the obstacle provides perceptual evidence against the virtual, and perhaps in favour of the physical hypothesis. Finally, navigating around the obstacle requires attending the physical instead of the VE. So, as long as the obstacle remains relevant to the user's task, *it is unclear how spatial presence degrades and recovers over time* (**RQ5**).

Further, it is unclear *whether having a weak SSM of the physical environment (PE), as in RQ3, interacts with the effect of obstacle collision* (**RQ4**). Compared to a user with a typical, strong SSM of the PE, we expect a user with a weak PE to be less spatially present in the VE. We assume the mechanism is the same as explained above. However, a user with a weak physical SSM may assume there are more invisible obstacles in the unknown PE. This means that navigating the physical space in VR requires constant attention. In contrast, a user with a strong physical SSM will be aware of the boundaries of the PE and may thus become spatially present again when interacting within the boundaries, where they do not perceive the physical environment anymore. On the other hand, the physical hypothesis remains weak, and although the user's mental models of the VE are inconsistent, they may still be *more* consistent, error-free, and evident than the physical, and thus be accepted as the primary egocentric reference frame [80].

## 7.3 Study 1

Based on the discussion in section 7.2, we formulate the following research questions that we aim to address in Study 1:

**RQ1:** How does the *knowledge* of obstacles in the physical environment—that are not perceivable in the virtual environment—affect spatial presence?

**RQ2:** How does the *collision* with obstacles in the physical environment—that are not perceivable in the virtual environment—affect spatial presence?

**RQ3:** How does a *weak spatial situation model* of the physical environment affect spatial presence in the virtual environment?

**RQ4:** How does a weak spatial situation model of the physical environment affect spatial presence in the virtual environment *after collision with an obstacle*?

**Method.** Study 1 is a $2 \times 2$, full-factorial, mixed-methods lab experiment. Our independent variables are the presence of an obstacle in the physical environment (Obstacle; between-participants) and whether participants were allowed to see the physical environment for the first time before entering virtual reality (Blindfolded; within-participants).

We tested the effects of these variables on spatial presence (SP) measured shortly after entering the VE ($SP_{pre}$) and at the end of the experience ($SP_{post}$). The order of all conditions was fully counter-balanced. This research was approved by the University of Melbourne's ethics committee under application number 25822.

**Independent variables.** *Blindfolded:* We operationalised the strength of the spatial situation model (SSM) of the PE by controlling whether participants could see the lab room before entering virtual reality (VR). In the Blindfolded condition, participants put on a VR headset and noise-cancelling headphones in a separate room and were guided by the experimenter into the lab space without touching any walls or surfaces. When not Blindfolded, participants could see the lab before wearing the headset and headphones. In addition, to strengthen the SSM in this condition, participants performed a controlled walk around the space.

*Obstacle:* We operationalised the presence of an obstacle in the environment by adding a soft partition wall that partially separated the lab room (see Figure 7.3b and Figure 7.5b). The location of the obstacle would interfere with the task in the virtual environment in some trials. The soft obstacle comprised a wall of cardboard boxes that absorb impact, resulting in a recognisable but safe collision.

In sum, we end up with the following four conditions: Blindfolded-Obstacle, Blindfolded-No Obstacle, non-Blindfolded-Obstacle, and non-Blindfolded-No Obstacle. The latter condition may be interpreted as a baseline condition that is comparable to everyday VR use.

**Dependent Variables:** Spatial Presence *(*$SP_{pre}$ *and* $SP_{post}$*)* is our primary dependent variable. We measure spatial presence using the Spatial Presence Experience Scale (SPES) [81]. The scale measures the two dimensions of spatial presence according to Wirth et al.'s model [311]: self-location (SL) and perceived possible actions (PA). The questionnaire consists of four questions per dimension that a participant rates on a 1–7 Likert scale from "Strongly disagree" to "Strongly agree." The SPES was administered within the VR application during the task (see Figure 7.4b).

We conducted an initial measurement of spatial presence ($SP_{pre}$) after the participant completed two of the ten trials. This allowed participants time to become spatially present in the virtual environment (VE). We conducted the second measurement after completing all ten tasks ($SP_{post}$). The SPES was designed to work with various media, from books to VR, so it refers to the object of the questionnaire as "the environment of the presentation." To remove any ambiguity, we changed it to "the environment of the Viking village." The exact questions are provided in the supplementary material.[1]

To further illustrate and contextualize our spatial presence results, we collect qualitative data on participant behavior. During the experiment, two cameras recorded the user. Each camera was placed on the ceiling at an opposite angle, so we could view participants' behavior throughout the space. Intuitively, we are interested in whether a participant's spatial behavior (how they move, navigate the space, circumvent obstacles,

[1] `https://osf.io/v6uy4/?view_only=d86d3395b80945a2998066ae82938600`

(a) Empty Lab Room (b) Lab Room with Partition Wall

Figure 7.3: An overview of the physical environment for Study 1 and Study 2. The room is approximately 5.5m×7m and comprises a carpet floor and soft, padded walls for the most part. In (b), the partition wall is shown that partially separates the space and acts as an obstacle in the task.

etc.) changes due to an effect of Obstacle or Blindfolded. Such behavioral data can be highly informative for explaining results that may otherwise remain in the domain of effect sizes and ordinal ratings.

First, we coded the video footage of the experiment, counting the number of *collisions* per trial. We further differentiate between collisions (typically unintentional, contact with head or torso) with the obstacle wall and the room, and *contact* moments (deliberately touching the PE, typically due to "scanning" while moving).

At the end of the experiment, we conducted an approximately 5-minute semi-structured interview. We used the interview to ask participants directly about their *experience*, their *awareness* of the physical space, the effect of *collision*, and how they *coped* (changed behaviour, emotional state, or presence) with the obstacle. Two authors used these four themes to code transcripts of the interviews deductively.[2] The transcripts were generated by Otter.ai[3] and then edited for clarity by the experimenter.

**Experimental setup.** The experiment occurred in a university user experience laboratory (UX lab) with a large rectangular experimental space (5.5m×7m, see Figure 7.3a) and an adjacent observation room. In the Obstacle condition, a partition wall was placed at the halfway point, partially splitting the room in half (see Figure 7.3b). The wall blocked a length of 300cm across, leaving a 235cm gap in the space for the participant to move through.

In the Blindfolded condition, we fitted the participant with the VR headset (turned off) and headphones in the observation room and then guided them through the rest of the UX lab for approximately one minute before leading them into the lab room to start the experiment.

[2]Using the free Taguette software: `https://www.taguette.org`

[3]`https://otter.ai`


(a) Selecting an item on the workbench. (b) SPES question #4.

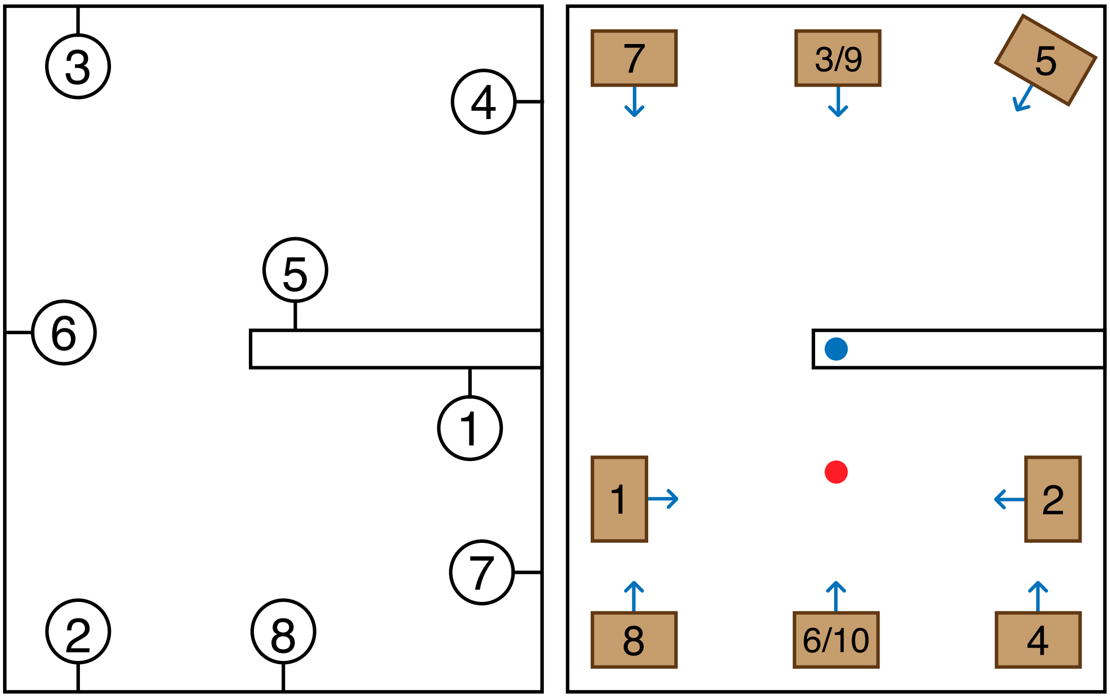
Figure 7.4: An example of the items and workbench used for the task (a) and an example of the SPES questionnaire from the participant's point-of-view (b).

The virtual environment (VE) was a Viking village based on the Unity "Viking Village URP" demo [275]. We adapted the assets and scene to run at a stable 72 frames-per-second on the Oculus Quest 2 headset. The participant interacted with the VE using the Quest controllers displayed in the VE as two hands. The hands were animated according to button presses on the controller. There was no virtual avatar other than the hands. We constructed two task locations within the village with a flat, open space of at least 10m$\times$10m. The VE and physical environment (PE) were aligned so participants would not touch the lab walls during the task. The order of the locations was counterbalanced across participants and within-subject conditions. An example of the locations is shown in Figure 7.3b. The application is available in the supplementary material.

**Task.** During the briefing, participants were told they were playing a part in a story:

> You are a Viking, part of a group of Vikings settling down in a new village. As such, the construction of the village is not finished yet. Today, your group has gone raiding, leaving you behind to finish the village construction. Your task is to walk to the different workbenches in the village and pick the item that makes the most sense to build the construction in the image. If you get it wrong, try again to find the correct one.

Each trial consisted of walking to a workbench in the virtual environment (VE) and picking an item. Each condition comprised ten workbench locations, shown in Figure 7.5b. The locations were designed to guide the participants through the space in a zig-zag pattern that conflicted with the obstacle in the conditions with an Obstacle. In particular, trials 3, 4, 5, 6, and 10 were designed so that the participant had to circumvent the obstacle to complete the task.




(a) Top-down view of the physical space with the task locations for the controlled walk in the non-Blindfolded condition.

(b) Locations of the virtual workbenches mapped to a top-down view of the physical space.

Figure 7.5: A top-down overview of the task locations and their order. Figure 7.5a shows the locations that participants visited in the physical environment during the controlled walking task at the start of the non-Blindfolded conditions. In Figure 7.5b the workbench locations in the virtual environment are shown relative to the physical environment. The blue dot marks the center of the room. The red dot marks the participant's starting position. The rectangle in the middle depicts the partition wall. In this example, the partition wall is present. In the No Obstacle conditions, the wall would be removed.

In each trial, each workbench displayed three items and a picture of the village with a building to be constructed. When the participant selected the correct item, the building was constructed in the village. When they selected an incorrect item, it was highlighted in red, and the participant needed to try again until they found the correct item. We did not measure participants' performance on these tasks, as they were only meant to elicit movement around the space.

**Participants.** We recruited 40 participants from the local university community. Both between-participant groups included 10 men and 10 women (gender was self-reported through a free-text form, and we randomly assigned them to each group while maintaining an even balance). The call was posted on the university notice board, in lectures, and advertised through word-of-mouth. We excluded participants known to the researchers and those familiar with the lab space. Upon completing the experiment, each participant was thanked for their time with a gift card worth $\approx 13$ USD.

The mean total experiment duration was $43 \pm 6.6$ (SD) minutes. The VR exposure time (excluding tutorial) for the first condition had a mean duration of $5.9 \pm 1.6$ minutes, and for the second task, $5 \pm 1.5$ minutes. We asked participants how often they had used VR for 30 minutes or more: Most reported to have *Never* (n=24) used VR, with some using VR *1 or 2 times a year* (n=13) and a few *1 or 2 times a month* (n=2) or *1 or 2 times a week* (n=1).

**Procedure.** When participants arrived in the observation room, we obtained informed consent and then measured their inter-pupillary distance (IPD) and explained how to wear and adjust the hardware.

In the Blindfolded condition, we explained that we would take them to a different room while they were "blindfolded" (wearing the turned-off headset and noise-cancelling headphones). We then led participants on a route through the lab by carefully leading them along by holding the controllers they were holding. This route went into another room, turned back, and entered the lab room through a secondary door. The route was intended to make participants believe they were in a different room or at least to reset their beliefs about their physical surroundings. This was plausible, given that the laboratory included multiple lab rooms. We turned on the headset once the participant arrived at the starting position.

Participants completed a tutorial in VR at different moments depending on the condition. The tutorial was implemented in the VR application in an empty VE with one example building and a workbench. The tutorial explained the task to the user using text prompts and object selection exercises (no walking). During the tutorial, the experimenter stayed nearby to answer any questions. In the non-Blindfolded conditions, participants first came into the lab room, completed the tutorial, and then took off the VR equipment to complete a quick exercise in the lab room: At each of the locations shown in Figure 7.5a they had to solve a simple addition that pointed them to the next location. This ensured that they walked through the entire physical environment and were aware of the wall, if applicable. Then, the participant would put on the VR equipment once again in the starting position, and the main task would start. In the Blindfolded condition, the participant was led into the lab room, the tutorial was started, and the main task started immediately after.

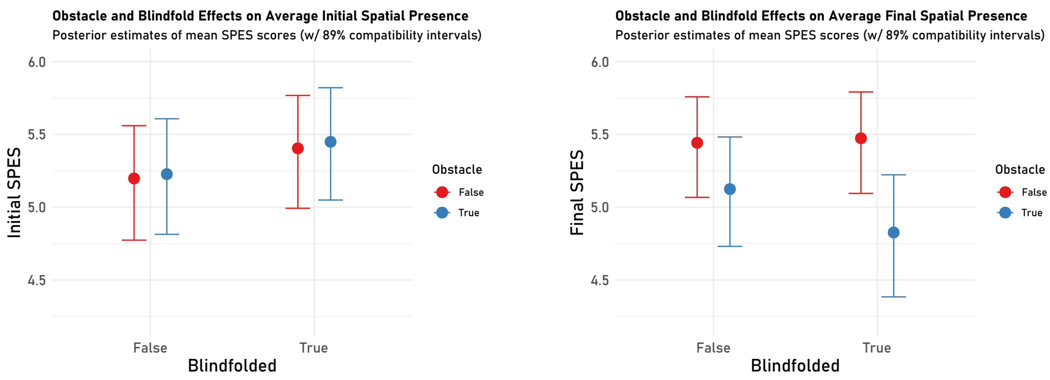
When the main task was finished, participants took the VR system off and walked back to the observation room. Then, the next condition was started per the procedure above. Finally, after the second task, we conducted the interview in the observation room.

**Statistical Analysis.** We analyze our results using Bayesian statistical methods. We chose this approach for its additional flexibility, ability to quantify uncertainty, and ability to facilitate future work to build upon it. For a comprehensive argument for using Bayesian methods instead of conventional frequentist statistics in HCI, see Kay et al. [107]. We refer readers unfamiliar with such methods to McElreath [159] for a didactic introduction and to Schmettow [233] for their application in HCI examples. As such, we draw attention away from p-values and null-hypothesis significance testing and focus our discussion on causal modeling and parameter estimation.

We model the initial and final SPES scores (both total scores and split by SL and PA) in the same multivariate model. The value expected for each response is based on a cumulative probit model applied to a latent variable in relation to six thresholds, estimated from the data (we refer the reader to Liddell and Kruschke for a tutorial on this kind of analysis [143]). This models each ordinal category's relative probability by slicing a continuous latent space at 6 cut-points. Our latent variable is modeled as coming from a normal distribution with a scale of 1 and a mean that varies from trial to trial. We use weakly informative regularizing priors for the model parameters (see Kurz [119] for a tutorial). The priors for the thresholds are drawn from normal distributions with a standard deviation of 2 and means obtained by slicing the latent variable with regions of the same probability mass. Main and interaction effects are drawn from a normal distribution with a mean of 0 and a standard deviation of 0.5, except for the effect of $\mathrm{SP}_{pre}$ on $\mathrm{SP}_{post}$, which was drawn from a normal with a mean of 1. We model participant-dependent and question-dependent random effects as partially pooled intercepts drawn from a normal distribution with a mean of 0 and a standard deviation that was estimated from the data.

We fit our models using the `brms` package [33], which implements Bayesian multilevel models in R using the Stan probabilistic programming language [36]. We assessed the convergence and stability of the Markov Chain Monte Carlo sampling with R-hat, which should be lower than 1.01 [296] and the Effective Sample Size (ESS), which should be greater than 1000 [33]. All our estimates fit these criteria. We report the posterior means of parameter estimates, the standard deviation of these estimates, and the bounds of the 89% compatibility interval (a.k.a. credible interval) for them in Table 7.1. In using 89% compatibility intervals, we follow McElreath's recommendation to avoid confusion with the frequentist 95% confidence interval [159], which has a different interpretation.[4] The full model details and implementation can be found in the supplementary material.

[4]An 89% compatibility interval indicates that, given the data, the model specification, and the prior belief, there is a 89% probability that the true estimate lies within the given range.




(a) Initial spatial presence

(b) Final spatial presence

Figure 7.6: Posterior estimates of the conditional effects of obstacle and blindfold on initial and final spatial presence scores.

## 7.4 Results

We built two models: a more flexible one modeling the effects of all independent variables and their interactions on our dependent variables and a simplified one including only our theoretical claims. Figure 7.6 shows the posterior estimates of the conditional effects of the presence of the obstacle and coming into the lab blindfolded on the initial and final spatial presence scores. The obstacle had a negligible main effect (mean = 0.04 [-0.43, 0.51]) and interaction effect (mean = 0.02 [-0.24, 0.27]) on the initial presence. In turn, the main effect of coming in blindfolded on the final presence was negligible, once accounting for its effect on the initial presence (mean = 0.04 [0.16, 0.24]). As such, we removed these effects in our final theorized model (reported in Table 7.1).

We compared the two models with leave-one-out cross-validation as implemented in the `loo` package [295]. The simpler model demonstrated better performance, and the difference in expected predictive accuracy ($\Delta ELPD = -1.5$) was five times larger than its standard error ($SE(\Delta ELPD) = .3$).

The parameter estimates reported in Table 7.1 are in the scale of the latent variable. Because this distribution has a standard deviation of one, parameter estimates for dummy-coded variables can be interpreted as a measure of effect size similar to a conditional Cohen's $\delta$ [119].

As expected, there was a positive association between the initial and final SPES scores (mean =.42 [.34, .49]). Coming into the VR environment blindfolded led to higher initial presence ratings (mean = .24 [.11, .38]). The obstacle in the middle of the room had an overall negative effect on the final spatial presence (mean = -.42 [-.86,.03]). Being blindfolded led to no meaningful increase in the final presence (mean = .07 [-.13,.27]) when there was no obstacle but compounded the detrimental effect of collision with an obstacle (mean = -.36 [-.55,-.17]), as evidenced by the interaction between these variables.

To explicate the mechanisms through which our conditions have an effect on spatial presence, we built two additional models that split responses by the underlying dimensions of the SPES, *self-location* and *perceived possible actions*. Table 7.1 and Figure 7.7

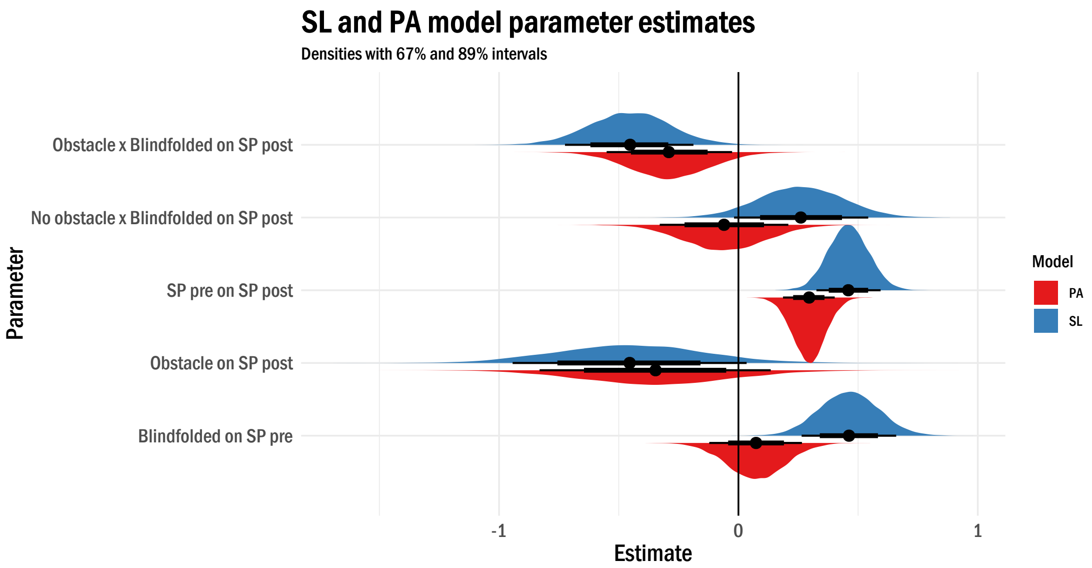



Figure 7.7: Distributions of parameter estimates for the models for self-location (SL) and perceived possible actions (PA)

Table 7.1: Summary of the multivariate model for presence ratings with the full SPES, self-location questions only (SL), and possible action questions only (PA). We provide the posterior means of parameter estimates (Est.), posterior standard deviations of these estimates (SD), and the bounds of their 89% compatibility interval. All parameter estimates converged with an ESS well above 1000 and an R-hat of 1.00.

| | **SPES (all)** | | | **SL** | | | **PA** | | |
|---|---|---|---|---|---|---|---|---|---|
| **Parameter** | **Est.** | **SD** | **89% CI** | **Est.** | **SD** | **89% CI** | **Est.** | **SD** | 89% CI |
| **SP**$_{pre}$ | | | | | | | | | |
| $\tau_{pre}[1]$ | -2.99 | 0.29 | [-3.44, -2.53] | -3.32 | 0.51 | [-4.23, -2.16] | -2.88 | 0.43 | [-3.52, -2.17] |
| $\tau_{pre}[2]$ | -2.50 | 0.26 | [-2.90, -2.09] | -2.75 | 0.46 | [-3.53, -1.66] | -2.32 | 0.40 | [-2.90, -1.66] |
| $\tau_{pre}[3]$ | -1.62 | 0.24 | [-2.01, -1.23] | -1.78 | 0.43 | [-2.49, -0.72] | -1.39 | 0.39 | [-1.93, -0.73] |
| $\tau_{pre}[4]$ | -0.99 | 0.24 | [-1.37, -0.61] | -1.17 | 0.42 | [-1.85, -0.11] | -0.69 | 0.38 | [-1.22, -0.04] |
| $\tau_{pre}[5]$ | 0.39 | 0.24 | [0.01, 0.78] | 0.46 | 0.42 | [-0.20, 1.54] | 0.65 | 0.38 | [0.13, 1.31] |
| $\tau_{pre}[6]$ | 1.39 | 0.25 | [1.00, 1.78] | 1.72 | 0.43 | [1.72, 0.43] | 1.50 | 0.39 | [0.97, 2.17] |
| B$_{pre}$ | 0.24 | 0.09 | [ 0.11, 0.38] | 0.46 | 0.12 | [0.22, 0.71] | 0.07 | 0.12 | [-0.12, 0.27 ] |
| **SP**$_{post}$ | | | | | | | | | |
| $\tau_{post}[1]$ | -1.79 | 0.40 | [-2.44, -1.15] | -2.16 | 0.63 | [-3.38, -0.92] | -2.21 | 0.56 | [-3.09, -1.32] |
| $\tau_{post}[2]$ | -0.89 | 0.38 | [-1.50, -0.27] | -0.84 | 0.58 | [-1.95, 0.35] | -1.34 | 0.53 | [-2.17, -0.49] |
| $\tau_{post}[3]$ | 0.28 | 0.38 | [-0.33, 0.90] | 0.40 | 0.58 | [-0.70, 1.59] | -0.09 | 0.53 | [-0.91, 0.77] |
| $\tau_{post}[4]$ | 0.86 | 0.39 | [0.25, 1.49] | 1.02 | 0.58 | [-0.08, 2.21] | 0.51 | 0.54 | [-0.33, 1.37] |
| $\tau_{post}[5]$ | 2.24 | 0.39 | [1.63, 2.88] | 2.39 | 0.59 | [1.28, 3.60] | 2.01 | 0.55 | [1.17, 2.89] |
| $\tau_{post}[6]$ | 3.89 | 0.41 | [3.24, 4.55] | 4.09 | 0.61 | [2.94, 5.36] | 3.61 | 0.57 | [2.75, 4.52] |
| SP$_{pre}$ | 0.42 | 0.05 | [0.34, 0.49] | 0.46 | 0.12 | [0.22, 0.71] | 0.29 | 0.07 | [0.19, 0.40] |
| O | -0.42 | 0.28 | [-0.86, 0.03] | -0.45 | 0.31 | [-1.04, 0.15] | -0.35 | 0.30 | [-0.83, 0.13] |
| O$_{false}\times$B | 0.07 | 0.13 | [-0.13, 0.27] | 0.26 | 0.18 | [-0.08, 0.60] | -0.06 | 0.17 | [-0.33, 0.21] |
| O$_{true}\times$B | -0.36 | 0.12 | [-0.55, -0.17] | -0.45 | 0.17 | [-0.79, -0.12] | -0.29 | 0.16 | [-0.55, -0.03] |

show that our independent variables' effect was not uniform across the two dimensions.

The initial increase in spatial presence that happens by coming into the VE blindfolded happens through an increased self-location score (mean = .46, [.22,.71]) but not through perceived possible actions (mean = 0.07, [-.12, .27]). In the absence of an obstacle, this effect was also observed on the final scores (mean effect on SL = .26, [-.08, .60]; mean effect on PA = -.06, [-.33, .21]). However, the detrimental effect of a collision led to a decrease in presence in both dimensions (mean effect on SL = -.42 [-.86, 0.03]; mean effect on PA = -.35 [-.83, .13]). The interaction effect of being blindfolded when colliding with an obstacle was also observed in both dimensions (mean effect on SL = -.36 [-.55, -.17]; mean effect on PA = -.29 [-.55, .03]).

## 7.5 Study 2

In Study 1, we only collected two spatial presence measures in each trial. As such, it is unclear how the effects evolved over time. In particular, we were left with two important questions: What happens after repeated encounters with an obstacle, and would presence recover as participants got used to avoiding the obstacle, or would it decrease further? This is specified in the following research question that Study 2 addresses:

**RQ5:** How does removing the risk of collision with an obstacle in the physical environment affect spatial presence in the virtual environment?

**Method.** To investigate, we set up a lab study that is identical to Study 1 except for the following variations. We only evaluated one condition (Blindfolded-Obstacle), but we administered the SPES multiple times throughout the experiment. We measured participants' spatial presence before interaction with the physical environment (stage 1, similar to trials 1 & 2 in Study 1), immediately after collision with the obstacle (stage 2), after repeatedly having to circumvent the obstacle to complete the virtual task (stage 3), and after completing the task on a different path that avoids the obstacle (stage 4). Study 2 comprised 16 trials instead of 10. In particular, we conducted a spatial presence measurement at the end of trials 6, 7, 11, and 16. Before trial 6, the task guided the participant between locations 7 and 8 in Figure 7.5b, so they had no interaction with the physical environment (PE). Between 6 and 11, the task locations alternate between 4 and 5, so the participant had to circumvent the obstacle to complete the task. After trial 11, the task path changed back to 7 and 8, so the participant could once again complete the task without interaction with the PE.

**Participants.** We recruited 20 participants from the local university community. There were ten men and ten women (gender was self-reported through a free-text form). The call was posted on the university notice board, in lectures, and advertised through word-of-mouth. We excluded participants known to the researchers and those familiar with the lab space. Upon completing the experiment, each participant was thanked for their time with a gift card worth $\approx$7.5 USD.

| Parameter | Estimate | Est. Error | 89% CI |
|---|---|---|---|
| $\tau_{pre}[1]$ | -4.18 | 0.42 | [-4.84, -3.52] |
| $\tau_{pre}[2]$ | -2.96 | 0.34 | [-3.50, -2.42] |
| $\tau_{pre}[3]$ | -1.85 | 0.33 | [-2.36, -1.32] |
| $\tau_{pre}[4]$ | -1.28 | 0.33 | [-1.79, -0.75] |
| $\tau_{pre}[5]$ | -0.36 | 0.33 | [-0.87, 0.16] |
| $\tau_{pre}[6]$ | 1.09 | 0.33 | [0.58, 1.62] |
| Stage 2 | -0.65 | 0.12 | [-0.85, -0.45] |
| Stage 3 | -1.00 | 0.12 | [-1.20, -0.80] |
| Stage 4 | -0.67 | 0.12 | [-0.87, -0.47] |

Table 7.2: Summary of the ordinal regression model for the SPES ratings. We provide the posterior means of parameter estimates (Est.), posterior standard deviations of these estimates (SD), and the bounds of their 89% compatibility interval. All parameter estimates converged with an ESS well above 1000 and an R-hat of 1.00

## 7.6 Results

Similarly to our approach in Study 1, we operationalized spatial presence as the four SPES scores, modeled with a cumulative probit model applied to a latent variable. We use the posteriors from Study 1 as priors for this model. We model participant-dependent and question-dependent random effects as partially pooled intercepts drawn from a normal distribution with mean zero and standard deviation estimated from the data. We built the model and assessed its convergence in the same way as in Study 1. Table 7.2 shows the model estimates.

As in Study 1, we observed a substantial drop in spatial presence after the collision with the obstacle (mean = -.65 [-.85, -.45] ). Having to repeatedly avoid the obstacle led to a further drop in spatial presence (mean = -1.00 [-1.20, -.80]). Removing the obstacle from the task path yielded a partial recovery of spatial presence, although not to the baseline level (see Figure 7.9), but similar to the initial drop in presence caused by the first collision (mean = -.67 [-.87, -.47]). Figure 7.8 shows the distributions of the effect estimates relative to the baseline for each stage of the experiment and Figure 7.9 shows posterior predictive conditional effects on the ratings.

## 7.7 General Discussion

In this section, we discuss the results of Studies 1 and 2 with respect to our research questions, the theory outlined in section 7.2, and the qualitative data. Our aim is to interpret the results in section 7.4 and section 7.6 in a broader context and discuss implications and possible limitations.

**RQ1: How does knowledge of obstacles in the physical environment—that are not perceivable in the virtual environment—affect spatial presence?** In the first study, we compared the initial spatial presence scores of participants who could see the physical environment (PE) before entering virtual reality (VR) (the non-Blindfolded condition) to

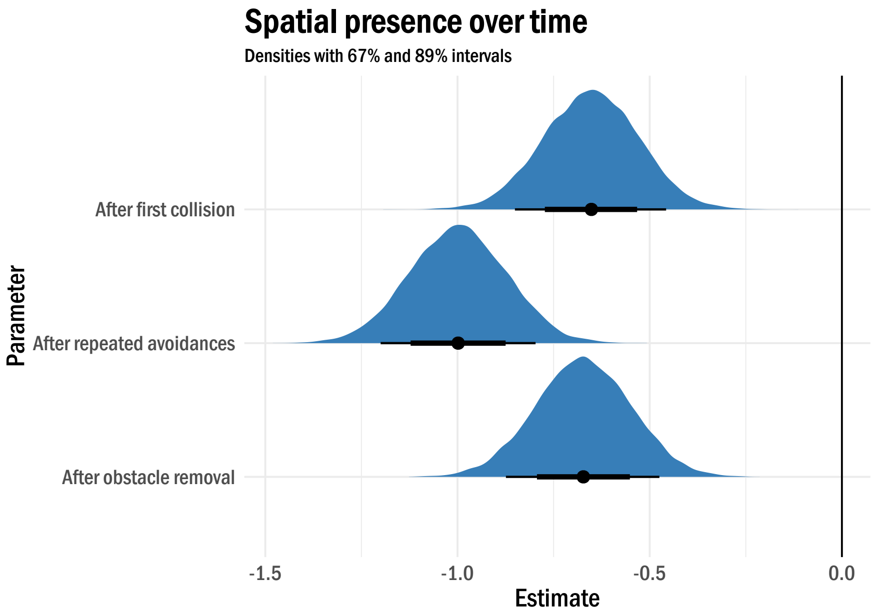



Figure 7.8: Distributions of effect estimates for the decrease in SPES scores relative to the initial, after the first collision with an obstacle, after having to repeatedly avoid the obstacle, and after repeated interactions that did not require the user to avoid the obstacle.

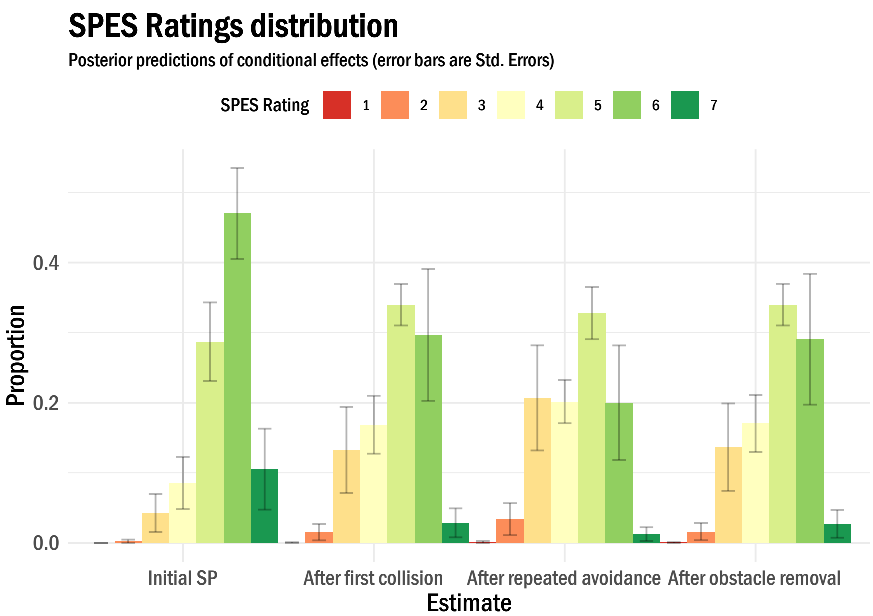



Figure 7.9: Model posterior predictions for SPES ratings at the four stages of the second experiment. Error bars represent the standard error of the estimates.

those who were blindfolded and unaware of any obstacles (the Blindfolded condition). In subsection 7.2 we considered the possibility that *knowing* the boundaries of the PE or that there is an obstacle would prevent a user from becoming spatially present. However, the estimated effect was negligible. This suggests that merely having knowledge of PE's limitations is not enough to negatively affect spatial presence in the VE. Participants completed two tasks in the VE without any perception of, or interaction with, the PE and thus had ample time and opportunity to become spatially present. Only user conviction or conflicting evidence from the PE would have prevented spatial presence formation.

By design, there was no such conflicting evidence in the first two trials. However, In the third trial, participants had to cross the space and could collide with an obstacle. That was an opportune moment for participants to remember their physical surroundings and adjust their behaviour. However, all ten participants who experienced the non-blindfolded condition first collided with the obstacle. This is in contrast to starting blindfolded: In that case, all participants had previously collided with the obstacle and all avoided collision. This indicates that the obstacle simply "being there" is not enough to convince users to alter their behaviour or prevent spatial presence. However, collisions with the physical environment are. We tested for this order effect statistically but found no meaningful differences in SPES scores.

This point is further corroborated by remarks in the interview from four participants with VR experience (P29, P36, P38, P39), who hesitated to move around because they had experienced collisions in VR before and assumed there would be boundaries somewhere. For example, P29 said: "I was really hesitant to just simply walk because when you guided me in, I didn't have a perception of how big the room is. Coming from my previous VR experiences, I won't be able to fully enjoy something before I know my boundaries." These participants also noted that this hesitation disappeared as they completed the tasks. Unfortunately, we had only a small number of experienced participants, and experience was not evenly distributed among the conditions, so we could not test this statistically. On the other hand, previous work has shown that increased game experience can lead to higher spatial presence levels [14, 128, 301]. Future work should investigate the effect of previous VR experience on spatial presence formation.

Three possible limitations could explain the observed result. First, participants were never told to avoid obstacles or boundaries, only to walk in VR. Thus, the relevance of the obstacle in the context of the VR task was not evident, so it is unlikely that participants paid much attention to it. Second, although we allowed participants to familiarise themselves with the PE before entering the virtual environment (VE), this was a short experience. We cannot assume that their spatial situation model (SSM) of the PE was as strong as that of their home environment. P12 said "I think its hard to maintain those spatial boundaries when you're inside a completely different environment … Your mind immediately just switches into that context, and the surroundings you see become the surroundings that you also tend to look out for." Future work should investigate whether the stronger SSM of familiar spaces further hinders spatial presence formation. Third, participants could have perceived the room as a safe space (e.g., "I trusted that you would put me in a very open space," P17). Indeed, the padding on the walls and the obstacle made the risk of injury negligible. Raising the perceived stakes of a collision may have led to more careful behaviour. However, special care must be taken to design such an experiment safely and ethically.

**RQ2: How does collision with obstacles in the physical environment—that are not perceivable in the virtual environment—affect spatial presence?** In section 7.2, we discussed that upon collision, spatial presence should drop and over time could either recover or decrease. The results of Study 1 support the latter—we found a large negative effect of the obstacle on spatial presence in both the self-location (SL) and perceived possible actions (PA) dimensions. This supports the first part of our hypothesis. Study 2 corroborated this and showed evidence for a further decrease: We observed a large drop in spatial presence immediately after a collision and an additional drop after participants had to avoid the obstacle repeatedly. This supports the idea that the invisible obstacle is not ameliorated with the virtual SSM but instead requires frequent, possibly constant, attending to the physical space, causing frequent breaks in spatial presence.

We observed a large variation in the effect of the obstacle on spatial presence in Study 1. Judging by the variety of participant behaviour we observed in the videos, we suspect user characteristics would explain this. First, we observed generally two types of users in the first conditions with an obstacle: 12 of the 20 participants became quite cautious after a collision, showing a mixture of slow walking, arms or hands outstretched, and a limited indication that they were trying to walk around the wall (e.g., "I tried to like slow down my walking … usually putting my hands in front to make sure I can touch the wall," P16). However, 8 participants continued almost normally after the collision. Some used "scanning strategies," like holding out their hand to detect the wall in time, but maintained their walking speed and quickly adapted to avoid the obstacle. For example, P6, P14, and P17 all mentioned that the collision made them realise their experience was virtual reality and not real. On the other hand, P12 said: "I did not feel like I was taken out of [the virtual] world, because I thought, well, there are so many sensory inputs and this was just one sensory input that was taking me out of the experience. The audio, the visuals were still in that Viking world. So I was mostly still anchored in that reality, and [the collision] was just mild annoyance." So, there appear to be important differences in how users coped with the unexpected obstacle, so there may have been different effects on spatial presence. We tried incorporating both the number of collision and contact moments and the order of the conditions into the model to explain the variance, but we found no effect. More work is needed to quantify or control participant behaviour to investigate how physical obstacles affect spatial presence.

Our experiment design and results provide some support for spatial presence being a binary experience [311, 252]: Spatial presence scores were not extremely low, despite the negative effects of obstacle (See Figure 7.9). If spatial presence is a binary experience, it may switch on and off frequently during a VR experience, and users may internally average over their spatial presence "count" to give an ordinal rating on a questionnaire like the SPES. In the Obstacle condition, the obstacle is only relevant when crossing the space, requiring attention to the physical world. However, the tasks at the workbenches are still "safe" and allow the user to become present again. The Obstacle condition is then a series of alternating on/off spatial presence experiences that result in a lower, but not near-zero rating of spatial presence.

Finally, two limitations could have affected the effects of obstacles on spatial presence. In both studies, a few participants overcompensated when avoiding the obstacle and touched the opposite wall. We intended the obstacle to be the only contact point, and it is unclear how this unexpected behaviour affected the results. We speculate that the additional contact could have caused additional breaks in presence, leading to lower spatial presence scores in the obstacle conditions. Further, most participants attempted to touch the obstacle to affirm its position and guide themselves around it. It is unclear whether this “grounding” has a positive or negative effect.

Second, typical collisions during VR use, such as a hand brushing against an object or a leg touching the couch, are more subtle than colliding with a (soft) wall. The collisions in our study are also very different from observing a chaperone boundary in VR and being reminded of the physical environment in that way. Previous work has shown that different visualizations of a chaperone system can negatively affect presence (e.g., [313, 72, 85]), but it is unclear whether those affects are as strong as the ones in this work, especially after repeated encounters.

The chaperone system (“Guardian” on Oculus systems) and its impact on spatial presence deserves more attention in general. Several participants discussed feelings of trust and betrayal in their interviews, suggesting that they had expected us, the experimenters, to keep them clear of obstacles. This is an important caveat of lab studies in general, but it may also carry over to the chaperone: When users first initialise a VR session, most headsets require them to specify the boundaries of their play space. The user is then reminded of these boundaries by a visual grid during play. In this way, the user hands off the responsibility for maintaining awareness of the PE to the system, thus allowing for greater spatial presence in the VE. On the other hand, collisions still happen (e.g., [50]), for example in in fast-movement experiences such as BeatSaber or PistolWhip, where the guardian does not react fast enough. This may also lead to more cautious behaviour and lower spatial presence going forward. The interaction between spatial presence, user awareness of the PE, and chaperone systems deserves further exploration.

**RQ3: How does a weak spatial situation model of the physical environment affect spatial presence in the virtual environment?** In section 7.2, we expected two possible outcomes: either spatial presence is lower because users are cautious or higher because the virtual egocentric reference frame is “the only option.” The results show a positive effect of blindfolding on initial spatial presence, which supports the latter. According to Wirth et al.’s model, this makes sense: a strong spatial situation model (SSM) is formed through multimodal congruent and internally consistent spatial cues over time, so blindfolding will lead to a weaker SSM of the physical environment (PE). The hypothesis that the virtual environment (VE) is the primary egocentric reference frame is relatively stronger.

Once we controlled for initial spatial presence, we did not observe an additional effect on final spatial presence. The initial spatial presence score has, as expected, a large positive effect on final spatial presence. This suggests that the initial trials set a baseline for spatial presence that was not further affected by being blindfolded. This baseline was higher when blindfolded, meaning that all other things being equal, having a weak SSM of the physical environment leads to higher spatial presence.

In the non-Blindfolded condition, the “virtual-as-PERF” hypothesis requires more evidence to be accepted, as the physical hypothesis is relatively strong. However, it is likely that the first two trials provided participants ample time and opportunity to collect perceptual evidence in favour of the virtual hypothesis, with minimal to no evidence in favour of the physical. So, we assume that the virtual hypothesis was stable by the time of the initial measurement, meaning that the participant was spatially present in both the non-Blindfolded and Blindfolded conditions. The small size of the positive effect of Blindfolded is compatible with this. However, the effect was clearly positive, suggesting that there may have been differences in the stability of the virtual hypothesis or the participant's level of spatial presence. This raises additional questions about the binary nature of spatial presence and the degree of "stability" of a perceptual hypothesis that is required for it to be accepted. Wirth et al.'s model does not further specify this, so more work is needed to investigate this.

Figure 7.7 and Table 7.1 showed the effects for the self-location (SL) and possible actions (PA) dimensions. While the obstacle has a negative effect on both SL and PA, being blindfolded only affects SL. Self-location questions included concepts like "*I was actually there*," "*my true location*," and "*physically present*." We speculate that the awareness of another environment would have affected these responses. Possible-actions questions, however, speak more to the task at hand: "*I could do things with the objects*," or "*I could be active*." Intuitively, these questions should not be affected by whether the participant is blindfolded or not in the context of the virtual task. So, our results are compatible with an intuitive interpretation of the SPES questions, but more work is needed to clarify the role of the possible actions dimension in spatial presence.

Overall, our results suggest that the weaker the SSM of the PE, the higher the spatial presence in VR. Although entering VR blindfolded might seem contrived in everyday use, it might be plausible in professional VR arenas and installations. Nevertheless, a potential prediction from these results that future work could test is that using VR in unfamiliar spaces will lead to higher spatial presence. A limitation of our experiment is that although we designed our manipulations to lead to different SSM strengths, we did not directly measure their existence or strength. As such, our discussion is based on the assumption that perceiving minimal to no spatial cues leads to a weak SSM. However, it is possible that participants who were not blindfolded failed to build this SSM due to inattention, and it is possible that some blindfolded users constructed a stronger SSM than we expected. We believe our assumption to be reasonable based on Wirth et al.'s elaboration on what contributes to a strong SSM [311]. However, future work should investigate additional ways of controlling the strength of the physical SSM, such as conducting the experiment in participants' homes (for a stronger SSM) or in rooms with dynamically changing layouts (for a weaker SSM).

**RQ4: How does a weak spatial situation model of the physical environment affect spatial presence in the virtual environment after collision with an obstacle?** The results suggest that entering VR with a weak SSM is a double-edged sword: spatial presence may be higher (initially) but drop more when colliding with an obstacle in the physical environment (PE). Wirth et al.'s model elaborates on the factors contributing to the formation of spatial presence but is unclear about what factors contribute to its deterioration. As such, we do not know how having a weak physical SSM can catalyse the reduction in spatial presence due to collision with the PE. Based on our observations, we speculate on a possible explanation as follows:

When users collide in the non-Blindfolded condition, their spatial presence breaks as expected. However, compared to being blindfolded, they have a stronger SSM of the physical space, so they can more easily circumvent the obstacle and continue the virtual task (e.g., “I knew that there was a wall that I should try to avoid. And I knew that I could wrap around it and the rest of the room was there,” P8). As discussed in RQ2, we expect that once the obstacle has been avoided, the user can become spatially present again, and this process may repeat as long as there is an obstacle in the way. Blindfolded users, on the other hand, needed most of their attentional resources dedicated to the PE after the collision: First, to circumvent the obstacle, and subsequently to navigate the unknown physical space in front of them to reach the virtual task location. The user may reasonably assume that there are more obstacles. Without a good SSM of the physical space, it is difficult to integrate encountered obstacles into an egocentric reference frame, leading to few opportunities for spatial presence to recover. For example, P29 said that the biggest factor in increasing their confidence in the task was learning the room boundaries in the second (non-Blindfolded) condition. In sum, having an SSM of the PE allows the user to know where the boundaries are, attend the VE whenever possible, and thus become spatially present more often. Being blindfolded has the opposite effect, where constant attention to the PE is needed to complete the task. Future work should investigate whether, over time, the user updates their physical SSM, alleviating these detrimental effects.

**RQ5: How does removing the risk of collision with an obstacle in the physical environment affect spatial presence in the virtual environment?** In Study 2, we measured the participant’s spatial presence before interaction with the physical environment (similar to trials 1 and 2 in Study 1’s Blindfolded-Obstacle condition, stage 1), immediately after collision with the obstacle (stage 2), after repeatedly having to circumvent the obstacle to complete the virtual task (stage 3), and after completing the task on a different path that avoids the obstacle (stage 4). In section 7.2, we discussed that we expect presence to degrade over time as long as the obstacle remains relevant. The results of Study 2 provide evidence that this is the case: immediately after collision, spatial presence scores drop, but after repeated encounters with the obstacle, spatial presence scores drop even further. When the task changes to a path where the obstacle is no longer relevant, presence recovers.

Earlier in this section, we discussed how the obstacle leads to a need for increased attending of the physical environment (PE), which in turn results in lower presence scores. Here, we consider another possibility: Participants initially had little evidence for the “Physical-as-PERF” hypothesis. The repeated exposures to the obstacle—be it through direct contact with it or the need to navigate around it—provided increasingly more evidence for the hypothesis that the physical environment should be the primary egocentric reference frame (PERF). Likely, the attention and evidence explanations are part of the same: the increased need of attending the PE leads to increased evidence for the “physical-as-PERF” hypothesis, strengthening it and thus making it more difficult to accept the “virtual-as-PERF” hypothesis (which would lead to spatial presence).

In the final stage of Study 2, participants no longer had to avoid an obstacle to complete the task, leading to an increase in spatial presence. This is a positive result, but it is also somewhat disappointing that the spatial presence scores did not recover to the initial levels. A possible explanation is that in our study design we changed the path of the task to naturally avoid the obstacle, but the obstacle was still present in the room. It seems likely that participants were aware of this and kept attending to it, or, similar to our discussion of RQ4, expected other obstacles to be present in the new path. Therefore, it is unclear whether the lower spatial presence is due to the historical effect of previous collisions or the awareness of the risk of future collisions. Users' trust could be an important factor here, as suggested by our discussion in RQ2 and other authors [72]. A particularly interesting direction of future research is to investigate how we can recover user trust and thus fully recover spatial presence after collisions with the physical environment.

## 7.8 Conclusions

This paper demonstrates that spatial presence in virtual reality not only depends on what happens inside the headset but also outside. We found that the mere knowledge of potential obstacles in the physical space does not meaningfully affect spatial presence upon entering the VE. Colliding with these objects, however, significantly lowers spatial presence. We found that, in line with Wirth et al.'s process model of spatial presence formation, the lower the evidence for the perceptual hypothesis of the physical space as the primary egocentric reference frame, the stronger is the sense of presence in the VE. We found evidence for this by bringing participants into VR blindfolded, which hindered the formation of the SSM of the PE. We saw that participants in this condition exhibited higher initial spatial presence, but collisions with physical objects led to a steeper reduction. We also found that repeatedly having to avoid such obstacles led to a further reduction in spatial presence, which was partially recovered when the risk of collision with was removed. This suggests that to maximize spatial presence, users must trust that their movement in the PE is unimpeded, as having to manage this risk lowers presence.

# 8 Sicknificant Steps

This chapter presents the paper “Sicknificant Steps: A Systematic Review and Meta-analysis of VR Sickness in Walking-based Locomotion for Virtual Reality” [292]. At the time of writing the paper was accepted for revision at CHI ’24 with encouraging reviews.


## Abstract

Walking-based locomotion techniques in virtual reality (VR) can use redirection to enable walking in a virtual environment larger than the physical one. This results in a mismatch between the perceived virtual and physical movement, which is known to cause VR sickness. However, it is unclear if different types of walking techniques (e.g., resetting, reorientation, or self-overlapping spaces) affect VR sickness differently. To address this, we conducted a systematic review and meta-analysis of 96 papers published in 2016–2022 that measure VR sickness in walking-based locomotion. We find different VR sickness effects between types of redirection and between normal walking and redirection. However, we also identified several problems with the use and reporting of VR sickness measures. We discuss the challenges in understanding VR sickness differences between walking techniques and present guidelines for measuring VR sickness in locomotion studies.

**Title:**
Sicknificant Steps: A Systematic Review and Meta-analysis of VR Sickness in Walking-based Locomotion for Virtual Reality.

**Authors:**
*Thomas van Gemert*, Niels Christian Nilsson, Teresa Hirzle, Joanna Bergström.

**Venue:**
The 2024 CHI Conference on Human Factors in Computing Systems.

**What was the role of the PhD student in designing the study?**
The student designed and carried out the study.

**How did the PhD student participate in data collection and/or theory development?**
The student carried out theory development and part of the data collection and analysis.

**Which part of the manuscript did the PhD student write or contribute to?**
The student wrote and contributed to the entire manuscript.

**Did the PhD student read and comment on the final manuscript?**
Yes.

## 8.1 Introduction

The ability to travel in virtual reality (VR) is one of the key components of interaction within an immersive virtual environment [130]. Walking-based locomotion offers numerous benefits compared to other travel techniques in VR [4], such as improved spatial awareness [124, 217, 225, 122, 195], a higher degree of presence in VR [231, 319, 124, 287], a better user experience [177, 287], and better task performance [122, 231]. However, with normal walking the user cannot cover a virtual environment larger than their physical one. To overcome this limitation, researchers have developed walking-based locomotion techniques that redirect the user in the physical space by manipulating the virtual motion or the virtual environment. This results in a mismatch between the user's perceived virtual and their real, physical movement, which can cause VR sickness, a form of motion sickness that affects many users [204, 210, 316]. However, the large variety of walking-based locomotion techniques, as well as the different methods used to assess VR sickness, make it difficult to understand the causes of VR sickness and the effects of walking techniques on VR sickness.

Several recent reviews report that hardware specifications, application aspects, and user characteristics all influence a user's VR sickness response [39, 215, 230], and these responses, as well as symptoms, differ greatly between users [214]. Apart from these factors, an important cause of VR sickness is a mismatch between perceived motion and true bodily motion, according to the oft-cited "sensory conflict theory" [212, 109]. This often happens even in normal walking without additional manipulation, when the VR system fails to provide completely matching motion feedback (e.g., perception of distance and self-motion is mismatching [100, 96]). VR sickness is often considered to be similar to cybersickness or simulator sickness (see [259, 39, 45, 158], but is unclear to what degree these are the same. Furthermore, VR sickness is assessed and reported in many different ways [39]. Therefore, the causes for sickness have remained difficult to disentangle from each other, and as a consequence, to assess VR sickness of individual walking-based locomotion techniques.

What we call walking-based locomotion techniques are essentially the techniques in the mobile, body-based locomotion category of Nilsson et al.'s taxonomy [184]. These techniques allow the user to traverse the physical space (mobile) while their virtual motion is mapped from the motion of their physical body (body-based). The physical motion can be mapped to a virtual one isometrically (i.e., normal walking where 1 physical meter equals to 1 virtual meter), but this constrains the range of virtual motion to the boundaries of the physical space. Therefore, the walking techniques typically apply motion gains with some constant ratio or with a function to manipulate the user's perspective in VR, such as rotational gains in reorientation (see [211, 186]) or walking with high translational gains in repositioning (e.g., [97, 307]). Other walking-based approaches use "resetting" techniques (e.g., [305, 315]) or manipulate the virtual scene, such as with self-overlapping spaces (e.g., [267, 57]). Recent reviews that considered walking-based locomotion and VR sickness have found that walking techniques in general are more likely to cause VR sickness than isometric walking [230, 38]). However, these reviews did not specifically consider different types of walking-based locomotion techniques. As the various types of redirection techniques (e.g., perspective manipulation, resetting, and environment manipulation) influence the virtual motion (and hence the mismatch) differently, they also may have distinct effects on VR sickness.

To investigate how different types of walking-based locomotion (e.g., normal walking, redirected walking, and the sub-types of redirection) may affect VR sickness, we conduct a systematic literature review of 96 studies published in 2016–2022 that use walking-based locomotion in VR and that report a measure of VR sickness. In the review process, we expand Nilsson, Serafin, and Nordahl [184]'s taxonomy to include different walking-based locomotion types. The taxonomy is then used to conduct a meta-analysis of the Simulator Sickness Questionnaire (SSQ) scores which are structured according to the identified walking-based locomotion types. We find that VR sickness effects differ between types of redirection, and between normal walking and redirection. We also encountered several problems in the meta-analysis due to the ways of assessing VR sickness in the studies. Therefore, we discuss the implications of understanding the effects of walking-based locomotion types on improving existing redirection techniques and designing new ones, and provide guidelines for measuring VR sickness.

## 8.2 Background

In this section we provide background information on VR sickness, its measures, and theory. We then elaborate on the relation between (walking-based) VR locomotion and VR sickness.

**VR Sickness and Measurements.** Exposure to immersive Virtual Reality (VR) can cause negative effects that are known as Virtual Reality-induced Symptoms and Effects (VRISE) [45], more commonly known as "VR sickness." VR sickness is an ailment similar to motion sickness, but typically presents more disorientation symptoms (dizziness, difficulty in focusing, vertigo, vision problems) than nausea (general discomfort, sweating, salivation, or vomiting) [259]. VR sickness may be referred to as "cybersickness" for non-immersive virtual environments or "visually-induced motion sickness" or "simulator sickness" in the absence of user motion and in simulators, respectively [113, 115]. VR sickness is polygenic and polysymptomatic, meaning that not everyone gets affected and that the symptoms and severity can differ between affected users [214, 215, 110]. Individual differences, lack of agreed-upon definitions, and an unclear symptom profile make it particularly difficult to assess VR sickness in studies where many factors cannot be controlled.

The most common measure of VR sickness [39] is the Simulator Sickness Questionnaire (SSQ) [111]. The SSQ consists of 16 symptoms that are rated on a 0–3 scale from "None" to "Severe." The score calculation is based on three sub-scales: *SSQ-N*ausea, *SSQ-O*culomotor, and *SSQ-D*isorientation. Each sub-scale sums the scores for its seven symptoms and multiplies it by a constant factor. The SSQ Total Severity (*SSQ-TS*) score is calculated by summing all (unscaled) scores from the sub-scales and multiplying by a different constant factor. The SSQ is often also applied before exposure to the virtual environment ("Pre-SSQ") as well as after, so that the difference between the sub-scale scores indicates a change in symptoms. Despite its popularity, the SSQ has been criticized and is likely not a valid and reliable measure of VR sickness in modern VR systems [240, 15, 289, 91]. Furthermore, the questionnaire is long, and the overall scores are sometimes not calculated correctly from individual questions and sub-scales [15, 230]. Other measures have also been developed to measure sickness, such as the VRSQ [115], the CSQ [265], or the Fast Motion sickness Scale (FMS) [112], the 2-factor SSQ [23], but they are little used compared to the prevalence of the SSQ.

The original paper that proposed the SSQ mentions a couple of key points that are often forgotten in practice [111]. For one, "unhealthy" participants (i.e., those scoring more than 0 on any symptom) should be excluded. Second, the SSQ was intended as a post-exposure measurement only; its behavior as a difference measure is undefined and questioned. Furthermore, the SSQ was developed on flight simulators using a military population. It is unlikely that the values translate well to modern VR systems [240, 91]. Finally, in related work Stanney, Kennedy, and Drexler reported that cybersickness (motion sickness resulting from virtual environments) is not the same as simulator sickness. Furthermore, the SSQ data is typically left-skewed, and the authors suggest that "as sample sizes range from 50–100, arithmetic means of raw data are reasonable, but for smaller samples medians or log transforms are suggested." In sum, there is ample evidence to believe that the SSQ is not the correct tool to measure virtual reality-induced symptoms and effects, but yet, it remains by far the most common metric [39].

The most widely cited theory of motion sickness is the *Sensory Conflict*theory [212, 190]. Simply put, the theory states that when the combination of perceived motion cues differs from expectation, motion sickness can occur. This often happens with VR locomotion techniques: when a user is standing still and using a joystick to move through the virtual world, the perceived visual motion is not in accordance with the perceived vestibular and proprioceptive motion cues. Generally, greater concordance (e.g., when physically walking) should lessen the risk of VR sickness. For a more detailed overview on the theory of motion sickness see, for example: [129, 51, 21].

Different factors in hardware, software, and demographics can further influence VR sickness [39, 215, 230, 51]. A recent review by Tian, Lopes, and Boulic [278] provides an overview of many individual user factors that have been shown to affect VR sickness. Another recent review highlights gender imbalance issues in VR sickness research [149]. Although modern VR systems have alleviated many of the earlier hardware limitations (e.g., low refresh rate, expensive positional tracking), VR sickness remains a problem. Its complex nature makes it difficult to investigate and calls for a level of rigor that is often hard to achieve when evaluating a locomotion technique on other qualities, such as presence. For additional background information, we refer the reader to these two recent reviews: [215, 230].

**VR Sickness in Walking-based Locomotion.** In the category of mobile, mundane, body-based locomotion techniques [184] there are two main sub-types: techniques that use an *isometric* mapping of physical to virtual movement, and techniques that use a *non-isometric* mapping. In isometric walking, the physical motion is mapped to the virtual counterpart with a "1:1" mapping so that one virtual meter is perceived as equal to one physical meter. Non-isometric locomotion techniques change this mapping—sometimes imperceptibly—by adding translational or rotational gains [211]. This makes it possible to manipulate the user's physical path to ensure they stay within the bounds of the space (see Nilsson et al. [186] for an overview), or to increase their speed and range of motion (e.g., Williams-Sanders et al. [307] and Interrante, Ries, and Anderson [97]). It is worth noting that there exists a range of locomotion techniques that can create a relatively “natural” walking experience. For example, walking-in-place or omni-directional treadmills. In these techniques, the user physically remains stationary. In this work, we are specifically not interesting in such techniques, and instead focus on walking-based locomotion where the user physically moves through the space.

Two recent reviews find that isometric motion and “natural walking” cause consistently lower SSQ scores than non-isometric motion [38, 230]. However, the SSQ scores are non-zero and it is not clear what type of motion can cause VR sickness in walking. Even “normal” walking could cause VR sickness, because visual perception in VR is not the same as in real life (e.g., Interrante, Ries, and Anderson [96] and Janeh et al. [100]). Previous work is inconclusive: There is evidence of normal walking causing high VR sickness scores [266, 269], but others found no difference in a small room compared to other locomotion techniques [319]. Furthermore, isometric walking may cause more VR sickness than walking with a slight gain [42]; This can occur because walking in VR causes gait detriments [100, 99, 5] and users may underestimate distances [151] and self-motion velocity in VR [7, 42]. Thus, a small speed increase may feel more natural than strictly isometrically mapped walking.

Redirected walking (RDW) is a common non-isometric locomotion technique in virtual reality (VR) research. By manipulating translation, rotation, curvature, or bending gains the user can be tricked into avoiding the physical boundaries without them noticing the manipulation [211, 186, 263]. Many works have investigated the perceptual thresholds of these gains, but VR sickness is rarely directly investigated and the reported numbers are inconsistent. A recent paper investigated the VR sickness effects of redirected walking, and reported high SSQ scores [90]. However, many different steering algorithms, gains, and varying degrees of perceptibility make it difficult to generalize from individual RDW studies [90, 186]. Furthermore, techniques that intentionally create a large mismatch by using a high translational gain can cause VR sickness [281, 307, 97], but careful design of the interaction technique can avoid this (e.g., Gemert, Hornbæk, and Bergström [71] and Cmentowski, Kievelitz, and Krueger [43]). In sum, the relationship between VR sickness and redirected walking remains unclear.

## 8.3 Methods

We conducted a systematic literature review and meta-analysis to identify how walking-based locomotion in virtual reality (VR) affects VR sickness and how the simulator sickness questionnaire (SSQ) is used to assess VR sickness. We followed the PRISMA guidelines for reporting systematic reviews and meta-analyses [192] for the identification and screening of the relevant literature, as well as for the data collection, extraction, and synthesis. We report the results of this process in Figure 8.1. To synthesise our results, we conducted a meta-analysis using the tools and procedure provided by Suurmond, Rhee, and Hak [273]. In essence, we collect SSQ Total Score values from included papers, which we use as the effect size measure for the meta-analysis.

**Research Questions.** The review is guided by the following research questions (RQs):

**RQ1:** What are the effects of isometric walking on VR sickness in virtual reality?

**RQ2:** What are the effects of various redirected walking techniques on VR sickness in virtual reality?

**Protocol and Search Strategy.** The review protocol was developed iteratively through discussions with all authors. The goal was to find research contributions that use *virtual reality* and that report a user study where the user *physically walks* through the space and a *VR sickness* measure is recorded. Thus, our search query consists of three parts that are connected with an AND operator, covering the system (VR), the locomotion technique (walking), and the sickness effects (VR sickness). This resulted in the following search query:

```
title-abstract-keywords("virtual reality" OR vr) AND
fulltext-metadata(sickness OR cybersickness) AND
fulltext-metadata(locomotion OR walking)
```

**Identification.** We performed our search in four scientific databases that publish work on virtual reality: ACM Digital Library,[1] IEEE Xplore,[2] Springer Link,[3] and Elsevier ScienceDirect.[4] We used filters to limit the search results to the for us relevant years (2016-2022) and publication type (full research papers in English published in proceedings or journals). We report the database-specific search queries in section A.2. The searches for articles from 2016-2021 were performed on 26 September 2022 and the searches for the year 2022 were performed between 18-22 August 2023. We removed duplicates from the list of papers by automatically identifying and flagging papers with the same digital object identifier (DOI).

The search resulted in 393 articles in ACM DL, 737 articles in IEEE Xplore, 716 articles in SpringerLink, and 245 articles in ScienceDirect. The total amount of records identified is 2091 (see Figure 8.1).

**Evidence Screening and Selection.** We adopted a two-phase screening process. In the first phase, we screened the papers based on title, abstract, and author keywords. In the second phase we performed full-text screening.

*Eligibility Criteria:* Based on our research questions, we defined one inclusion criterion and ten exclusion criteria that we checked the papers against. We included papers if the following *inclusion criterion* applied: "The paper presents a user study where the user wears a *virtual reality headset* and *physically walks* through the space and a *VR sickness measure* is recorded." Our *exclusion criteria* (EC) were as follows:

[1]ACM DL. https://dl.acm.org
[2]IEEEXplore. https://ieeexplore.ieee.org
[3]SpringerLink. https://link.springer.com/
[4]ScienceDirect. https://www.sciencedirect.com

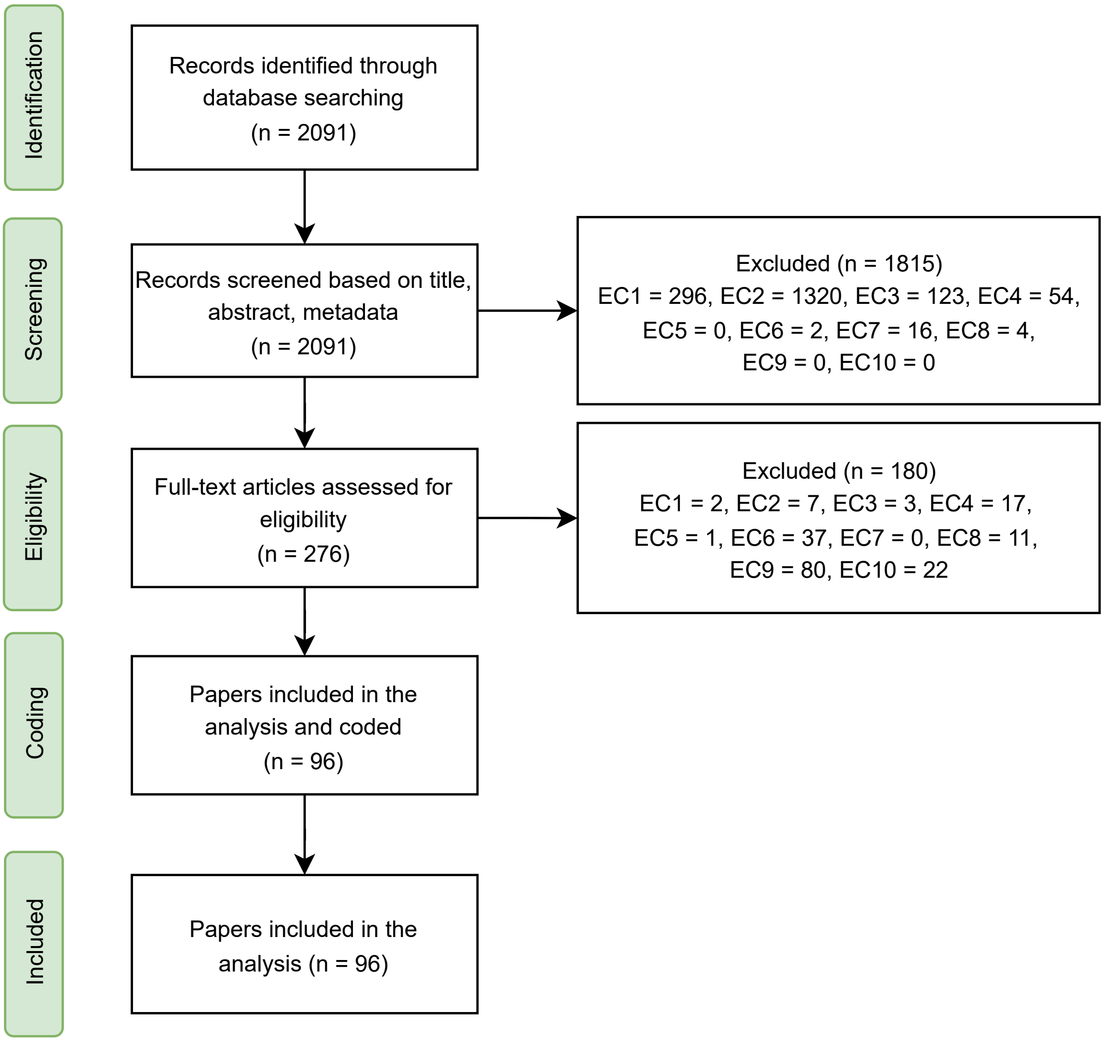



Figure 8.1: PRISMA flow chart detailing the paper numbers for the identification, screening, eligibility, and coding phases.

**EC1:** The paper is not published in the main proceedings of a conference or a journal. Excluded are: non-English papers, workshop contributions, (extended) abstracts, posters, short papers, opinion pieces, work-in-progress papers, reviews, book chapters, essays, duplicates, etc.

**EC2:** Off-topic: The metadata of the paper do not mention walking locomotion (or synonyms) or virtual reality, or the implementation excludes the possibility of walking. For example, in seated VR or when all locomotion techniques are non-walking.

**EC3:** Incorrect technology. We exclude papers using other immersive technologies such as CAVE systems, stereoscopic displays, omnidirectional (360°) video, or augmented reality.

**EC4:** Papers that use repositioning devices and proxy gestures. For example, treadmills or walking-in-place techniques.

**EC5:** The paper uses a VR system that does not use positional tracking.

**EC6:** The paper does not present walking in VR in the user study. For example, only walking out of VR, or just standing instead of walking: we exclude user studies where the user *could* walk, but does not due to task requirements (e.g., object selection, teleportation).

**EC7:** Vertical movement. We exclude papers with studies where the walking is done mainly in the context of vertical movement such as jumping, stairs, etc.

**EC8:** Papers that do not present a user study.

**EC9:** The paper does not use a VR sickness measure. Custom Likert-style scales for items like “Nausea,” “Sickness,” “Discomfort,” etc., are accepted.

**EC10:** The paper does not report a numerical result of the VR sickness measure. For example, only reports anecdotal, qualitative, or test statistic results.

**Rationale for Filters and Eligibility Criteria.** VR technology is rapidly changing in terms of both hardware and research. To find the most relevant papers we only include those published between 2016 and 2022. This cut-off is determined by the release date of the Oculus Rift and HTC Vive (2016), which have both become popular VR systems for consumers and academics. Furthermore, we only include full research papers that are published in main conference proceedings or journals. Although this filter was set for all database searches, we discovered some papers that did not meet this criteria in the search results, which is why we added it as an exclusion criterion (EC1).

The exclusion criteria were created based on our research questions and through iterative screening of the literature, which helped us identify the exact criteria (e.g., to exclude all VR systems that were not using an HMD). Before the screening phase, we selected 62 (3%) papers at random that were screened by two authors to define and fine-tune the exclusion criteria. For the papers from 2016-2021 author A[5] and author B performed the screening on 50 papers. For the papers from 2022 author A and author C

[5]We refer to the four authors of this paper as authors A, B, C, and D.

performed the screening on 12 papers. Each set represented 3% of the paper corpus of these years respectively. Discrepancies were resolved through discussion and updating the criteria until consensus was reached.

Another set of 62 papers was then selected at random and screened by the same authors (50 for years 2016-2021 by author A and B, 12 for the year 2022 by author A and C). We used ReCal2 [68] to calculate an agreement percentage on the former set of $98\%$ and Cohen's $\kappa = 0.929$ and 91.67% on the latter set, indicating almost perfect agreement. Any further discrepancies were resolved through discussion.

*Screening:* We concluded to go ahead with the following definitions of locomotion-relevant terms and sickness-relevant terms (in compliance with the exclusion criteria EC2 and EC3). For walking-based locomotion: natural locomotion, natural movement, walking, redirected walking, stepping, and room-scale movement. For VR sickness: cybersickness, visually-induced motion sickness (VIMS), virtual reality-induced symptoms and effects (VRISE), simulator sickness, simulation sickness, and motion sickness.

Author A and C then screened the title, abstract, and metadata of the 2091 identified records based on the eligibility criteria. If the criteria were not clearly violated (e.g., the abstract does not always specify the inclusion of a user study) they erred on the safe side and accepted the paper for full-text screening in the next phase. A total of 1815 papers was excluded because of [reason (criterion, #reject)]: paper type (EC1, 296), relevance (EC2, 1320), technology (EC3, 123), repositioning or proxy gestures (EC4, 54), no walking (EC6, 2), vertical movement (EC7, 16), and lacking a user study (EC8, 4). In total 276 ($13.2\%$) papers were accepted in this phase (see Figure 8.1).

*Eligibility:* We assessed the eligibility of the 276 articles based on their full text. We first checked for a user study (EC8) and that this included at least one walking condition (EC2, EC6). Then, we checked that a VR sickness measure was used as a dependent variable (EC9), and that the measure outcomes were reported correctly (EC10). If these criteria were satisfied, we screened the paper for the rest of the criteria. For the papers from 2016-2021 authors A and B performed the full text eligibility phase, while for the papers of 2022 authors A and C screened the full text for eligibility. In this phase, we excluded 180 papers because of [reason (criterion, #reject)]: Paper type (EC1, 2), relevance (EC2, 7), technology (EC3, 3), repositioning or proxy gestures (EC4, 17), no positional tracking (EC5, 1), no walking (EC6, 37), no user study (EC8, 11), no VR sickness measurement (EC9, 80), not reporting VR sickness measurements (EC10, 22). Finally, a total of 96 papers were included to be coded.

**Data Collection.** The papers were coded to identify key features of the paper and the VR sickness results. Authors A and B developed an initial code book based on our inclusion criterion, being split into the following parts: type of walking locomotion, study design and methods, the manipulation of walking, and the VR sickness measurement(s). All four authors then discussed and refined the code book over two iterative sessions. All authors then each coded the same four papers, and in another session the results were compared and any discrepancies resolved through discussion. Finally, this method ensures that the meaning of each code and the required level of detail was clear and consistent among the coders.

We code each condition that reported a VR sickness result on a separate row. This means that one paper can produce multiple data points. Some example codes are: number of participants, study design (conditions), immersion time, locomotion type, transfer function/gains used, environment, path shape, physical space size, VR sickness metric, SSQ-TS mean, SD, SE, and qualitative comments by the authors and us. The full overview of codes is available in the coding guide in the supplementary material.[6]

During the coding process, we decided to exclude Nogalski and Fohl [188] because all of their participants were blind-folded: This makes it hard to compare their VR sickness results to those that were produced from a visual stimulus. We also decided to exclude Bhandari, Tregillus, and Folmer [13] because their results suggest that the participants spent considerably more time using walking-in-place than walking, but the VR sickness results cannot be separated.

*Missing values and Data Transformation:* We dealt with missing data as follows. One, if the paper only reported boxplots or median and IQR statistics, we use the method proposed by Wan et al. to convert these to a mean and standard deviation value [299]: the method provides a procedure to calculate a standard deviation and upper and lower bounds for the mean based on a combination of sample size, median, min, max, $25^{th}$ $75^{th}$ percentiles. We use the average of the two bounds. Second, if the paper does not state what the unit of a reported value is, we make a best-effort guess. For example, this typically results in assuming an “SSQ score” or “mean SSQ” refers to the SSQ-TS score and $7.9 \pm 5.8$ refers to a mean and standard deviation. Third, if (part of) the VR sickness results were only reported in a graph, we derived the scores from the graph. To this end, we downloaded the image from the publisher’s website, calculated a SSQ-point-per-pixel value from the axis indicating the scale, and then calculated the values by measuring distance in pixels to the 0-line. We used measurement tools in image manipulation software, primarily GIMP, for this.

Finally, if a standard deviation or standard error value was not available for an SSQ score we calculated this as follows. Winkel, Talsma, and Happee [310] performed a meta-analysis of SSQ scores and noted that standard deviation values correlated very strongly with mean SSQ scores ($\rho = 0.880, p = 2.141 \cdot 10^{-37}$). We follow their procedure and perform a regression analysis of standard deviation on SSQ-TS scores for the pre-exposure SSQ results in our sample. We choose this data because it includes many scores that were calculated from raw data (which we assume to be reliable), and that come from a theoretically homogeneous sample. We used the Analysis Toolpak in Microsoft Excel 2023 for this. Using 36 observations, we find an intercept of $1.074 \pm 1.195$ (SE) and a coefficient of $1.083 \pm 0.105$, $R^2 = 75.9\%$. The details are available in the supplementary material. Thus, we calculate missing standard deviation values as: $SD = 1.074 + 1.083 * SSQ$, where SSQ is the mean SSQ-TS value.

*Data Requests:* As previously reported (e.g., Bimberg, Weissker, and Kulik [15], Tian, Lopes, and Boulic [278], and Saredakis et al. [230]) the quality of reporting of SSQ results varies wildly. We observe the same issue in our sample of papers. This makes it very difficult to perform an analysis on combined results, since combining the results is not trivial. Some analysis groups may have very little complete data compared to others. So, we decided to contact the authors of the papers that report incomplete SSQ data to

[6] `https://osf.io/78j2s/?view_only=f8a1f75b49be4bbda4d5242c773c73e2`

request the raw data, or at least the complete summary statistics.

The criteria for determining what data to request were as follows: whenever a paper did not report summary statistics for all four scales of the SSQ (SSQ Total Score, SSQ-Nausea, SSQ-Oculomotor, and SSQ-Disorientation), or we suspected that the reported result was incorrect we flagged it to request the raw data. For example, we would suspect a result of $0.32 \pm 0.12$ being incorrect, since it is suspiciously low for a redirected walking technique considering the scale of the SSQ, typical data characteristics, and the results of other papers that use similar techniques. Most likely, the authors averaged the responses (which are on a 0–3 scale) over the 16 symptoms.

We contacted the authors of 49 papers, and we received the data for 26 of those. Where possible, we used the raw data to calculate the scores. We note that for for 9 papers the scores generated by the raw data did not match what was reported in the paper. For the papers where we have incomplete results and did not receive data, we included a paper's SSQ-TS scores if valid and available, and exclude it otherwise. In the case of suspected incorrect results, we exclude the paper. In section 8.4 we present these exclusions and justifications in each group.

**Synthesis.** Based on our data and previous work by Nilsson et al. Nilsson et al. [186], Nilsson, Serafin, and Nordahl [184], and Nilsson et al. [187] we developed a taxonomy extension to group the studies for synthesis. After coding the papers, authors A and D went through all the coded papers and used affinity diagramming to group observations (sickness result per technique) into mutually exclusive categories. These categories were then discussed with all authors and adapted accordingly. The extended taxonomy broadly categorizes techniques based on the spatial and temporal characteristics of the manipulation that are likely to influence sickness, such as applying rotational or transition gains or using overlapping spaces. Table A.1-Table A.6 show the grouping of all included 96 papers into the categories of the taxonomy. Figure 8.2 presents the taxonomy we use for synthesis. At the most general level we differentiate between two categories: isometric walking and redirected walking.

*Isometric walking* involves a 1:1 mapping between the user's real and virtual movements, and the mismatch between motion cues is minimal. This is sometimes also referred to as "natural," "normal," or "real" walking.

*Redirected walking* refers to a collection of techniques that manipulate the users' physical walking path either by using a non-isometric mapping between the users real and virtual movements (*perspective manipulation*), by manipulating the virtual environment to change the users' path (*scene manipulation*) [186], or by resetting their virtual view when reaching the boundaries of the physical space (*resetting*).

*Resetting* usually involves an overt intervention and a task that will ensure that the user faces in a desired direction. For example, "2:1 turn" [305] is a popular resetting technique that instructs users to physically turn on the spot while the VE rotates at twice the speed, thus allowing the user to continue along the same virtual path, while walking in the opposite physical direction. Other resetting techniques include *freeze-turn* and *freeze-backup* resetting [305]. Resetting can be used in combination with isometric walking and other redirection techniques. *Perspective manipulation* can be further subdivided into

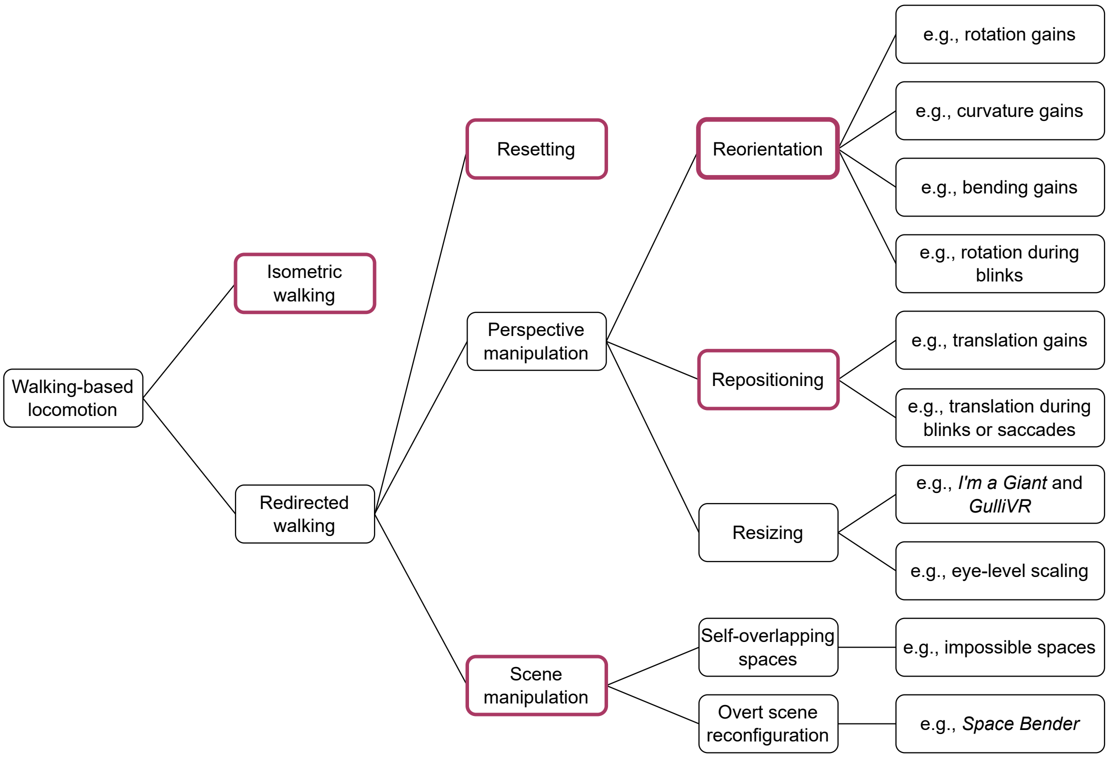



Figure 8.2: We extended Nilsson, Serafin, and Nordahl [184]'s taxonomy providing more details for walking-based locomotion techniques. We used this taxonomy to group our results for synthesis. The groups for which we report results are highlighted in purple.

techniques that involve reorientation of the user (e.g., rotation [211], curvature [263], and bending gains [125], or discrete rotations during blinks and saccades [182, 271]); techniques that involve repositioning of the user (e.g., translation gains [97, 71, 307] or translations during blinks and saccades [126]); and techniques that involve resizing the user (e.g., uniform resizing of the user [117] or non-uniform resizing [3, 307]). *Scene manipulation* can be further split into at least two sub-categories: self-overlapping spaces (e.g., impossible spaces [267] and change blindness redirection [268]) and overt scene reconfiguration (e.g., overtly bending [248], folding [79], warping [59] parts of the scene).

*Meta-analysis:* We use Meta-Essentials v1.5 [273] for our meta-analysis. We use mean SSQ-TS scores and standard error directly as effect size. This has benefits for interpretatbility and our ability to provide reference values. Furthermore, standardized effect sizes are typically not available in the papers included in this work. Using the mean SSQ-TS is a valid method because all observations are on the same scale (SSQ-TS, 0–235.62). We use a random-effects model with a 95% confidence level. We report heterogeneity statistics in the results. We expect the data to be mostly heterogeneous due to the differences in study design, locomotion technique, hardware, etc. In that case, confidence and prediction intervals should be interpreted with care: we include them mainly as an indication of the spread of the data. Similarly, most bias estimation techniques are only valid for homogeneous samples [273], so we exclude those from our analysis.

We create a separate Meta-analysis workbook [273] for each analysis group, shown in purple in Figure 8.2. In addition, we create a workbook for the pre-exposure SSQ analysis. For each group, we enter the mean SSQ-TS values and their standard errors from the observations. As a reminder: we code the papers so that each unique combination of condition and VR sickness result is an observation. One paper can thus have several observations, for example: if they evaluate multiple walking techniques or evaluate different gain levels and report a VR sickness result for each condition. This entails that we do not separate independent and dependent measurements; in practice completely independent measurements are quite rare. We consider a VR sickness measurement independent if it was the result of a single condition (i.e., one SSQ score for 1 gain level condition in a between-subjects study). In practice, much of the data in our sample is dependent, meaning the VR sickness score may have been affected by other locomotion techniques or manipulations within the study. This is a limitation of the papers included in our review: limiting the selection to only independent observations would leave too little data for meaningful analysis. Finally, we report mean and standard error pairs as $M = 2.0 \pm 1.5$, for example, where a standard deviation is indicated by sigma, for example: $M = 2.0, \sigma = 3.0$.

## 8.4 Results

In this section we present the results of our meta-analysis, grouped by type of walking technique according to the taxonomy in subsection 8.3. First, we present a meta-analysis of the pre-exposure results in our review. This will provide the reader with an understanding of baseline SSQ scores that can be used to compare the following techniques. Then, we introduce the isometric walking ("normal" walking) results, following by redirected walking in the form of resetting, perspective manipulation, and scene manipulation. We discuss perspective manipulation separately as reorientation and repositioning approaches, while for scene manipulation we present the results collectively due to the small number of papers available for meta-analysis. Resizing techniques are only present with two papers in this review [3, 117], so we exclude these from the meta-analysis. Finally, we present some results on study design methods and VR sickness assessment and reporting in the studies included in this review. The papers included in this systematic review are cited in their respective groupings.

**Pre-exposure SSQ.** Pre-exposure SSQ results come from the use of the SSQ before exposure to a virtual reality (VR) stimulus. It is typically used to calculate difference scores to investigate an increase in symptoms or to exclude participants that show symptoms before exposure to VR. The goal of this section is two-fold: to provide reference values for normal ranges of SSQ scores *before* VR exposure, and to argue whether the theoretical baseline of 0 is correct.

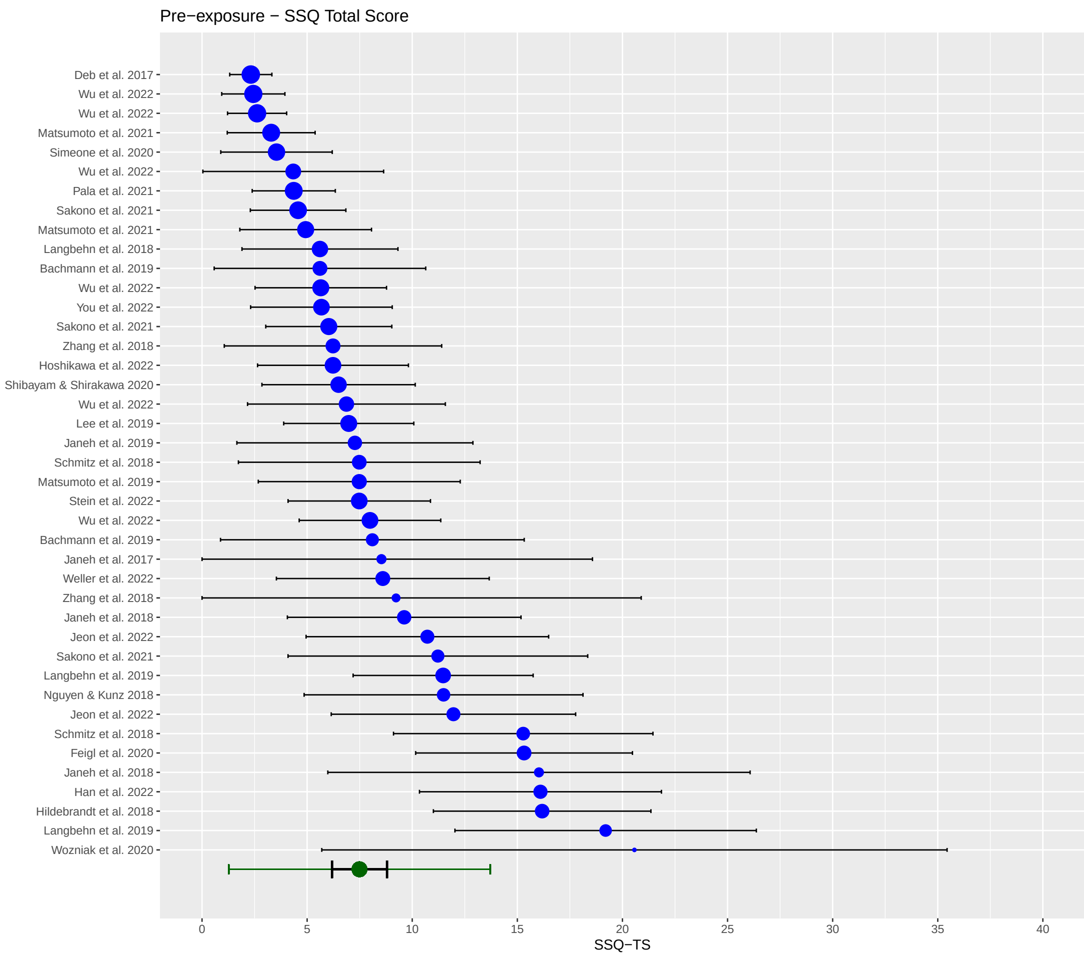



Figure 8.3: Forest plot of the pre-exposure SSQ-TS scores. Black intervals are confidence intervals. The green point is the combined SSQ-TS with the CI (black) and prediction interval (PI) (green). Blue point size is proportional to weight in the model. Note that the x-axis scale is exceptionally 0–40 in this figure, whereas the following figures will display 0–80.

Figure 8.3 shows the results of the meta-analysis of SSQ-TS pre-exposure scores. 23 (23.9%) papers provided pre-exposure SSQ-TS scores, resulting in 41 measurements. We excluded 20 (20.8%) papers because they did not report the pre-exposure scores or because we suspected incorrect calculation. The papers are cited in the following sections in their taxonomic groups. A random-effects model provides a combined effect size (SSQ-TS) of $7.49 \pm 0.65$ (SE). The confidence interval (CI)[7] is $[6.18, 8.80]$ and the prediction interval (PI)[8] is $[1.27, 13.71]$. The data is heterogeneous, with $Q = 201.13, I^2 = 80.11\%, \tau = 3.01$. As a side-note, if the data is heterogeneous, CIs and PIs should not be interpreted as such, but we still provide them as an indication of the dispersion of true effects.

The results show a relatively low SSQ-TS score, as would be expected. However, Figure 8.3 also shows 12 studies that report scores > 10. In some cases, the reason can be attributed to recording the pre-SSQ before each condition in a within-subjects design (e.g. Langbehn et al. [127]). Due to the common practice of counter-balancing or randomizing condition order it is typically not possible to determine the first measurement.

**Isometric Walking.** Isometric walking is simply "normal" walking, but in virtual reality (VR). While its range of movement is limited in the typical physical spaces available to users, it is generally considered a safe and beneficial locomotion technique for VR (see section 8.1). However, we have also discussed how normal walking could still cause VR sickness (see section 8.1 and section 8.2). In this section, we can see whether isometric walking shows a trend of VR sickness, and we can compare the results here to other groups in the following sections. The papers in this group often used isometric walking to investigate street crossing (e.g., Pala et al. [193, 194]) or obstacle avoidance behavior (e.g., Bühler and Lamontagne [31] and Wozniak et al. [313]), gait (e.g., Janeh et al. [98, 99]), or to compare to other locomotion techniques (e.g., Mayor, Raya, and Sanchez [156] and Min et al. [165]).

33 papers (34.4%) in our sample use natural walking as a locomotion technique. 23 of those papers (69.7%) provide valid SSQ-TS scores [156, 31, 313, 99, 65, 32, 183, 308, 63, 44, 298, 231, 234, 243, 19, 171, 52, 194, 62, 197, 12, 114, 237], resulting in 30 measurements, of which 18 are independent. A random-effects model finds a combined effect size (SSQ-TS) of $15.99 \pm 0.99$ (SE). The confidence interval (CI) is $[13.96, 18.01]$ and the prediction interval (PI) is $[6.22, 25.75]$. The data is heterogeneous, with $Q = 110.42, I^2 = 73.74\%, \tau = 4.67$. The results are visualized in a forest plot in Figure 8.4.

Five walking papers used a non-SSQ measure of VR sickness. Borrego et al. [20] reports that "experience with the systems did not cause relevant levels of sickness" ($2.4 + -0.6$ out of 7). Kwon et al. [121] measured VR sickness on 200 participants using an undefined tool but report that "most participants reported no notable symptoms or cybersickness during the whole experiments in this study. Instead, in the follow-up questionnaire, a minority of those reported discomfort with the wearing of VR equipment (11%) and slight symptoms of nausea and dizziness (6.5%)." Notably, they measured sickness af-

[7]The confidence interval provides the range of scores in which, given sufficient repeat experiments, 95% (chosen value in this work) of future confidence intervals will fall.

[8]The prediction interval gives the range in which, in 95% (chosen value in this work) of the cases, the outcome of a future study will fall, assuming that the effect sizes are normally distributed.

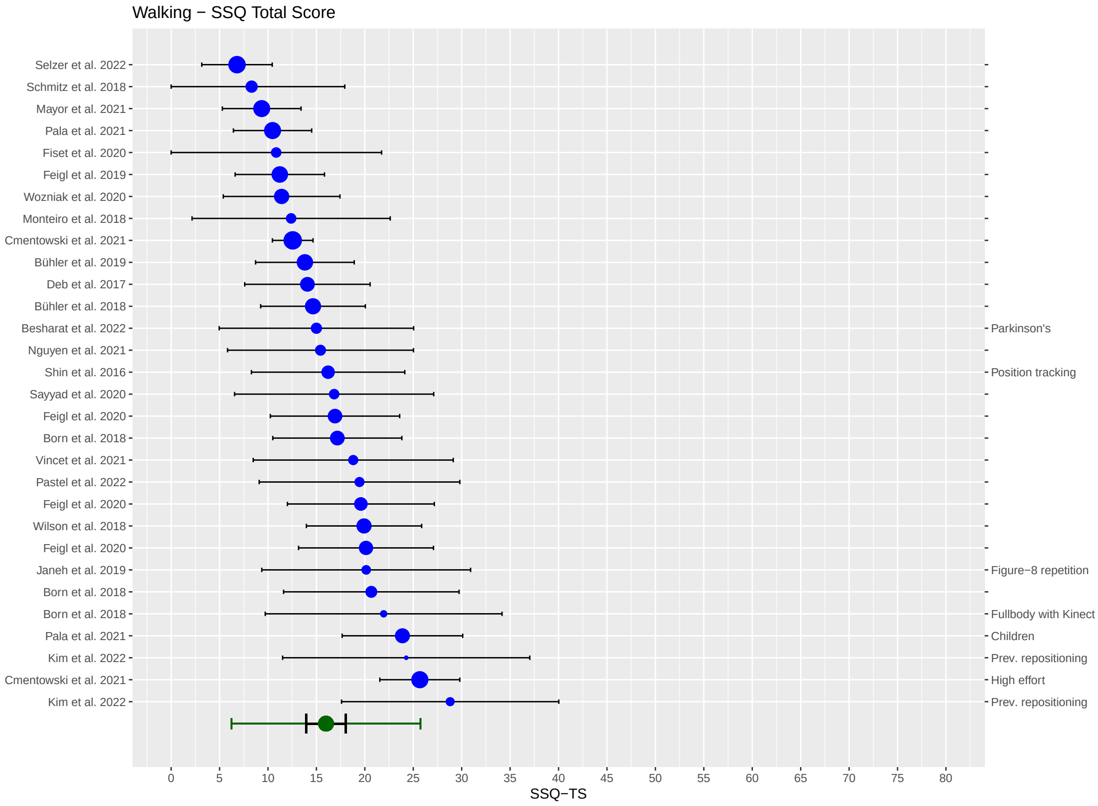



Figure 8.4: Forest plot of the SSQ-TS scores of isometric walking techniques, intervals are CI. The green point is the combined SSQ-TS with CI (black) and PI (green). On the right, the notes highlight some relevant differences between the studies. Point size is proportional to weight in the model.

ter 1 minute of familiarization in VR, and exclude affected participants. Wang et al. [300] investigated the street crossing behavior of 102 children, 43 adolescents, and 48 adults. They use the SSQ, but do not report the results. Instead, they report that four children and one adolescent withdrew due to sickness and that “1.6% reported a little nausea; 2.5% stomach discomfort; 2.5% sweating, and 3.1% vertigo; none reported intense motion sickness symptoms.” In a similar study, Bindschädel, Krems, and Kiesel [16] measure VR sickness using the Misery Scale [22] and report that four participants reported mild symptoms of discomfort or dizziness. Finally, Pala et al. [194] report SSQ-TS difference scores of $M = 5.54$ $\sigma = 11.33$ for older adults and $M = 6.11$ $\sigma = 8.81$ for younger adults after a street-crossing study.

We excluded [174, 165, 160, 255, 224] because we suspect they did not calculate the SSQ scores correctly by either averaging over the symptom responses, which are on a 0–3 scale, or simply adding the symptom values, resulting in a value on a 0–48 scale. As a reminder, the SSQ-TS scale is 0–235.62. In [63] we excluded the no-VR baseline condition, and the naive position estimation model due to exceptional tracking deviation.

Pastel et al. [197] provide a nice example: although their reported SSQ scores are relatively high ($M = 19.45 \pm 4.95$), they report that no participant complained about any symptoms. We suspect that this is an example of how sensitive the SSQ scores are to participants responding "slight" to some symptoms. As another example of the nuances of the SSQ, Selzer, Larrea, and Castro [237] report that "Many participants also highlighted some difficulties with understanding the difference between some of the SSQ symptoms. For instance, some reported that symptoms like difficulty focusing and difficulty concentrating felt very similar. Some others reported that they did not fully understand symptoms like fullness of head or stomach awareness."

**Resetting.** When a VR user walks to the boundary of their physical space, a simple way to allow them to continue walking to perform a "reset." Resetting techniques typically involve the user turning around physically while the virtual environment is frozen or rotates faster or slower than the physical rotation. This ultimately results in the user physically walking in the other direction, while they still follow the same path in VR. Our sample includes mainly papers that compare resetting to other locomotion techniques (e.g., [165, 248, 79]) and notably one that improves resetting through the use of distractions [257].

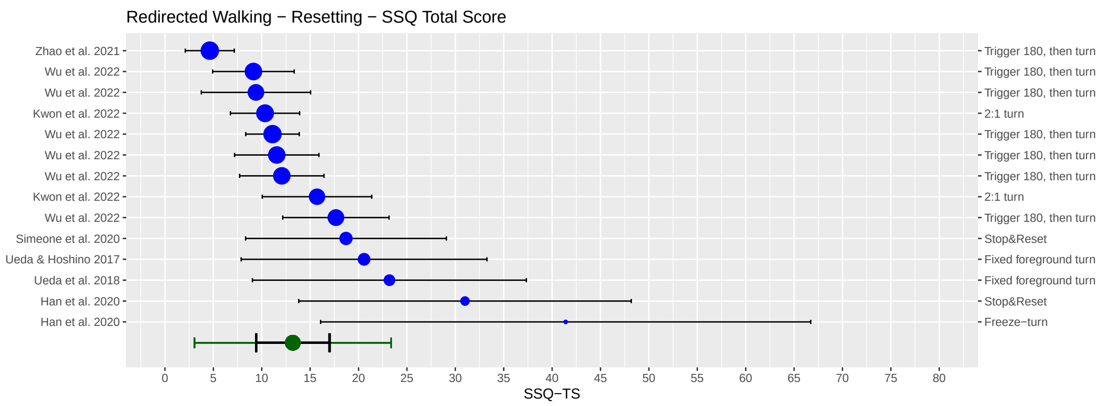



Figure 8.5: Forest plot of the SSQ-TS scores of RDW/Resetting techniques, intervals are CI. The green point is the combined SSQ-TS with CI (black) and PI (green). On the right, the main differences are noted. Point size is proportional to weight in the model.

The results are shown in Figure 8.5, which includes a note on what resetting technique was used: "Trigger 180" and "Stop & Reset" refer to techniques where the virtual environment (instantly) rotates 180°, after which the user turns around to continue their original virtual path [305, 46]. "2:1 turn" refers to techniques where, while the user is turning, the virtual environment rotates 2x faster or slower [305]. Finally, the "freeze-turn" technique freezes the virtual environment so that it rotates with the user as they physically turn around [305]. This may be combined with a "fixed foreground" or other stable reference frame to improve user comfort [285].

11 papers (11.5%) in our sample use resetting as a locomotion technique. Seven of those papers (63.6%) provide valid SSQ-TS scores[248, 285, 286, 321, 121, 314, 79], resulting in 14 measurements, of which eight are independent. A random-effects model finds a combined effect size (SSQ-TS) of $13.21 \pm 1.76$ (SE). The confidence interval (CI) is $[9.42, 17.00]$ and the prediction interval (PI) is $[3.05, 23.37]$. The data is heterogeneous, with $Q = 60.47, I^2 = 78.05\%, \tau = 4.36$. The results are visualized in a forest plot in Figure 8.5.

Sra et al. [257] used two different types of resetting: one where the scene is rotated while the user is distracted by a secondary task, and one without a distractor task. Users reported “dizziness” on a 7-point Likert scale. The authors report $M = 1.4$, $\sigma = 0.7$ for the distractor task condition, and $M = 2.1$, $\sigma = 1.2$ for the overt task. Paris et al. [196] compares walking-in-place and resetting in difference physical space sizes, and report that “participants who completed the experiment did not exhibit any undue symptoms of simulator sickness, either using our simulator sickness evaluation based on the method of Fernandes & Feiner, or in post-test reports. However, 25/140 subjects withdrew from the experiment before it ended, giving us a dropout rate (18%) that is higher than other user studies we have run.” The dropout rate was balanced across conditions, making it difficult to say if any particular technique was at fault.

We exclude [165, 70] because we suspect incorrectly calculated scores. Interestingly, Gao et al. [70] reports SSQ difference scores that are exceptionally high: $M = 138.41 \pm 6.23$ for the resetting technique.

**Repositioning.** Repositioning techniques use translational gains to reposition the user in the virtual space as they are walking in the physical space. A well-known example is the “Seven-League Boots” technique [97]. These techniques typically apply a gain to the user’s movement that can range from <1 (moving slower, e.g., [100, 98]) to [1.0, 2.0] (slightly faster, e.g. [308], to 10+ (extremely fast, e.g., [2, 43, 307]). Recent research has also investigated better ways to apply such high gains by designing novel transfer functions (e.g., [307, 71]) or by blocking the optical flow (e.g., [43]). In this section, we only consider observations that only use repositioning. There is a variety of redirected walking techniques that combine reorientation and repositioning techniques, which we discuss in Figure 8.4. Figure 8.6 shows the results and includes a note to describe the gain level used.

17 papers (17.7%) in our sample use a repositioning technique. 14 of those papers (82.4%) reported valid SSQ scores [281, 320, 118, 308, 100, 59, 122, 282, 317, 43, 114, 237] and were included in data analysis, resulting in 25 measurements, of which 6 are independent. A random-effects model finds a combined effect size (SSQ-TS) of $25.68 \pm 2.49$ (SE). The confidence interval (CI) is $[20.55, 30.81]$ and the prediction interval (PI) is $[3.55, 47.81]$. The data is heterogeneous, with $Q = 194.23, I^2 = 87.64\%, \tau = 10.43$. The results are visualized in a forest plot in Figure 8.6.

Williams-Sanders et al. [307] ran two pilot studies with 6 participants each to test different configurations of their transfer function. They asked participants to rate their “sickness” on a scale of 1–10. When testing at what walking speed to apply a 10x gain, they found sickness ratings of $M = 5.8$, $\sigma = 2.4$ for “immediate” acceleration and $M = 1.3$, $\sigma = 0.5$ and $M = 2.1$, $\sigma = 0.7$ for slower acceleration. In the second study, they found that a quadratic ramping function was slightly worse ($M = 3.4$ $\sigma = 1.8$) than a cubic or exponential function ($M = 1.4$ $\sigma = 0.4$, $M = 1.3$ $\sigma = 0.4$), respectively.

Tirado Cortes, Chen, and Lin [281] use an interesting method of splitting up their participants by those who got VR sick and those who did not. The combined scores are in the middle of the pack (see Figure 8.6), but the individual results reveal that the unaffected group had an SSQ-TS of maximum 28, whereas the VR sickness group scored between 30–80 SSQ-TS. This observation matched with what we observed in much of the raw

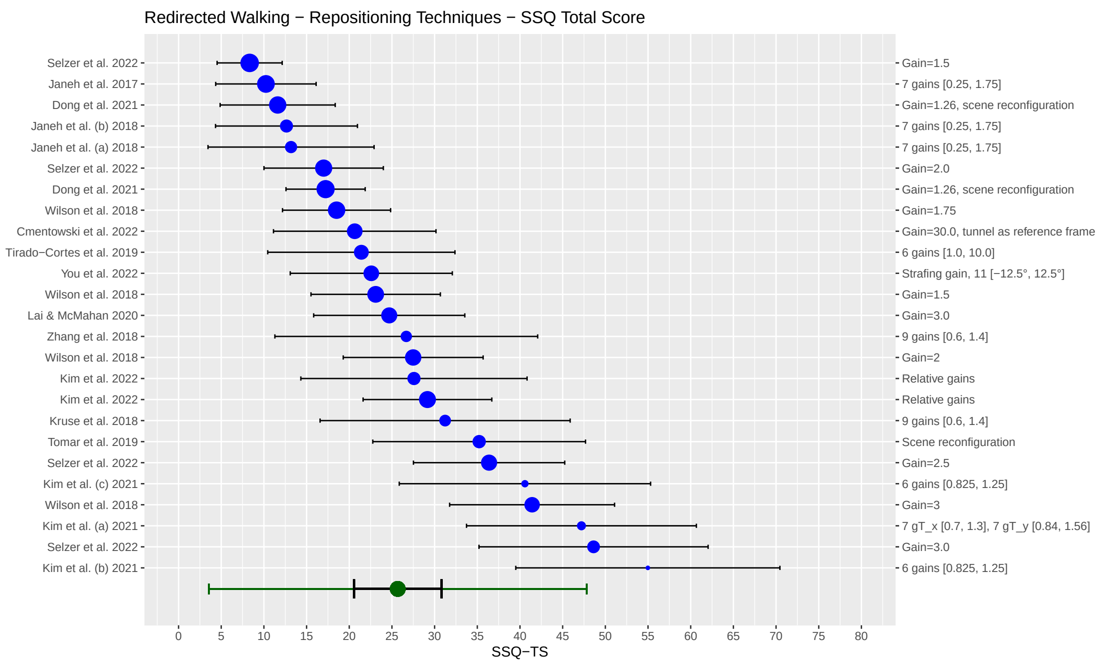



Figure 8.6: Forest plot of the SSQ-TS scores of RDW/Repositioning techniques, intervals are CI. The green point is the combined SSQ-TS with CI (black) and PI (green). On the right, the main differences are noted. Point size is proportional to weight in the model.

data: there are clear differences between participants, and some participants appear to be severely affected, while others are not at all.

You et al. [317] evaluate their technique of using strafing gains and used both the Fast Motion Sickness scale (FMS) during the whole study, and the SSQ over the experiment. While the FMS showed no sickness during the course of the study (“all scores averaged less than 2” [317]), the SSQ showed a significant increase from $\approx 5$ to $\approx 22$, with a large $\sigma = 24$.

We exclude [3, 165] because we suspect they did not calculate the SSQ scores correctly but instead averaged over the symptom responses, resulting in a 0–3 scale. However, Abtahi et al. [3] also report results from a custom VR sickness question, “I felt discomfort and motion sickness when walking around in this mode” with a 1–5 scale. They report a score of $M = 2.9$ $\sigma = 1.4$ after participants used a Seven League Boots-like technique with gains of 3x, 10x, and 30x.

**Reorientation.** Reorientation techniques rotate the virtual environment slightly, causing the user to adjust their physical path. This results in the user being steered away from the physical boundaries, while often not being aware of this redirection. Reorientation techniques has received the most attention from research in recent years, and many different studies have been published, including but not limited to, those that introduce new techniques (e.g., [6, 271]) or controllers (e.g., [134, 40]), those that investigate imperceptibility thresholds (e.g., [127, 234]), or those that design multi-user redirected walking (e.g., [101, 135]). Reorientation techniques are often combined with elements from repositioning techniques, or use resetting as a back-up option or complementary redirection method. In this section, we consider all of these since it is typically not possible to separate them. Another note is that the exact gains used and how they were applied is often not reported in enough detail or too complex (e.g., changing over time dependent on other users) to summarize in a handful of sentences. Figure 8.7 shows the result, with a best-effort note to indicate what technique and/or gain was used. For details we refer the interested reader to the individual papers.

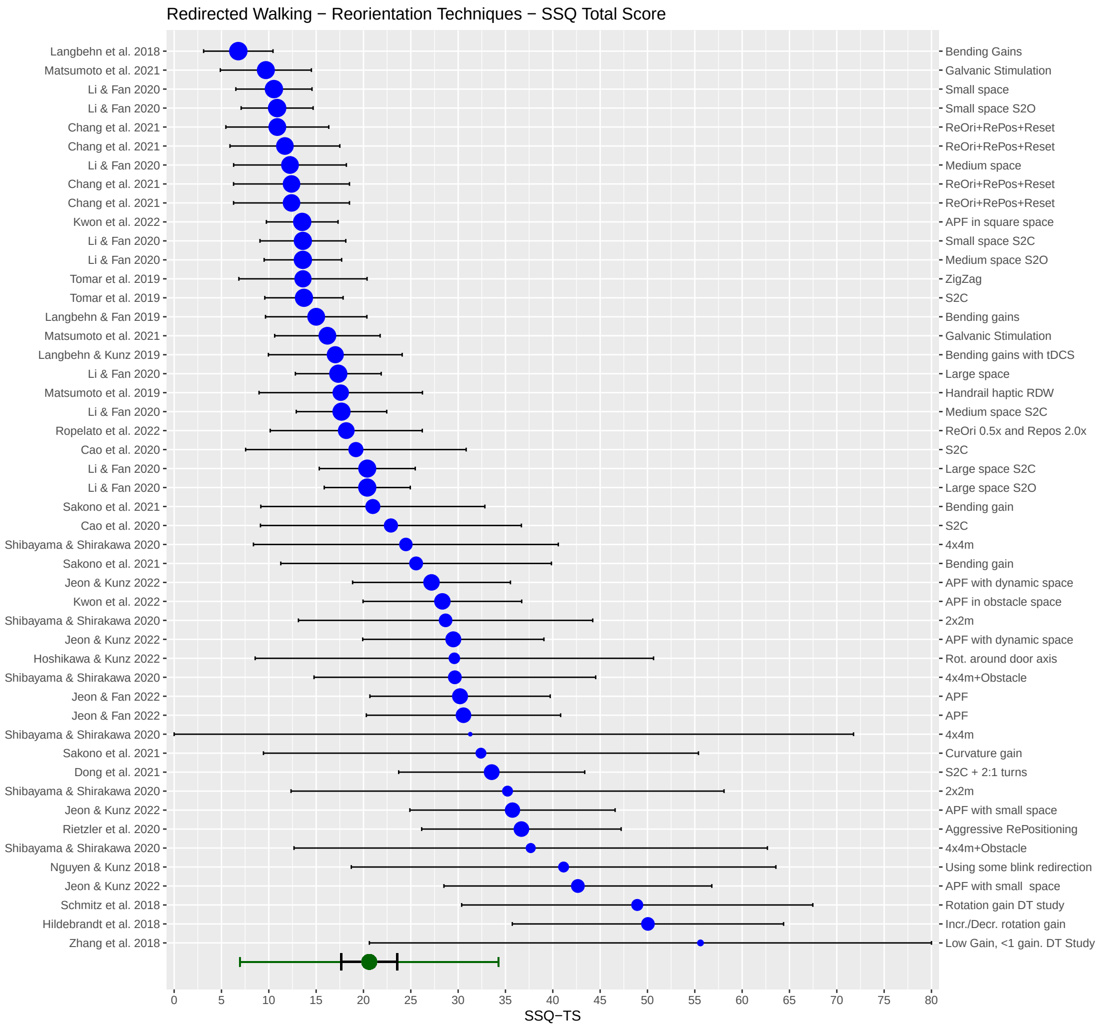



Figure 8.7: Forest plot of the SSQ-TS scores of RDW/Reorientation techniques, intervals are CI. The green point is the combined SSQ-TS with CI (black) and PI (green). On the right, the main differences are noted. Point size is proportional to weight in the model.

31 papers (32.3%) in our sample use a reorientation technique. 20 of those papers (64.5%) reported valid SSQ scores [320, 126, 35, 142, 182, 226, 153, 40, 242, 127, 59, 234, 220, 90, 282, 154, 101, 222, 121, 93] and were included in data analysis, resulting in 48 measurements, of which 4 are independent. A random-effects model finds a combined effect size (SSQ-TS) of $20.61 \pm 1.48$ (SE). The confidence interval (CI) is $[17.64, 23.58]$ and the prediction interval (PI) is $[6.94, 34.28]$. The data is heterogeneous, with $Q = 259.23, I^2 = 81.87\%, \tau = 6.63$. The results are visualized in a forest plot in

Figure 8.7.

Matsumoto et al. [152] asked users “How sick do you feel?” on a 100-mm line anchored by “not sick at all” and “extremely sick.” They tested different curvature gains in 8 conditions with different paths, and they report mean sickness percentages between 24% and 55%, suggesting that participants, on average, did not feel very sick. Bozgeyikli et al. [26, 27] evaluated a technique that combined reorientation, repositioning in direction of travel, and resets. For participants with high-functioning autism they reported $M = 0.42$, $\sigma = 0.32$ and for healthy adults $M = 0.61$, $\sigma = 0.20$ on a modified version of Pensacola Diagnostic Criteria on motion sickness [133]. This measure has a scale of 1–4 (none, minimal, moderate and major). The authors note that “redirected walking was the second choice of the participants in the preference ranking among the eight techniques. It did not induce motion sickness and it provided the highest level of presence.” Bölling et al. [18] investigated how participants adapted to increasing curvature gains over the course of three days. They report SSQ difference scores of $M = 13.3$, $\sigma = 1.7$; $M = 5.0$, $\sigma = 1.8$; $M = 7.8,$, $\sigma = 1.8$, respectively (based on Bouchard et al's 2-factor version of the SSQ [23]).

Schmitz et al. [234] investigate what the threshold of limited immersion in redirected walking and how human factors affect VR sickness. In a study with an increasing rotation gain, they report SSQ-TS scores of max=222, min=2.47, and $M = 48.92$, $\sigma = 45.92$. Out of the 26 participants, some clearly got sick, and a few very much so. They also measured VR sickness 10 minutes after experiment: $M = 29.53$, $\sigma = 40.84$, $Max = 172.6$, $Min = 0$. Eight participants dropped out due to cybersickness. Hildebrandt et al. [90] dropped 12 participants due to sickness: “Right after the experiment, there was no participant without any symptom of cybersickness at all (Min = 3.74, M=50.05, SD=44.80).” After a while, participants left the building with $M = 30.29$, $\sigma = 39.58$. These two works show that rotation gains can easily cause severe VR sickness effects. Rietzler et al. [219] investigated the use of overt curvature gains: They asked “How strong was the feeling of nausea or disorientation during walking?” on a scale from 1: “non-existing” to 7: “I wanted to abort the test.” They used very noticeable curvature gains to test the acceptability, but only a small exposure. The authors note that higher gains can be applied, since they are still perceived as usable, although they significantly increased nausea and disorientation [219]. The median score increased mainly with gain, from 1 to 1,333, then to 3,261; and finally to 5,285; signifying strong nausea or disorientation.

We excluded [146] because of missing scale details preventing interpretation of the reported values. We exclude [6, 135, 165, 134, 58, 271, 70] because we suspect they calculated the SSQ scores incorrectly (e.g., using a 48-point scale). We exclude Weller, Brennecke, and Zachmann [302] because their virtual environment was mostly dark and the path was mostly straight, resulting in an unfair comparison to other techniques due to the lack of visual motion cues. In the case of Gao et al. [70], who report exceptionally high SSQ difference scores, we suspect that they may have multiplied the scaled subscales by 3.74 to obtain the SSQ-TS, instead of multiplying the *unscaled* subscales: $171.75/3.74 = 45.9$, which is much more reasonable compared to related techniques in Figure 8.7.

**Scene Manipulation.** Scene manipulation is a type of redirected walking where the virtual environment is changed, either perceptibly or outside of the user's awareness, to provide the user with a new path that guides them away from the physical boundaries. In this section, we consider both self-overlapping spaces techniques (e.g., [180, 116]) and overt scene reconfiguration (e.g., [248, 79] due to the limited number of observations. Figure 8.8 shows the results with a note to indicate what technique was used.

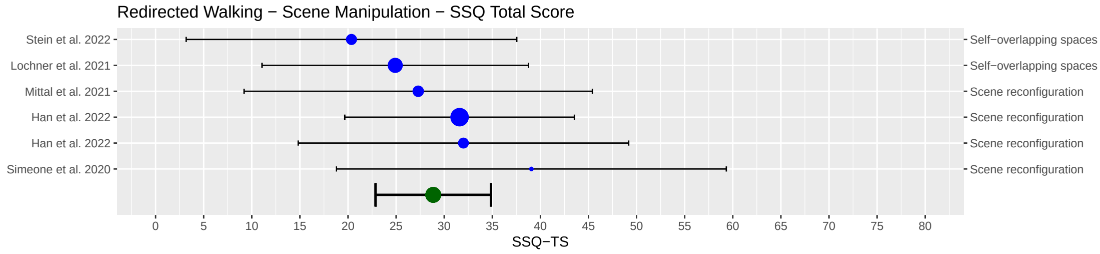



Figure 8.8: Forest plot of the SSQ-TS scores of RDW/Scene manipulation techniques, intervals are CI. The green point is the combined SSQ-TS with CI (black) and PI (green). On the right, the main differences are noted. Point size is proportional to weight in the model.

16 papers (16.7%) in our sample use a scene manipulation technique. 5 of those papers (31.3%) reported valid SSQ scores [79, 147, 248, 166, 260] and were included in data analysis, resulting in 6 measurements, of which 2 are independent. A random-effects model finds a combined effect size (SSQ-TS) of $28.86 \pm 2.33$ (SE). The confidence interval (CI) is $[22.87, 34.86]$ and the prediction interval (PI) is the same. The data appears homogeneous, with $Q = 2.97, I^2 = 0\%, \tau = 0$. The results are visualized in a forest plot in Figure 8.8.

Neerdal et al. [180] used the VRSQ to measure VR sickness and reported very low scores of <0.3 for the oculomotor and distraction scales. They report that "from distraction, the most prominent symptoms were headache, fullness of head, and blurred vision, each with 2–3 participants having an increase from none to slight." Koltai et al. [116] also used the VRSQ and report a score of $M = 9.5, \sigma = 10.7$, but detail is lacking and it's not clear what scale the value is on or why it is an so much larger than Neerdal et al. [180]'s result. Sun, Wei, and Kaufman [270] report difference scores based on Bouchard, Robillard, Renaud, et al. [23]'s SSQ: $\delta$SSQ-N $M = 2.85, \sigma = 3.39$ and $\delta$SSQ-O: $M = 2.57, \sigma = 2.37$. They further note that "Two users reported dizziness right after the first experiment, but they recovered and felt comfortable for the remaining two experiments [...] Another participant expressed concerns about highly bent angles, which may cause users fatigue and discomfort after sustained usage." Vasylevska and Kaufmann [294] report difference scores, which we assume are SSQ-TS: $\delta$SSQ-TS: $M = 2.5, \sigma = 2.77$ and $M = 1.15, \sigma = 2.6$ for different room layouts. We excluded [35, 165, 57, 239, 58] because we suspect that the scores were calculated incorrectly, similar to what we discussed in previous sections.

## 8.5 Discussion

In this section, we first briefly discuss how to interpret SSQ scores, how to use the SSQ as a pre-exposure baseline. Then, we discuss and compare the VR sickness results of the different types of walking-based locomotion we presented in section 8.4. Finally, we provide guidelines for the use of VR sickness metrics in VR locomotion research. Our discussion of VR sickness assessment practices is based on our interpretations of the papers in our sample, the coded observations with respect to study design aspects, and our experience from the construction of this review. A formal evaluation of VR sickness assessment is beyond the scope of this work, but the data from this review, which we provide in the supplementary materials,[9] provides a good starting point for future work.

**How to interpret SSQ results?** In this work, we observed that the standard deviations of SSQ scores are practically the same as their mean values. This dovetails with previous work by Winkel, Talsma, and Happee [310], who found a strong correlation between the two. Such large standard deviations indicates that there was a lot of variation in how individual users scored on the SSQ. It is well-known that user characteristics affect VR sickness [230, 214], but it is unclear how this affects our interpretation of SSQ scores when comparing techniques. The individual differences are highlighted in Tirado Cortes, Chen, and Lin [281], and we observed the same in our sample of raw data: some users score highly, whereas other appear to not be affected at all. The (high-scoring) outliers skew the mean and standard deviation measures, making it difficult to compare different techniques when the mean values are relatively similar. This is somewhat expected, as it is well-known that SSQ scores are not normally distributed (all papers in our sample mention that the SSQ data was not normally distributed or do not mention these details at all) (see [259, 310]): mean and standard deviation measures are typically not suitable for this type of data and mask the true range of VR sickness effects.

For example, in a study of 20 participants, four may score 0, 12 may score around 15, 2 may score around 20, and 2 score above 100 (example). While the majority of users did not experience meaningful sickness symptoms, the two participants make it seem that the locomotion technique generally causes VR sickness. Vice-versa, if a given locomotion technique evaluation reports an SSQ-TS score of M=55, sigma=40 (example), this does not mean that VR sickness is relatively low (55/235,62=23% of the maximum). Instead, it means that some users were severely affected, while others were not. We propose the following thresholds on SSQ-TS scores for easy of interpretation: None (<5), Low (5–15), Medium(15–30), and High (30+). Note that these are purely for ease of comparison in the current work. Furthermore, the mapping will differ depending on sample size, user characteristics, and type of locomotion used.

The design of the SSQ exacerbates the issues because it does not count all symptoms equally, some are included in multiple sub-scales and thus count doubly towards the SSQ-TS score (difficulty focusing, nausea, difficulty concentrating, blurred vision). Furthermore, user will likely suffer from different symptoms, meaning that two techniques with the same SSQ-TS score may have arrived there because of different symptoms. Another example is how SSQ scores are easily inflated compared to the 0 baseline: a participant who only reports “slight” fatigue, “slight” eye strain, and a “slight” difficulty

[9] https://osf.io/78j2s/?view_only=f8a1f75b49be4bbda4d5242c773c73e2

focusing will already have an SSQ-TS of 14.96. It is easy to imagine that these symptoms resulted from the task or the hardware used. You et al. [317] reported that FMS scores did not increase beyond 2 (out of 20) during the study, but their SSQ scores showed a large increase from 5 to 22. To conclude, as a measure of general discomfort in VR use, as the SSQ is typically used, the SSQ is ill-suited [91].

For VR designers, it is not good enough to assume that given an SSQ-TS score of 24 for a given technique, users will, on average, only have mild VR sickness, if that means that some users will experience severe discomfort. However, that is the situation we find ourselves in now. In general, we suggest to interpret mean and variance values of SSQ scores carefully, and compare them to reference values, such as those in this work, to assess the relative VR sickness risk. We urge researchers to avoid reporting SSQ scores as mean and standard deviations, and instead provide measures that work well with non-normally distributed data, such as median values and an inter-quartile range. Bayesian methods are more flexible and are better able to capture the effects of individual users and the level of uncertainty in the data, and it is relatively straightforward to include ordinal data (such as the SSQ scales) in Bayesian models. Although none of the papers in our sample employed Bayesian methods, we suggest that future work seriously consider this possibility. For an introduction, see [233, 107, 159]. Finally, we urge researchers and VR sickness investigators to provide raw data and qualitative comments to illustrate the VR sickness results. This will aid future work in determining the symptom profile and prevalence of VR sickness.

**On the zero-sickness baseline of the SSQ.** The results in section 8.4 show that the combined SSQ-TS score before VR exposure is 7.49. Looking at the range of values in the observations in Figure 8.3, it seems clear that Pre-SSQ scores are low, but certainly not zero. Kennedy et al. [111] recommend that "unhealthy" subjects should be excluded (anyone who is not in their usual state of fitness before starting the experiment). The pre-exposure SSQ measurement can be used to determine this. On the one hand, it seems a reasonable assumption to assume that a typical participant has no simulator sickness when arriving at the experiment. However, they may be sweating or dizzy (both SSQ symptoms), or they may suffer from headache or eye strain, which are often caused by screens in our daily life [91]). Furthermore, it may be difficult for a participant to understand some symptoms, causing them to answer inaccurately. As discussed in Figure 8.4, Pastel et al. [197] found that participants had trouble understanding the difference between symptoms, which could lead to them answering inaccurately. The authors suggest that future work should employ VR sickness measures other than the SSQ.

The presence of substantial heterogeneity in the Pre-SSQ results makes it difficult to draw generalizable conclusions about average sickness states of participants before VR exposure. However, our results are in agreement with those in related work: Beadle [8] report a mean and standard error of Pre-SSQ-TS $= 10.4 \pm 0.5757$ (SE) after combining data from several studies (875 participants total). Their mean value is similar and their reported SD ($\sigma = 17.03$) also indicates a large amount of variance. Brown, Spronck, and Powell [29] report on a study that specifically aimed to investigate the responses on the SSQ in a normal population before an intervention. They find much higher SSQ-TS scores ($M = 50.751 \pm 36.638$) with 93 participants. After discussions with the authors, we speculate that the difference may be explained by several factors that are a-typical of the VR user studies in our sample: 1) in Brown, Spronck, and Powell [29] the participants did not receive an intervention which may cause demand characteristics; 2) there was a limited number of native English speakers which may have led to incorrect interpretation of symptoms; and 3) the survey was filled out online and in the middle of a pandemic, and indeed the data in [29] suggests that participants scored highly on symptoms of "difficulty concentrating/focusing" and "fatigue." It is interesting to consider the apparent large differences between a participant population that participates in a VR experiment and a more general population, but we leave this discussion for future work.

To conclude, in theory, we could assume that a group of participants will not report 'slight' or worse symptoms on the SSQ before VR exposure. That is, they should have a PreSSQ-TS score of 0. However, the evidence above strongly suggests that assuming a baseline score of 0 is flawed. It may seem tempting then, to always perform a pre-exposure measurement and report the difference scores from the post-intervention measurement. However, this does not account for symptoms subsiding during the experiment, which would result in negative SSQ scores that are difficult to interpret. On the other hand, not using a pre-exposure measurement unnaturally inflates the post-exposure SSQ scores if symptoms do not subside, making it difficult to conclude the effect of the intervention on VR sickness. So, the original recommendation by the SSQ authors remains the preferred option: to discard participants that have a non-zero pre-exposure score. However, our data shows that this guidelines is rarely, if ever, observed in practice.

**Does isometric walking cause VR sickness?** The SSQ-TS scores fall roughy between 5 and 26 (see Figure 8.4). The combined SSQ-TS is relatively low (16), but clearly not zero. In fact, it is higher than we initially anticipated. This can be partially explained by some of the highest scoring observations having clear indications that other factors lead to an increase of symptoms, for example: high physical effort (NASA-TLX) leading to an increase in sweating or fatigue [43]; or the use of repositioning techniques before evaluating an isometric walking condition [114]; or low refresh-rate body tracking systems leading to a sensory mismatch [19]. A straight-forward way of confirming this would be to further examine the symptom responses or the sub-scales (Nausea, Oculomotor, Disorientation) of the SSQ. However, this was rarely done in the papers in this review. We do not have enough sub-scale observations to make meaningful comparisons.

The discussion of non-SSQ scores provides some insight: Pastel et al. [197] report a medium SSQ score of 20, but also that no participant complained about any symptoms. While the question of how participants complain versus answer questionnaire is beyond the scope of this work, the intuition is supported by several other works in the walking group: Two studies with large sample sizes and reported that only a small percentage of users experience symptoms related to VR sickness, such as nausea or dizziness Kwon et al. [121] and Wang et al. [300]. Similarly, Pala et al. [193] reported small difference scores after walking in VR ($\delta$SSQ=5).

While this evidence can be interpreted to say that VR sickness was evidently non-zero (at least some participants were affected), we assume that the increase in symptom severity was due to other factors in the studies. In particular, it is well-known that hardware, user, and application factors affect VR sickness [215, 38, 230]. To conclude, we don't find convincing evidence that isometric walking in VR is related to an increase in VR sickness. However, additional empirical work is needed to confirm this.

**Does redirected walking cause VR sickness?** To start with a surprising result: Resetting has a lower combined SSQ-TS score than walking. Given visual manipulation involved in resetting it seems unlikely that this means that resetting causes less VR sickness. In particular, the isometric walking results include several dependent observations that may skew the results upward, and there are not many observations for resetting. Still, resetting seems like a promising technique: Clearly, it can be applied without much sickness, and it is easily implemented. Furthermore, it can be combined with distractions (e.g., [257]) and stable reference frames (e.g., [285, 286] to further reduce discomfort.

Some repositioning techniques clearly cause high VR sickness: eight observations report an SSQ-score above 30, up to 55. Interestingly, Selzer, Larrea, and Castro [237] and Wilson et al. [308] show a positive correlation between gain level and SSQ scores, but this relationship is not obvious when looking at Figure 8.6. We suspect that the design of the transfer function is an important determinant of VR sickness, as discussed by Williams-Sanders et al. [307] and related work [71]. As an example, Cmentowski, Kievelitz, and Krueger [43] shows medium VR sickness when using a tunnel to block the optical flow of a 30x gain.

The data in reorientation is difficult to summarize. The effects cover the entire range of scores we observed in this review: Some techniques appear to perform well, even in small physical spaces and combinations of manipulation; other studies that specifically investigated the limits of reorientation and show that it can definitely make you sick (e.g., [90, 234]). In this work, we did not directly consider whether the technique used overt or covert manipulation. The data did not typically provide enough detail to group based on this, and it is not guaranteed that the manipulation of a covert technique was indeed imperceptible in practice. Nonetheless, it will be interesting to consider whether covert manipulation causes less sickness than overt. Furthermore, blinking-based redirection (e.g., [126, 182]) is promising. Another interesting idea is to use overt manipulation, but rely on training or habitation to deal with discomfort (e.g., [90, 220]). Finally, a particular challenge in this analysis is the great variety of reorientation techniques from blinking-based approaches, to various transfer functions, to different gains. There is little overlap in test environments, procedures, and reporting standards. We urge future work to improve this to make redirected walking approaches more comparable in terms of user discomfort.

**Guidelines for measuring VR sickness.** As we discussed in section 8.2 and above the current state of reporting VR sickness measures makes it difficult to synthesize VR sickness effects and compare different papers. Although all current metrics of VR sickness have important limitations, we can alleviate some of them.

Bimberg, Weissker, and Kulik [15] provide an excellent short overview of the limitations of the SSQ and its use in practice. More importantly, they propose a number of guidelines that we echo here and build upon based on the results of this work.

**1. Take care to correctly calculate and report the SSQ scores.** The calculation method for the SSQ is not intuitive, and it is easy and common to make mistakes. See Bimberg, Weissker, and Kulik [15] and section 8.2 for an introduction to the use of the SSQ. Furthermore, report all scales of the SSQ, including Nausea, Oculomotor, and Disorientation.

**2. Consider whether to use the SSQ as a pre-exposure measurement.** Using the SSQ as a metric to measure an increase in symptoms due to exposure to a locomotion technique is preferred over using the SSQ strictly as an absolute measurement. However, it can also lead to results that are difficult to interpret (negative scores, lack of magnitude). The right choice likely depends on the goal of the study: to determine an effect of VR sickness (use difference scores but report all details) or to use the SSQ as a "control measure" (use a pre-exposure measurement to preemptively exclude participants, or a post-exposure measurement to exclude participant who were affect). It should be clear that the SSQ should in no circumstance be interpreted as an absolute measure of a participant's level of VR sickness, or simulator sickness, when used with virtual reality and walking locomotion.

**3. Consider other VR sickness measurements.** The SSQ is well-known and so there may be a degree of convenience in using it. Another argument is that using the same questionnaire as previous work allows for comparisons and meta-analyses. However, it is clear that this is not possible with a reasonable degree of accuracy. Instead, consider modern alternatives that we have discussed in section 8.2, for example: the Cybersickness Questionnaire [265] or Fast Motion Sickness scale [112]. We do not recommend a particular scale, and more work is needed to determine the right measure, but we refer the reader to Sevinc and Berkman [240] and Hirzle et al. [91].

## 8.6 Conclusions

We set out to synthesize how walking-based locomotion influences VR sickness. Our results describe the VR sickness effects of five types of walking-based locomotion—walking, resetting, reorientation, repositioning, and scene manipulation. We found overall low SSQ scores for isometric walking but higher for non-isometric redirected walking techniques. However, the measuring practices are mixed and there are open questions related to different movement types that need more empirical work. Based on our results we present three guidelines for the measurement and reporting of VR sickness.

# 9 Step On It

This chapter presents the paper "Step On It: Asymmetric Gain Functions Improve Starting and Stopping in Virtual Reality Walking" [71] that is published as an open-access, peer-reviewed paper in the Virtual Reality journal. The content in this chapter is predominantly similar to the published version-of-record, except for minor spelling, stylistic, and typographic improvements.


## Abstract

Transfer functions with a high translational gain can increase the range of walking in Virtual Reality (VR). These functions determine how much virtual movements are amplified compared to the corresponding physical movements. However, it is unclear how the design of these functions influences the user's gait and experience when walking with high-gain values. In a mixed-methods study with 20 users, we find that their best transfer functions are non-linear and asymmetrical for starting and stopping. We use an optimization approach to determine individually optimized functions that are significantly better than a common approach of using a constant gain. Based on interviews, we also discuss what qualities of walking matter to users and how these vary across different functions. Our work shows that it is possible to create high-gain walking techniques that offer dramatically increased range of motion and speed but still feel like normal walking.

**Title:**
Step On It: Asymmetric Gain Functions Improve Starting and Stopping in Virtual Reality Walking.

**Authors:**
*Thomas van Gemert*, Kasper Hornbæk, and Joanna Bergström.

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**What was the role of the PhD student in designing the study?**
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**Which part of the manuscript did the PhD student write or contribute to?**
The student wrote and contributed to the entire manuscript.

**Did the PhD student read and comment on the final manuscript?**
Yes.

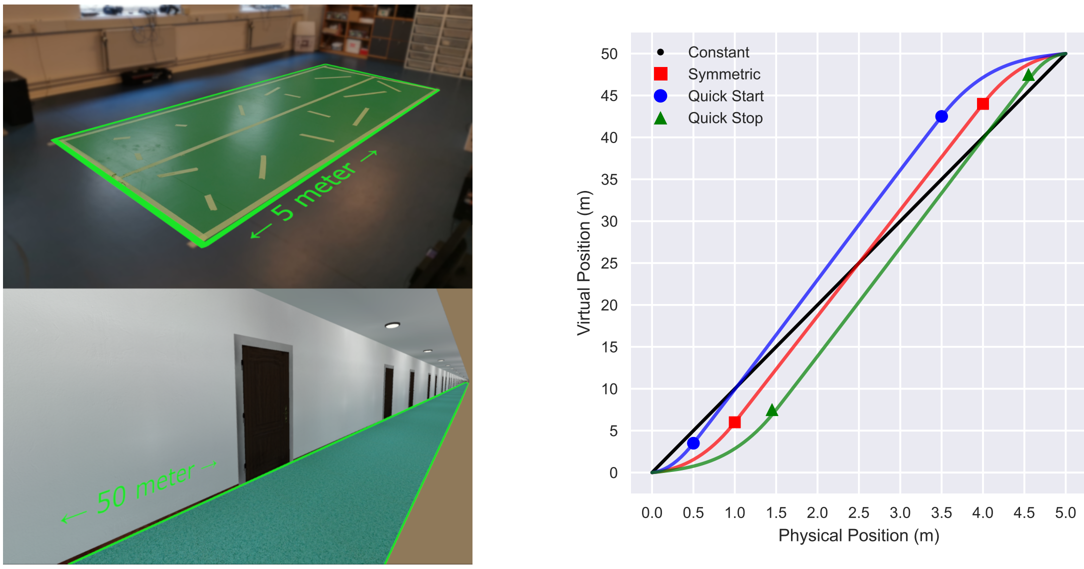



Figure 9.1: In this work, we explore the design of transfer functions that use separate acceleration curves for starting to walk and stopping to walk. By applying a translational gain, we can map a typically small VR play space (top left) to a much larger virtual space (bottom left). For example, on the right, we map the physical position ($x$-axis) to the virtual position ($y$-axis) with a gain of $10$. "Quick Stop" slowly increases the virtual velocity in the beginning but slows down rapidly when reaching the target. In contrast, the "Quick Start" configuration offers slight acceleration initially but uses a prolonged stop. Of course, other (asymmetric) configurations are also possible, such as one using a slow start and a slower stop.

## 9.1 Introduction

Walking is a good way to travel in Virtual Reality (VR) [124]. For example, it is more enjoyable, less sickness-inducing, and offers better task performance and spatial updating than teleportation or joystick control [124, 198, 177, 97, 306, 217, 225, 319, 287]. However, VR systems, by default, translate the user's physical movements to the virtual environment *isometrically* (i.e., one physical meter equals one virtual meter). Therefore, a user can walk only as far in VR as the physical space permits. A key challenge of walking in VR is overcoming the limited range of travel while maintaining the benefits of physical walking.

One way to extend the range of travel for walking in Virtual Reality is to apply a gain to the virtual movement, resulting in *non-isometric* walking. The gain value increases the virtual movement compared to the corresponding physical movement, allowing the user to travel faster and farther virtually. For example, walking a physical distance of 25 meters can be scaled to virtually walking a distance of 250 meters by applying a translational gain of 10. A *transfer function* describes the relationship between the physical and virtual movement [178]. The transfer function controls how the gain value is applied based on input from the tracked physical movement, and thus produces a non-isometric virtual movement.

The most common and straightforward transfer functions use a 1:N mapping so that the virtual displacement is always a constant factor N greater than the physical displacement (e.g., [306, 281, 308]). More advanced transfer functions instead use a non-linear or piece-wise mapping to scale the gain value dynamically, based on the user's velocity, for example. With a non-linear transfer function, users gradually accelerate to their maximum virtual speed and avoid jarring motion effects for small head movements. This approach has been shown to increase the usability and limit VR sickness effects of transfer functions with a high gain [307, 97]. However, the design space for transfer functions is extensive, and no guidelines exist on how to design these functions.

For relatively low gain values[1] of less than three, a 1:N mapping, resulting in a constant gain, can be used without affecting spatial orienting performance, user experience, or VR sickness too much [304, 308, 263, 307]. Even lower gain values are often used in redirected walking techniques to make the manipulation of the virtual movement imperceptible [263]. However, for larger gain values, the sudden acceleration (when starting to walk), deceleration (when stopping), and high virtual speed become problematic. For example, small head movements become distracting [306], gait and performance are significantly reduced [3, 308], and many users are affected by VR sickness [281]. Non-linear transfer functions can alleviate some of these issues but may also induce a "sensation of lag," and it is still difficult to be accurate at high-gain values [3, 97]. Furthermore, current transfer functions apply the same curve to both the moments of acceleration and deceleration, overlooking different requirements a user may have for starting swiftly and stopping accurately. Little work exists on the shape of the transfer function curve and how different configurations may align with different user preferences.

In this work, we explore the design and use of transfer functions that individually control the curves for acceleration (starting) and deceleration (stopping) in high-gain VR walking to improve performance and user experience. By specifying a mapping between a fixed physical and virtual distance, we can vary these curves separately in a controlled manner. We describe our approach for varying the acceleration and deceleration using only two parameters of the transfer function's curve. In the first part of a user study, a Bayesian optimization approach samples the different transfer functions to predict the best configuration based on walking performance and usability scores. In the second part, we interview the participants to study qualities of walking that matter to users and how these may vary across configurations.

## 9.2 Related Work

**Non-linear Transfer Functions.** The most straightforward approach to using non-isometric walking is to apply a constant gain (i.e., a transfer function with a constant 1:N mapping) to all directions of movement. The gain increases forward motion but also lateral and vertical motion. When walking, the head is also swaying side-to-side and bobbing up and down. Even simply turning the head when standing still results in some lateral motion, which would be greatly exaggerated when using high-gain values. This makes it difficult to control small, local movements and can result in disturbing

[1] Some authors have used gain values of up-to 100 (e.g., [307]).

motion while walking [308, 306, 307, 3, 281]. Williams et al. investigated the effect of non-isometric walking with constant gains of 1.0, 2.0, and 10 on spatial orientation and concluded that it is a viable locomotion method [306]. However, they noted that small head movements become distracting at a gain of 10. Wilson et al. [308] used a constant gain and relatively low gain values (1–3) to investigate its effect on interaction performance: they concluded that a constant gain of 2 is still usable, but accuracy, simulator sickness, and frustration become problematic above that. [3] also found that walking with high constant gain values (up to 30) diminishes positional accuracy and causes users to modify their gait due to lack of control.

Gradually increasing the gain values with the user's velocity avoids the problem of a high gain scaling small head movements [97, 307]. In "Seven League Boots," one of the first studies using non-isometric walking, Interrante et al. [97] did this by linearly scaling the gain value by the walking velocity: When the velocity is low, the gain value is also low. This approach minimizes the disturbing effects when maneuvering or moving slowly. In a pilot study, the authors reported that the Seven League Boots technique, using a maximum gain of 7, was strongly preferred over flying with a joystick, natural walking, or using a constant gain. They further described that enabling the technique via a button press may allow for a greater feeling of control while having it always on "may induce a sensation of lag in the system" [97].

Williams-Sanders et al. [307] investigated three non-linear transfer functions: quadratic, cubic, and exponential. Their piece-wise transfer function increases the gain non-linearly as the user's velocity increases, up to a certain threshold velocity, after which it applies a constant gain. They also investigated the position of this threshold and found that users prefer a threshold of $0.5$ m/s over $0$ m/s (effectively constant gain) and $1.0$ m/s (similar to Interrante et al.'s approach [97]). The authors gathered user ratings of "local control," "global control," "sickness," and "feeling unbalanced" for the three functions, but it is unclear how these relate to user experience or walking performance. Their main experiment used a large, open outdoor environment, and their results show that users can maintain good spatial orientation for gain values of up to 50.

A shared characteristic of the velocity-controlled transfer functions above is that the curve for increasing velocity (starting to walk) and decreasing velocity (stopping to walk) is identical. However, Abtahi et al. [3] reported that users found the Seven League Boots technique rather tricky to use and often required multiple smaller steps to stop on the target. Seven League Boots, unlike the other two methods in their study, diminishes positional accuracy at high gains, and users modify their walking behavior to compensate for their lack of control. The Seven League Boots technique became particularly difficult to use at a gain of $30.0$: Some participants said that they "would step too far or not enough and lose track of where it was, and would keep trying to correct and adjust to get on the right spot," or that it felt "disorienting and difficult to be accurate" [3]. So, it seems that transfer functions should be improved to better support stopping when walking with high gain.

Previous work suggests that non-linear transfer functions are a promising solution to prevent scaling small movements and disturbing motion when using a high gain. However, the effect of different transfer functions on the quality of walking remains unclear, particularly for different task requirements: For example, when the goal is to start moving quickly or to stop comfortably and accurately. We address this issue by changing the curve of the transfer function separately for the beginning and end of the trajectory with asymmetric transfer functions. This approach allows us to evaluate a broad range of transfer functions and determine how fast the transfer function should accelerate people when they start to walk and how fast it should decelerate them when they want to stop.

**Effects of Non-Isometric Walking on User Experience and Performance.** People readily adjust their locomotor control to changing circumstances [168]. Some work has shown that people re-calibrate their gait in the presence of unnatural optical flow, but not their walking velocity [218, 168]. However, previous work using virtual reality (VR) has shown that gait - including walking velocity - is significantly degraded compared to walking out of VR [169, 100, 99]. This effect is still worse for non-isometric walking [100, 3, 281] and it seems that translational gain, perceptible or not, affects walking velocity [181, 100, 3]. Janeh et al. [99] also showed that degraded gait effects persist with a longer duration of isometric walking in VR. Users walk more slowly with increased step frequency and decreased step length during non-isometric walking, and these effects may become more substantial for higher gain values [100, 281, 3]. However, it remains unclear how different acceleration curves and gain values influence gait.

Several different aspects of the subjective experience of non-isometric walking have been investigated. For example, Interrante, Ries, and Anderson [97] asked users to rate the Seven League Boots technique on the items “easy to use,” “feels natural,” and “induces cybersickness.” Tirado Cortes, Chen, and Lin [281] reported that walking with a constant gain function and high gain can induce significant simulator sickness, but only in some users.

Abtahi et al. [3] investigated a more extensive set of qualities by combining a custom questionnaire with parts of a Standard Embodiment Questionnaire (SEQ) and a workload questionnaire (NASA TLX). They performed a principal component analysis and found two factor loadings of “Preference” and “Embodiment.” The first contained the preference questions (e.g., “I liked walking around in this mode”) and the workload questions. The second factor contained the embodiment and physical demand questions. These results offer valuable insight into what the qualities of walking are. The authors recommend investigating dynamic gain changes next but warn that in a preliminary study, they found that dynamic changes can cause simulator sickness symptoms. However, “gradual and slight gain changes may be possible without inducing motion sickness or a sensation of lag” [3].

Previous work shows that transfer functions influence both pragmatic (e.g., gait, accuracy) and hedonic (e.g., simulator sickness) qualities of walking in VR. However, VR locomotion research usually compares non-isometric walking against alternative locomotion techniques instead of comparing different transfer functions. Furthermore, more work is needed to understand how non-isometric walking influences the user experience, particularly in terms of subjective qualities of walking with a high gain. We address this issue by measuring the effects of transfer functions on gait and usability and explore what subjective qualities of walking matter to users.

## 9.3 Designing Transfer Functions

Walking from a standstill to a target and stopping comprises three phases: gait initiation (accelerating), steady-state walking, and gait termination (decelerating and stopping). Since starting and stopping to walk have different requirements and gait behavior, we can apply a unique transfer function to either phase to create optimal behavior for both. Combining the two different behaviors into a single function results in an asymmetric transfer function. In this section, we 1) detail a design process for transfer functions for walking in virtual reality (VR) and 2) discuss how to best vary the gain for acceleration and deceleration independently. In the next section, we use this to 3) systematically generate different transfer functions, 4) experimentally determine the optimal transfer function, and 5) evaluate their effect on the quality of walking.

**Position-controlled Transfer Functions.** A typical transfer function for non-isometric walking takes a physical displacement or position value as input and multiplies this by the *gain* value to create a virtual displacement or position greater than the physical one (for gain values $> 1.0$). In a velocity-controlled transfer function, the gain is scaled (non-)linearly based on the user's physical walking velocity. In this work, we use position-controlled transfer functions with a defined trajectory between beginning and end points (see Figure 9.1). We assume a standstill-to-standstill travel task where the virtual target location is known, and the user can walk to the target in a relatively straight line. This assumption allows us to ignore the special cases of turning and reducing velocity during the trajectory, which we leave for future work. The transfer function then scales each physical point along the trajectory by the gain value to produce a farther virtual point. By varying the gain value along the physical points, the transfer function produces a non-linear movement along the virtual trajectory. The conceptual idea is exemplified in Figure 9.2.

In Figure 9.2 the virtual and physical trajectories are normalized so that $x = 0.0$ corresponds to the physical starting position and $x = 1.0$ corresponds to the physical target position. The transfer function is a Cubic Hermite Spline defined by four control points: one at the origin $(0, 0)$, one at the target position $(1, 1)$, and two variable points $c_1$ and $c_2$. Each control point is a tuple $(x, y, t)$ for the x-position, y-position, and tangent. The $c_{1,2}$ control points mark the end of the "acceleration phase" and the beginning of the "deceleration phase," respectively. In the steady-state walking phase, we apply a constant gain. The configuration of the transfer function can then be changed by changing the positions of the $c_{1,2}$ control points and adjusting the tangents to produce a smooth curve.

The ratio between the virtual and physical motion is typically referred to as *gain*, although it lacks a common definition. Previous work has referred to translational gain as "optical gains," simply "gain," or "scaled movements." In this work, we produce a non-isometric virtual position $\vec{p^*}$ by multiplying the physical position $\vec{p} = (p_x, p_y, p_z)$ by a scalar gain value $g$ (Equation 9.1).

$$\vec{p^*} = (g \cdot p_x, g \cdot p_y, g \cdot p_z) \tag{9.1}$$

To reduce disturbing motion, transfer functions often only scale the movement in the

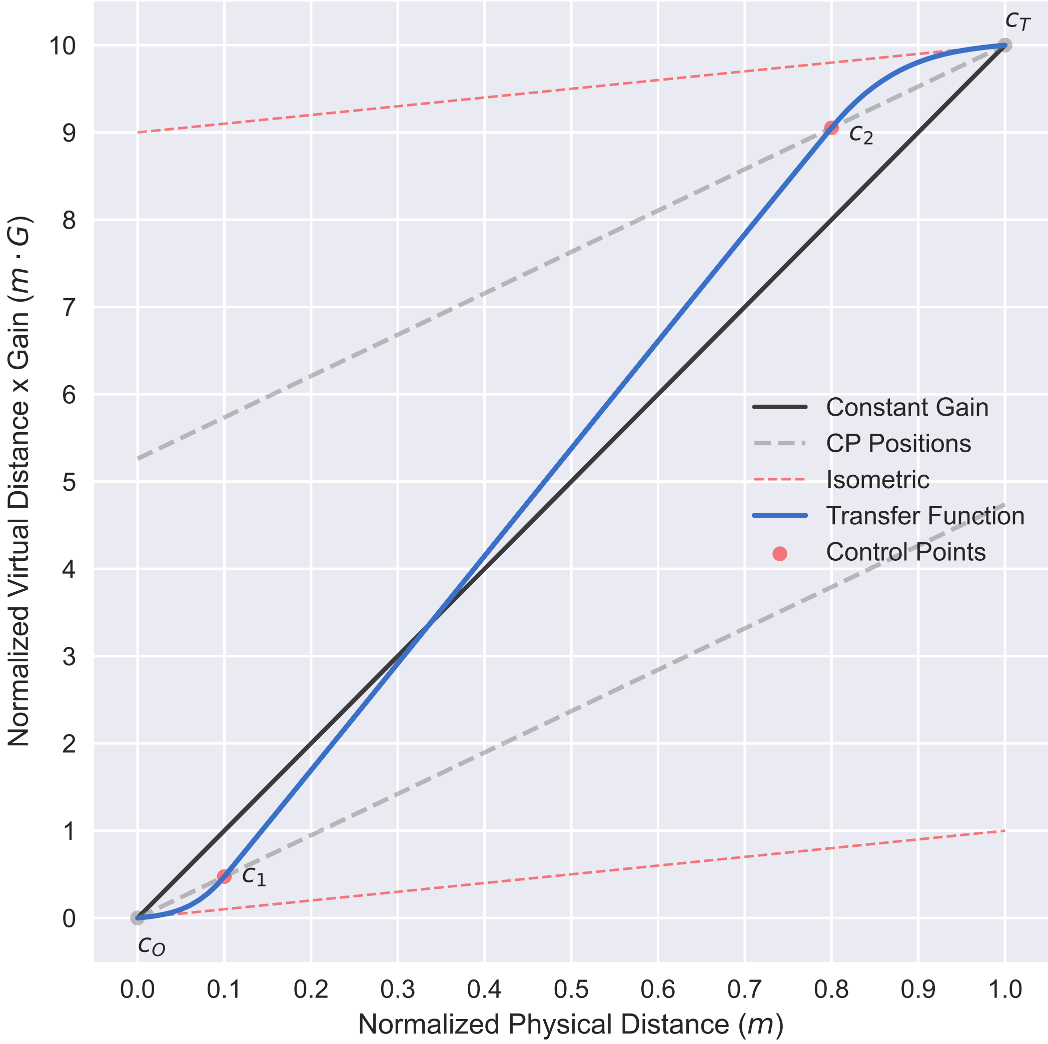



Figure 9.2: An example transfer function defined by two control points $c_1 = (0.1, 0.05)$ and $c_2 = (0.8, 0.90)$. The current configuration results in an asymmetric transfer function where the stopping moment is longer than the starting moment. With the current gain of $G = 10.0$ and a physical distance of 5 meters, the starting moment is 0.5 meters long, and the stopping moment 1 meter. The red dashed lines indicate the respective isometric ($G = 1.0$) boundaries. The dashed grey lines indicate the possible positions of the control points, respectively.

horizontal plane $(g \cdot p_x, p_y, g \cdot p_z)$ or - although this can be difficult to determine - the direction of travel $(p_x, p_y, g_z \cdot p_z)$.

The slope of the transfer function curve corresponds to the *effective gain* at a given time during the trajectory. The effective gain refers to the ratio between the user's perceived (virtual) motion and their physical motion. So, changing the distance over which the non-linear curves are applied varies the intensity of the acceleration and deceleration.

In the steady-state walking phase the effective gain can be higher than the average gain. This way, the virtual trajectory with the asymmetric function is the same distance as with a constant gain function. Based on our experiences and anecdotal reports (e.g., [307]), users seem to have little trouble with high, constant gain values during steady-state walking, and so we consider this a safe simplification of our design.

**Transfer Function Parameters.** The coordinates and tangents of the $c_1$ and $c_2$ control points dictate the resulting virtual movement from the transfer function. However, many possible configurations do not produce a useful transfer function. We have identified several guidelines for configuring the control points through our testing. The resulting constrained design space will likely produce useful and desirable transfer functions.

*Control Point Coordinates:* The solid black line in Figure 9.2 indicates the constant gain transfer function over the same distance. The $y$-coordinate of $c_1$ should not lie on or above this line. Vice-versa, the $y$-coordinate of $c_2$ should not lie on or below this line. If a control point does lie on this line, there is effectively no non-linear scaling of the gain value. If $c_1$ lies above the line, the curve would be downward concave around $c_1$, causing the user to accelerate at a high rate when starting to move to slow down during steady-state walking to reach a constant gain again. Vice-versa, $c_2$ being below the black line leads to a concave upward curve around $c_2$ which would cause the user to accelerate towards the target at a high rate instead of slowing down.

Similar bounds are given by the red dashed lines in Figure 9.2 that indicate the isometric mapping (i.e., $g = 1.0$). If the curve falls below the lower red line or above the upper red line, the user slows down at that point to less than their physical walking velocity ($g < 1.0$). This behavior is undesirable and can be avoided by bounding the $y$-coordinate of $c_1$ and $c_2$ to be between the constant gain and isometric lines and adjusting the tangents to keep the curve within those same bounds (see subsection 9.3).

The control point's $y$-coordinate can be closer to the black line to create a faster acceleration or closer to the red line to create a slower acceleration. For simplicity, we constrain the control points to lie on the grey dashed lines in Figure 9.2 that equally separate the solid black and red dashed lines. This guideline has produced good results in our testing.

The acceleration while starting and stopping to walk can now be controlled by only varying the $x$-coordinate of $c_1$ and $c_2$ respectively. We dub this $x$-coordinate $\alpha$ (alpha), resulting in two free parameters $\alpha_{start}$ and $\alpha_{stop}$, respectively.

*Control Point Tangents:* In order to provide a smooth virtual movement, the non-linear curves of the transfer function before $c_1$ and after $c_2$ should also be within the red and black guidelines in Figure 9.2. We set the tangent of the control points to be the slope of the line between $c_1$ and $c_2$. This tangent ensures a smooth transition between the non-linear and linear sections. We set the tangent of the origin and target control points to the slope of the isometric line ($\frac{1}{G}$) to prevent the curve from falling below the isometric gain line. If $c_1$ or $c_2$ are very close to the origin or target, the cubic spline may cause the curve to fall outside the isometric line regardless. In this case, we find the closest tangent value for the control point that keeps the curve inside the isometric line.

## 9.4 Study

The purpose of this work is to take the first steps towards designing asymmetric and dynamic transfer functions that improve the user's experience and performance when walking with a high gain.

The design space of our transfer functions consists of three variables that we can modify for a given distance: the *average gain* value $g$, the distance over which the user is accelerated from the starting point, and the distance over which the user is decelerated towards the target (controlled by $\alpha_{start}$ and $\alpha_{stop}$ respectively). However, this still leaves an extensive range of possible configurations; we do not know the effect of longer or shorter acceleration distances on user experience and walking performance.

We believe an optimization approach is necessary because it would be infeasible to test all possible values of $\alpha$, and it is unclear which points are most interesting to sample. We chose Bayesian Optimization because of its good performance with a small number of noisy samples, its ability to interpolate over unseen points, and its ability to provide a measure of the variance of the predicted score at any point. In this user study, we leverage Bayesian Optimisation to predict optimal transfer functions efficiently and evaluate their effect on user experience.

**Experiment Design.** The study consists of two parts. In the first one, we optimize $\alpha_{start}$ and $\alpha_{stop}$, and in the second, we perform a semi-structured interview with the participants about the qualities of walking. We optimize $\alpha$ individually in a `start` and `stop` condition respectively. Each of these conditions consists of 10 trials. Each trial uses a unique transfer function generated by the optimization method below. We aim to control the exposure to virtual walking across participants, so a fixed number of trials is preferred, even though finding the participant's optimal configuration after ten trials is not guaranteed. Figure 9.4 shows the procedure and study design in more detail. Half of the participants starts with the `start` condition and the other half starts with the `stop` condition.

Our primary dependent variables are the user experience and performance of the transfer functions. A typical travel task has several requirements, such as accuracy, speed, comfort, and ease of use of the technique, which we expect to be influenced by the transfer function design. In other words, a poor design will lead to a worse user experience and performance on the travel task compared to an optimal design. Since users control their walking through complex internal control models that we cannot directly access or evaluate, we use the user's subjective experience to measure the quality of walking. We combine this with an objective measure of the quality of walking by recording the gait parameters of the user.

As measures of user experience, we record the *perceived usability*, VR Sickness, and qualities of walking through the interview. For VR Sickness, we use the Simulator Sickness Questionnaire [111] which we record after each condition. For measuring perceived usability, we use the UMUX-Lite questionnaire [139], which asks participants about the ease of use and competence of a system. UMUX-Lite is both a recognized metric and contains only two items, so it is helpful for quickly evaluating the usability of single trials in the optimization process. We changed the word "system" in each question to "configuration" to clarify what the questions refer to (i.e., the different configurations of transfer functions, not the complete VR system). The UMUX-Lite score range is $[0, 100]$, where $100$ indicates the highest perceived usability.

As an objective measure of performance, we choose the *time-to-target* in seconds. The time-to-target directly relates to the user's average walking velocity due to the fixed distance in the task. Previous work has shown that walking with a gain degrades several gait parameters (e.g., walking velocity, step size, step count) [100, 281, 181], and that this degradation may be worse for stronger manipulation [100]. We expect to see variations in walking velocity based on the participants' comfort (e.g., walking more slowly) and how well they can control their virtual movement (e.g., faster for more "fun," slower for higher accuracy). The time-to-target is taken as the mean over the last six traversals and normalized to the range $[10.0, 4.0]$ seconds, where lower time produces a higher score. This range is based on a pilot study with four participants walking five meters in VR plus one second on each end.

The walking velocity measure does not consider a user's preferred walking velocity, but determining this is difficult, especially in VR, due to novelty effects, task requirements, and degraded gait compared to real walking [100]. However, since we optimize the transfer function configuration on a per-user basis, we can evaluate the within-user differences as effects of the transfer function.

**Optimization.** The optimal configuration of a transfer function should maximize the transfer function's usability and the participant's walking velocity. So, we formulate a fitness function $f(u, t)$ that is an equally-weighted combination of the usability score $u$ and the time-to-target in seconds $t$ for each trial (Equation 9.2).

$$f = 0.5 \cdot \frac{u}{100.0} + 0.5 \cdot \left(1.0 - \frac{4.0 - t}{4.0 - 10.0}\right) \tag{9.2}$$

We use Meta's Adaptive Experimentation Platform (Ax) [95] as our Bayesian Optimization Framework. Specifically, we use a Gaussian Process model and Expected Improvement optimizer (GP+EI) provided by the Ax software.

For a new trial with a condition (`start` or `stop`) we query the EI algorithm to propose a new $\alpha$ value to evaluate. We optimize this this condition to find the optimal value of $\alpha$, while keeping the other $\alpha$ fixed to $\alpha_{start} = 0.2$ or $\alpha_{stop} = 0.8$, respectively.

We bound the optimization of the `start` control point to $\alpha_{start} \in (0.0, 0.4]$, and the `stop` control point to $\alpha_{stop} \in [0.6, 1.0)$. The first four trials in each condition use four fixed points (see Figure 9.4) in randomized order to provide a prior to the model. For these initial trials, we use a higher uncertainty measure (SEM=0.055) to model the greater noise inherent to the user getting used to the evaluation scales and the fast walking. We use a lower uncertainty measure for the final six trials in each condition (SEM=0.035). In a pilot study, these values performed well and prevented the model from weighing noisy initial evaluations too heavily.

For each condition, we 1) evaluate the first four trials, 2) use the optimization algorithm to propose the next $\alpha$ to evaluate based on the Expected Improvement, 3) evaluate the fitness of the $\alpha$ using the participant, 4) update the model with the new data point, and 5) predict a distribution of fitness scores over all $\alpha$ values.

**Task.** The participant's task is to walk to and stop on a virtual target in a straight hallway using the selected transfer function, marking one *traversal*. Each trial uses one particular transfer function and consists of six traversals. We use ten traversals per trial to allow the user to adapt to the new transfer function to some degree. We found that the combination of six traversals by ten trials by two conditions is a good combination within a reasonable time frame (approximately 60 minutes for this experiment).

The target distance is five meters in a straight line from the origin (see subsection 9.4). A physical distance of five meters allows the users enough time to use normal gait initiation to accelerate to steady-state walking, walk at least another meter, and then stop with normal gait termination. It is a realistic distance for many large homes and labs and is feasible in our lab space with additional safety margins. A distance of two meters, for example, would already be challenging as the user will have covered most of the trajectory after just three steps.

We set the *average gain* to $g = 10$ throughout the experiment so that only $\alpha$ influences the gain experienced by the participant. This high gain value has been used in previous work ([3, 307, 281]) and produces noticeable acceleration and velocity effects to the participant.

The participant is instructed to walk at their preferred normal walking speed and to make a complete stop with both feet on the target. When a traversal begins, a traffic light appears on the right wall near the start mark on the floor, two meters in front of the user. When the user presses a trigger button, the light turns green after one second. The participant should hold the button and release it only when they feel they have made a complete stop on the target. The trigger and the traffic light ensure that no transfer function is applied before the participant is ready for the next traversal.

When the participant reaches the target, the target mark transforms into the start mark, and a prominent arrow symbol indicates the user to turn around (counter-)clockwise. The direction of the arrow is random for each participant. The resultant "figure-8" pattern keeps the participant within the physical space. Sound effects also indicate the beginning and end of the traversals.

**Environment.** The environment is a long, straight hallway, similar in appearance to those in hotels or ferries. Figure 9.3 shows the environment with additional detail. The transfer function only applies a gain to the forward direction (z-axis) between the start mark and the target mark. Outside of a trial or the marks, no gain is applied, and the


(a) View from the Start Mark (b) Target Mark (c) UMUX-Lite in VR

Figure 9.3: The hallway that was used in the experiment. (a) shows the view from the start mark. The red box covering the floor, walls, and ceiling marks the target location and is 30cm ($\approx$1ft) deep (b). The hallway is 2m wide and infinitely long in both directions. Doors are placed opposingly on each wall every 4m and 6m. Lamps are placed on the ceiling every 5m. The walls and ceiling are white with a light texture, and the floor is a blue carpet texture. The UMUX-Lite questionnaire that appears after each trial is shown in (c).

participants walk isometrically ($g = 1$). The hallway allows us to apply the gain only to this direction without the need for detecting the participant's walking direction, as it naturally constrains the walking direction with walls.

A red box covering the floor, walls, and ceiling indicates the target location. The virtual target is located at 50 virtual meters from the start mark, given the *average gain* of $g = 10$ and the physical distance of 5 meters. The target box is 30 centimeters (approx. 1 foot) deep ($z$-axis). The start mark is identical to the target mark, except for having a pink color, and indicates where the participant should stand to start.

**Interview.** Our initial tests suggested that users have some feeling about whether a particular configuration feels "right" or "a bit off." We want to explore these experiences further by collecting qualitative data on what aspects of (non-isometric) walking matter to users and how these experiences can change for different transfer functions. To do this, we perform a 15–20-minute semi-structured interview after the optimization. We use the following questions to structure the interview:

- What did you think of the experiment/fast walking (as a whole)?
- Did you notice any changes in either condition and if so, what?
- How did you feel about the changes? Why do you prefer one configuration over another?
- How did you interpret and score the questions on the UMUX-Lite questionnaire?
- What phase was more important to the participant, starting or stopping, and why?

During the interview, we asked 10 participants to try out their predicted best transfer function after the optimization part. Due to a technical error, this was not possible for the first 10 participants. We asked the participants to comment out loud on their experience while using their best transfer function.

**Participants.** We recruited 20 participants from an internal mailing list, word-of-mouth advertisement, and Facebook posts in university, student, and ex-pat groups for the greater Copenhagen area. We removed one participant from data analysis due to a software error causing incomplete data, so we recruited another who was assigned the same settings. Because the experiment and the interview were unaffected for this participant, we kept their interview data, resulting in 21 interview data sets.

We record the following demographics: *Age*, *Height*, *Gender*, *Inter-Pupilary Distance (IPD)*, and *Motion Sickness Susceptibility*. We measured the IPD by using a ruler on the participant's nose and approximating the distance between the pupils while the participant kept their eyes stationary and directed at the experimenter. The participants filled out their height when they signed up. If they did not know or were unsure we measured it while they stood up straight against a wall. We used Golding's revised Motion Sickness Susceptibility Questionnaire (MSSQ) and the provided instructions for scoring [77].

The participants were eleven (ten after removing the one) males and ten females. Fourteen participants were 20–30 years old, five were 30–40, one was 40–50, and one was 50–60. The mean MSSQ percentile for nineteen participants was $31.9 \pm 13.4$, but two participants had a 92$^{th}$ and 99$^{th}$ percentile score. IPD was $60.2 \pm 3.6$ millimeters. In terms of experience with VR: four participants reported never having used VR before, while four had used VR *1 or 2 times in total*, four participants use VR *once every half a year or less*, one participant uses VR *once every month or less*, four *once a week or less*, and one *multiple times a week*. Thirteen participants had normal vision without glasses or contacts; eight had corrected vision. The mean female height was $166.3 \pm 8.4$ centimeters, and the mean male height was $184.3 \pm 6.2$ centimeters.

**Materials.** We used an Oculus Quest 2 Virtual Reality HMD device to present the virtual environment and track the user. The application and headset were set to a rate of 72FPS/72Hz. The Quest 2 headset was running software version v29.

The physical play area of the Quest 2 was set to 2m by 5m plus 1 meter on all sides for running the study. The Guardian boundary settings were set to minimal sensitivity so the Guardian would not pop up unless the participant went outside the normal play area. The participants used only the primary trigger and "A" buttons on the right-hand controller to provide input, but they held the left-hand controller as well. We adjusted the IPD of the headset to the corresponding setting according to the Meta Quest Support recommendations [272].

We use Meta's Ax Adaptive Experimentation Platform [95] v0.1.20 in Python 3.8.10 for the optimization. The optimization software was running on a separate server. We used a simple JavaScript web page for the experimenter to start the experimental conditions, controlled by a local configuration file. The web page sends instructions to the server application running the Ax software while the client on the VR headset polls the server for a new task and executes the new task (e.g., a trial with particular settings). Communication took place on a local network through REST API calls.

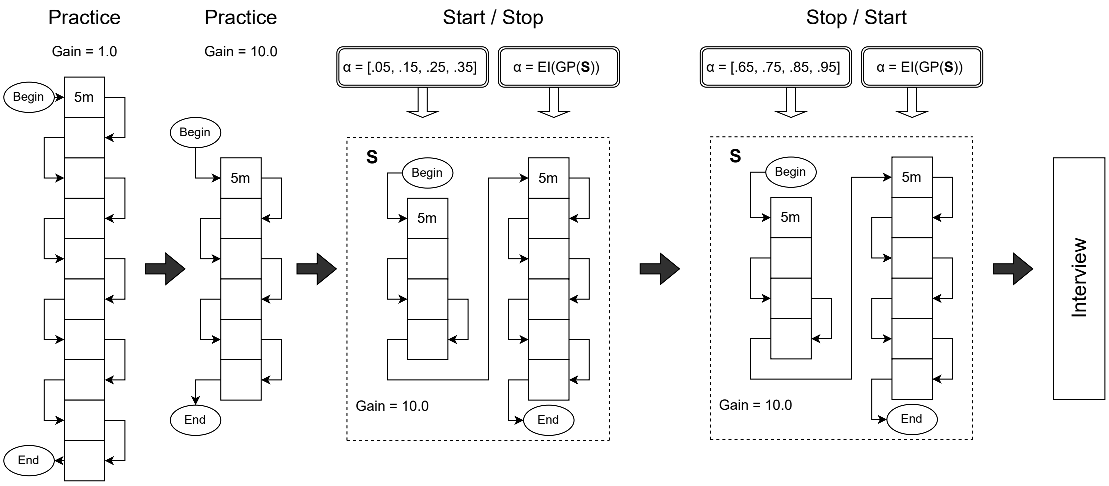



Figure 9.4: A flow chart of the procedure and conditions. Each square represents one traversal where the user performs the task by walking 5 meters and turning around. Two practice rounds are used to practice the task and high-gain walking respectively. After each optimization condition (dashed lines) we record the SSQ and take a short break. The $\alpha$-value initially comes from a fixed set, and then from the Expected Improvement (EI) prediction based on the Gaussian Process (GP) model of the current space (S) of evaluated pairs.

For the study application and its environment, we used Unity 2019.4.13f1 with the legacy VR SDK system[2] and Oculus Android 2.38.6. The transfer function was implemented in Unity using their AnimationCurve system [274] that uses Cubic Hermite Splines. The transfer functions were replicated in Python using suggestions on the Unity Forums [276]. Our source code is open-source and available upon request.

The demographics and VR sickness questionnaires were implemented online in Microsoft Forms and administered using a laptop during the experiment.

**Procedure.** The study starts with obtaining consent, gathering the demographic data, and assigning a random ID. We then fit the headset and adjust the IPD as needed. If the participant is wearing glasses, we use the glasses bracket provided with the Quest 2. After the participant has studied the task, a practice round begins. A paper overview and instructions, including the full 7-point scale and labels, inform the participants about the UMUX-Lite questionnaire.

Figure 9.4 details the procedure and settings for the practice rounds and optimization trials. At the end of each trial, the UMUX-Lite questionnaire appears in VR (Figure 9.3c). When the UMUX-Lite answers have been submitted, the subsequent trial with a new transfer function assigned by the optimization algorithm automatically begins. When the condition is finished, we take the participant out of VR and give them the SSQ to fill out. After a short break, we position the participant again on the start location with the headset properly fitted and start the final condition. Finally, we take the participant out of VR and invite them to sit down and inform them that the next part will be audio

[2]As opposed to the relatively newer XR Plugin Management.

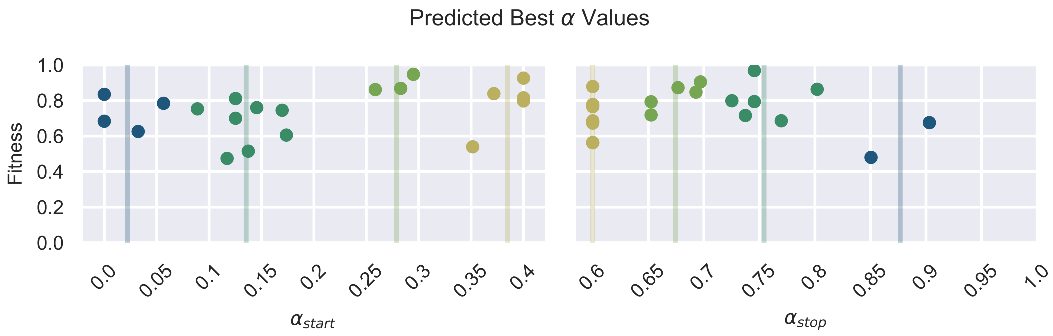



Figure 9.5: The predicted best $\alpha$ values for each participant. K-Means (n=4) clustering groups the predictions together and we plot the clusters here using 4 different colors. Colors indicate faster (blue) to slower (yellow) acceleration clusters.

recorded. We proceed with the semi-structured interview for a maximum of 20 minutes. After about five minutes, or when the topic presents itself, we ask the user to once more put on the headset and complete six traversals with their predicted optimal configuration. During this trial, we asked the participant to comment on how they felt and what they would change about the configuration.

The total experiment duration is approximately 60–70 minutes. The VR exposure duration is two conditions of continuous exposure with a mean duration of $11.1 \pm 1.28$ minutes per condition. The participant received a mix of beverages and candy valued at approximately $20 as a reward.

## 9.5 Results

After the optimization phase, the Gaussian process models predict a fitness score over $\alpha_{start}$ and $\alpha_{stop}$. In this section, we first present the predicted best parameters of the transfer function for each participant. We then present how different transfer functions affect usability, walking velocity, and VR sickness. Finally, we identify and present six qualities of walking from the interview.

**The Best Transfer Functions.** The per-participant models suggest that users have diverse preferences for starting and stopping acceleration. To visualize the predicted best transfer function parameters, we perform k-Means clustering on the best $\alpha$ values for each condition and show the color-coded results in Figure 9.5. In the `start` condition the cluster means appear evenly spaced, but the majority of values center around $\alpha_{start} \approx 0.14$. In the `stop` condition there appears to be a slight majority around $\alpha_{stop} \approx 0.75$. Additional data, including the Gaussian Process regression models for each participant, can be found in the supplementary material.

Figure 9.6 shows the best parameters of each participant's transfer function in more detail: the figure shows the best acceleration distances for starting and stopping and illustrates the relative asymmetry between $\alpha_{start}$ and $\alpha_{stop}$. Recall that lower $\alpha_{start}$

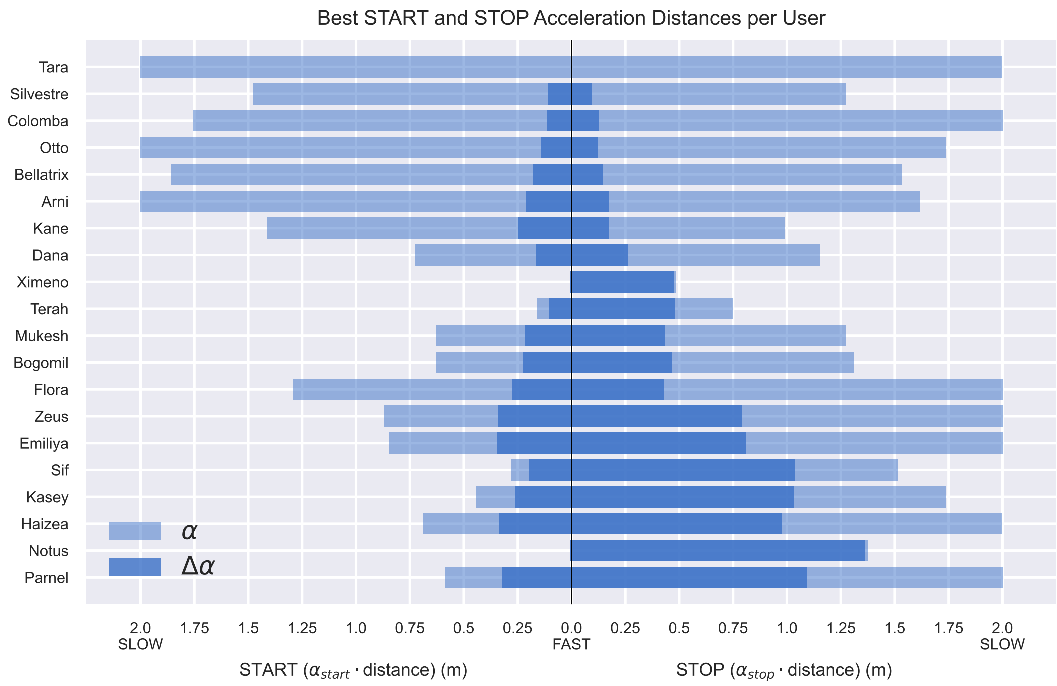



Figure 9.6: This figure shows the difference between the predicted best $\alpha_{start}$ and $\alpha_{stop}$ values. For increased readability the $\alpha$ values are converted to their respective distances from the start and stop points given the physical distance of five meters. A larger relative difference ($\Delta\alpha$, dark-blue) indicates a greater asymmetry between the starting acceleration distance and the stopping deceleration distance. The light blue bar spans the starting point $\alpha_{start}$ to the stopping point $\alpha_{stop}$.

values indicate a faster starting acceleration, while higher $\alpha_{stop}$ values indicate a faster stopping deceleration. Given the fixed task distance of five meters, we can directly convert $\alpha$ to the distance in meters: $\alpha = 0.1$ is a distance of 0.5 meters.

Here is an example of how to read the chart: consider Kasey, the 5$^{\text{th}}$ participant from the bottom in Figure 9.6. Their starting acceleration curve ends at approximately $0.5$ meters from the starting position, and their deceleration curve begins 1.75 meters before the target. In other words: Kasey's gain increases over 0.5 meters but decreases over 1.75 meters, resulting in a difference of 1.25 meters in the ($\Delta\alpha$) bar. Kasey prefers a slow stop, in contrast to Kane. We can see that 14 of the 20 participants prefer a configuration with a longer deceleration than acceleration distance, resulting in an asymmetric transfer function. The first six participants have a (nearly) symmetric function, and coincidentally those participants also prefer the slowest accelerations.

The width of the dark blue bars ($\Delta\alpha$) indicates the difference between $\alpha_{start}$ and $\alpha_{stop}$; greater differences indicate that the start and stop curves are more asymmetrical than smaller differences. The $\Delta\alpha$ bar leans proportionally left or right to indicate the relative asymmetry. For example, the bar being three times longer on the right-hand side than the left-hand side means that the user prefers a deceleration distance three times longer than their acceleration distance. The ends of each light-blue bar indicate the predicted

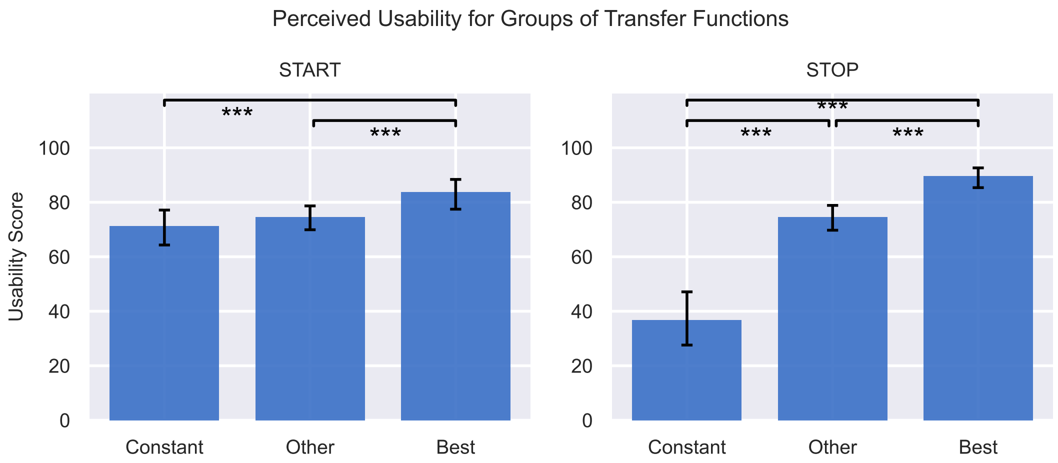



Figure 9.7: The usability score from the UMUX-Lite questionnaire. Error bars are bootstrapped 95% confidence intervals using BCa. *** indicates a significant difference with $p < 0.001$. "Constant" comprises $\alpha_{start} \leq 0.1, \alpha_{stop} \geq 0.9$ functions that result in acceleration similar to constant gain. "Best" comprises the predicted best functions for all users. "Other" comprises the remaining functions.

best $\alpha_{start}$ and $\alpha_{stop}$ values for that user. Values closer to the center on the x-axis indicate a faster acceleration for either condition: wider bars have longer acceleration distances.

**Usability.** Figure 9.7 shows the perceived usability of three groups of transfer function configurations: "Constant," "Other," and "Best." The "Constant" group contains the transfer functions with $\alpha_{start} \leq 0.1$ or $\alpha_{stop} \geq 0.9$ ($\approx 0.5$m). Such low/high $\alpha$ values result in a near-immediate acceleration similar to the use of a constant gain transfer function. The "Best" group contains the predicted best configurations, and the "Other" group contains the other evaluated transfer functions. The perceived usability score from the UMUX-Lite questionnaire was the first component of our fitness function, as we expected effective, pleasant, and easy-to-use transfer functions to result in a better assessment of usability.

The usability scores are not normally distributed, and so we perform a Friedman test on the groups, separately for the `start` and `stop` conditions. We find an effect of group on usability for the `start` condition ($F(1.9, 36.1) = 12.2, p < 0.001$) and a strong effect for the `stop` condition ($F(1.9, 36.1) = 85.1, p < 0.001$). Post-hoc tests using Wilcoxon tests with Bonferroni correction show large effects between Best and Constant ($p < 0.001$; Hedges' $g = 1.16$) and Best and Other ($p < 0.001$; Hedges' $g = 0.80$) for the `start` condition. For the `stop` condition we find a very large effects between Best and Constant ($p < 0.001$; Hedges' $g = 2.33$) and Constant and Other ($p < 0.001$; Hedges' $g = -1.73$), and a large effect between Best and Other ($p < 0.001$; Hedges' $g = 0.71$).

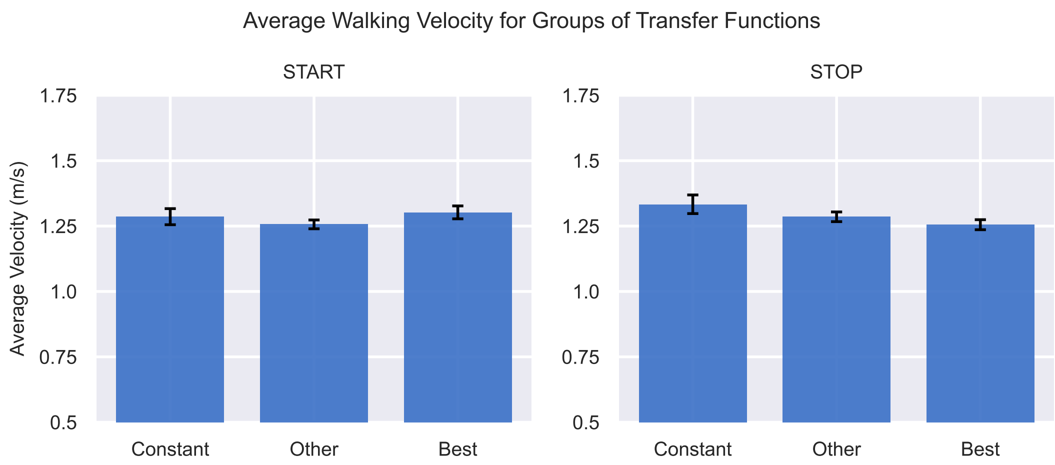



Figure 9.8: The average walking velocity per group, condition. Error bars indicate the bootstrapped 95% confidence interval using BCa. The average walking velocity is simply the time-to-target divided by the physical distance (5m). Lower velocity could indicate an effect of transfer function configuration on gait, but no significant differences were found. "Constant" comprises $\alpha_{start} \leq 0.1, \alpha_{stop} \geq 0.9$ functions that result in acceleration similar to constant gain. "Best" comprises the predicted best functions for all users. "Other" comprises the remaining functions.

**Walking Velocity.** Figure 9.8 shows the average walking velocity of the same three groups of transfer function configurations (see subsection 9.5). The average walking velocity is the time-to-target over the distance (5m). The walking velocity in our study is relatively high for walking in VR and on par with existing data on non-VR preferred walking velocity [175]. The time-to-target is the second component in our fitness function, as we expected disturbing or difficult transfer functions to result in users requiring more time to walk to the target.

The data was not normally distributed in either condition, so we used Friedman tests to investigate the effect of group on average velocity. For the `start` condition we find no significant effect ($F(1.9, 36.1) = 0.11$, $p = 0.12$), and neither for the `stop` condition ($F(1.9, 36.1) = 3.16$; $p = 0.06$).

Participants may have adapted their gait due to increased experience for each consecutive traversal with a particular configuration or increased experience with high-gain walking with each consecutive trial. The time-to-target data for traversal and trial was not normally distributed, so we performed a Friedman test to investigate the effect of traversal or trial on time-to-target. We found a marginally significant effect for Traversal on Time-to-target ($F(4.9, 93.1) = 6.86$; $p < 0.001$), but a post hoc Wilcoxon test with Bonferroni correction only found a small significant effect between traversal 2 and 5 ($p < 0.05$; Hedges' $g = 0.12$); 4 and 5 ($p < 0.001$; Hedges' $g = 0.12$); and 5 and 6 ($p < 0.001$; Hedges' $g = -0.13$). These differences are $\approx 0.1$ seconds on a distance of 5 meters, and thus practically irrelevant. We did not find a significant effect of Trial on Time-to-target ($F(8.9, 169.1) = 0.72$; $p = 0.69$).

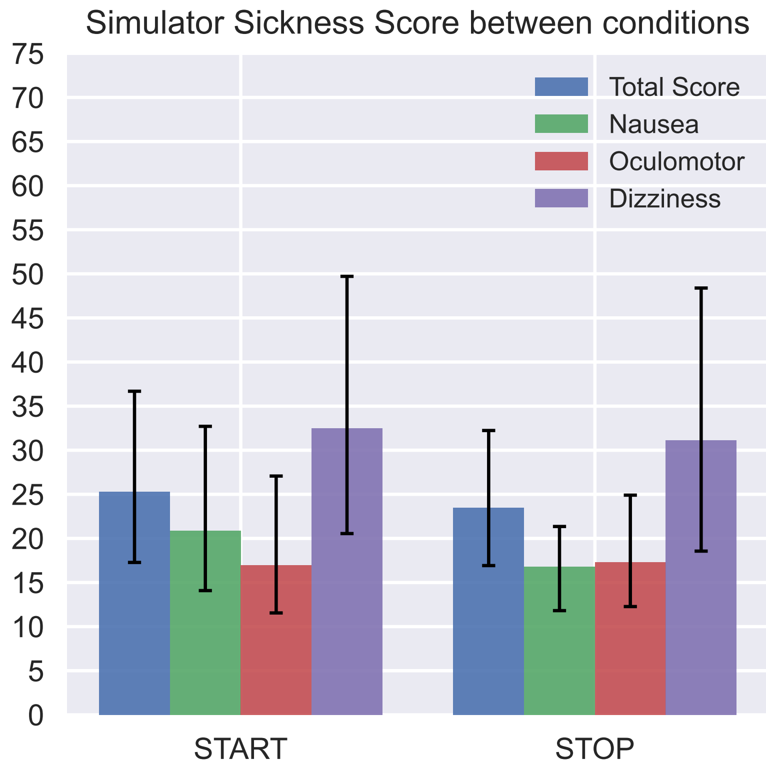



Figure 9.9: Simulator Sickness Scores for the `start` and `stop` conditions. Error bars indicate bootstrapped 95% confidence intervals using BCa. An SSQ score of $> 20$ is typically considered problematic sickness, but no participants mentioned feeling sick or significantly uncomfortable after the conditions.

**VR Sickness.** Figure 9.9 shows the Simulator Sickness Questionnaire scores for both conditions. The SSQ Total Score is relatively low, which corresponds to our participants saying they felt good after each condition. However, the Dizziness sub-scale shows high scores and a large confidence interval, suggesting that at least some participants suffered from dizziness symptoms. Based on the interviews, we know that some configurations caused dizziness, nausea, and balance issues. For instance: Kane reported that they felt nauseous when trying $\alpha_{start} = 0.4$ and in some other configurations, but their symptoms disappeared quickly in the following configuration. Other participants also reported dizziness and balance issues for slow starts and sudden stops. Some users looked at the floor or walls at some point and reported that this caused VR sickness symptoms.

A Mann-Whitney U-test shows no significant difference for any SSQ score between the two conditions (all $U > 200$, $p > 0.61$). We investigated a potential effect of gender, but a Mann-Whitney U-test showed no significant effect of gender on VR sickness ($U = 37.5$, $p = 0.23$).

Finally, we recorded the Motion Sickness Susceptibility Questionnaire for each participant and their experience with VR systems. These scores could be a predictor of higher VR sickness responses. A Spearman test of correlation between the SSQ Total Score and

MSSQ Raw score did not show a significant correlation for either the `start` or `stop` condition ($r = 0.07$, $p = 0.77$; $r = -0.01$, $p = 0.96$, respectively). Experience was converted from "No experience" – "Multiple times a week" to a Likert-style 0–5 scale. A Spearman test of correlation did not show a significant correlation between SSQ Total Score and Experience ($r = 0.0$, $p = 0.81$; $r = 0.27$, $p = 0.24$, respectively).

**Quality of Walking.** The semi-structured interview further explores how participants experience high-gain walking in VR and what qualities of walking are most relevant.

To analyze the interview data, we first transcribed all the participant statements from audio files into text snippets. Two authors then started organizing the text snippets into categories describing different qualities or features of walking through a 2.5-hour affinity diagramming session. One author labeled the snippets into categories on a digital sheet (some with many labels). The authors adjusted the categories during the session with edits, additions, and deletions.

We found the participants describing their experiences in terms of six qualities: Naturalness, Enjoyment, Difficulty, Comfort, Effort, and Control. We discuss our key findings here and provide a more detailed discussion in section A.1.

*Naturalness:* During the interview, participants often described their experience as "feeling natural" or "feeling like normal walking." Rokso said that "[It] was based on a feeling of whether it felt like good walking, more natural in a way, or felt kind of off." After trying out their predicted best configuration, another participant, Ximeno, said: "I guess I would say it just feels like normal walking." In contrast, the participants described more negative experiences often as "unnatural," "weird," or "a bit off." The moments of starting and stopping to walk were also related to creating or destroying a "natural" feeling: the sudden start was sometimes referred to as a "glitch" or "strange," while a wrong $\alpha_{stop}$ value would not "feel natural" due to having to compensate for the virtual movement.

*Enjoyment:* Almost all participants thought walking in VR with high gain was fun and said they enjoyed it. Bellatrix was enthusiastic overall and said that "[she] definitely had fun!" Enjoyment mostly relates to the high-gain walking as a whole and may have been influenced by novelty effects. Positive comments related to a specific configuration were mostly related to "Naturalness," but negative comments were often about a configuration being "annoying" if it did not behave as desired. For example: very long stops ($\alpha_{stop} \approx 0.65$) or very short stops ($\alpha_{stop} \approx 0.95$) were regarded as annoying.

*Comfort:* A large portion of participants used "comfort" to describe their experiences, both as a whole and for particular configurations. For example, Dana said: "I think comfort was my biggest requirement, right? Actually feeling that I trusted the system, but also feeling that I felt comfortable walking in the space." Haizea related comfort to their ability to control their walking, saying: "[Whether] I felt, like, safe walking, and [that I'm] not gonna, like, fall, or trip or lose my balance." However, particularly the short start and stop configurations ($\alpha_{start} < 0.05$ and $\alpha_{stop} > 0.95$) could be uncomfortable. For Kasey, the high starting acceleration was "not difficult, but uncomfortable," while others also found the overall speed to be "not that comfortable" (Flora). Participants often reported that "feeling comfortable" was a part of their assessment of the requirements and easy-to-use parts of the UMUX-Lite questionnaire.

> In some of the walks, you're made very aware that you're in a VR headset, and it just doesn't feel like the normal way of walking. Whereas in some others it feels more natural: even though you're walking very fast and stuff, you kind of forget that you're in a headset. (Rokso)

*Control:* In several instances, the participants reported that the system responded unexpectedly. Unexpected virtual movement occurred in all three parts of the traversal: the starting, steady-state walking, and stopping. Mostly, the comments regarding what might be a "feeling of control" related to the moment of stopping or the perceived virtual speed while approaching the target. Either the participant felt that they had to, and could, control their physical walking speed to adjust the virtual speed to stop on the target or that they were not in control of their speed. In particular, several participants noted that a very long stop would make them feel like they were being stopped before the target and that they had to take additional steps to arrive. For example, Kane said that "the times where I got annoyed with that, I had to walk so much further in the end. Because it's, I mean, I know I had to walk the same distance, but it felt like I had to walk further." In contrast, the sudden stops were difficult to use, and some participants reported that they felt they had to consciously and physically slow down to compensate. Participant expectations regarding the deceleration towards the target can be a source of increased difficulty: "… when I [messed up] it was because it did not stop. And I was expecting it to, like, slow down right before the end" (Flora).

*Effort:* When the system did not respond as expected, an additional physical and mental effort was needed to compensate. Some participants (e.g., Notus, Mukesh) felt that a good function would allow them to land on the target with their final step, not requiring additional effort, half steps, or walking velocity adjustment. Notus felt that a good function is easy to use: "I hit the target perfectly without having to think about [having to] adjust my step or anything. It just comes... fluidly." Others mentioned a mental effort of "thinking." For example, Mukesh said: "None of them required conscious thinking, but a couple of them made you revise your expectations about what a step does." Bellatrix preferred to "have time to get your bearings, and you know, figure, okay, this is where I want to go, instead of just, you know, having to adjust very suddenly."

*Difficulty:* Due to the accuracy demand of the task and the "easy-to-use" question in UMUX-Lite, many participants commented on a particular function being "easier" or "harder." Unsurprisingly, participants perceived the functions where there was a lack of control or that required additional effort as more difficult. Although interestingly, none of our participants felt that the `start` condition was difficult.

> Sometimes I had to, like, be careful about the step before it stopped. I had to time it a bit or take a bigger step to get there, or else I would have to take another step or something like that. And sometimes it stopped a bit before: like, it slowed down a bit before the red line, and then I had to take the decision whether I would take a couple more steps or just take a bigger step to get onto it. (Columba)

## 9.6 Discussion

The participants thought walking with a high gain was fun and easy to use. So, these techniques could not just be used for efficient transportation in the absence of discomfort but also as a more entertaining means to explore the virtual world. Some participants even said walking with their best transfer function felt "natural," like real-life walking. This response is highly encouraging for developing asymmetric transfer functions and using high-gain locomotion techniques. Typically, the main goal of such techniques is to allow users to travel quickly and comfortably across a large virtual world. While other techniques for this goal exist (e.g., flying or teleportation metaphors), non-isometric walking is directly coupled to physical walking. The benefits of physical walking may improve immersion, embodiment, or spatial orienting performance. This work shows that walking with a high gain can offer a good user experience and performance.

**Asymmetric Transfer Functions.** Figure 9.6 shows that the majority of participants (85%) prefer a long deceleration distance (i.e., a low $\alpha_{stop}$ value). About half of those prefer a deceleration much longer than their acceleration, resulting in strongly asymmetrical transfer functions. Our results suggest that giving users enough time to slow down is crucial while optimizing for smooth starts can further improve the user experience.

Users need time to plan and execute their stops to maintain a steady gait and avoid discomfort. We also found this requirement in the Qualities of Walking, such as Control and Comfort (see subsection 9.5). The results suggest that the stopping deceleration should closely match the users' "expectations" so that they do not have to think about their foot placement and movement. How much time or distance is needed is not immediately apparent, but it could be related to the user's velocity and step size: When walking through natural terrain or driving through corners, we use a feed-forward control that requires looking ahead $\approx 1.5$ seconds [155, 123]. By lowering the gain during the target approach, we can give users more time to plan their stops for accuracy and comfort. Controlling the stop velocity is more difficult in existing velocity-controlled functions, where the gain only lowers when the user physically slows down, typically at the last steps before the target. Future work should investigate the requirements for stopping when traveling at high speed in VR and how we can apply this to transfer function design.

The task requirement to stop accurately in a particular location may have led to participants wanting to slow down to improve accuracy. In contrast, the moment of starting to walk has no accuracy requirement and simply going as fast as is comfortable is sufficient. However, participants always stopped close to the target regardless, even in the sudden stop configurations, because the gain would be disabled after. Since the accuracy requirement is easily satisfied, we believe that the low regard for sudden stops is due to the adverse effects on the user experience. Future work should investigate whether the best stopping deceleration changes if, instead, the goal is to stop as quickly as possible and whether this could be more important than stopping comfortably. However, based on our results, we propose that stopping in high-gain walking always requires a smooth deceleration, although the amount of "smoothness" may depend on the individual user.

In the interview, many participants expressed no strong preference for a particular starting configuration. This also shows in the results in Figure 9.6, where the best $\alpha_{start}$

values are more evenly distributed than the $\alpha_{stop}$ values. Based on the usability scores and interview comments, the benefit of optimizing the starting configuration may be less than for the stopping configuration (Figure 9.7). However, some participants mentioned that very short or very long stopping distances could break immersion or cause VR sickness. Interestingly, the optimization algorithm was able to determine a clear optimal value in most cases, even if the participant did not verbally express a preference between starting configurations. Therefore, we suggest always using non-linear acceleration when starting to walk and avoiding sudden or prolonged acceleration moments. However, we expect the best starting configuration to vary based on the task requirements, such as preventing high gain values during maneuvering (as in [307]), requiring high accuracy when starting to walk, or repeated accelerations in quick succession.

The qualities of walking overlap with qualitative comments reported in previous work: Abtahi et al. [3] reported that preference was based on feeling more in control, more natural, or more comfortable, meeting user expectations, and being easy to use. It is promising that similar walking-based techniques for long-distance travel share similar qualities of walking. Future work should investigate how these qualities vary between techniques, how we can reliably measure this effect, and whether the quality of walking constitutes a measurable core component of travel in VR. Such a measure of user experience could provide a better assessment of the quality of VR travel in general.

**Optimizing Transfer Functions.** Although combining user studies and optimization can be tricky, we have successfully demonstrated that this approach can be used to determine good designs quickly. We have used a Bayesian Optimization approach to efficiently sample and evaluate transfer functions across a wide range of possible configurations. The results showed marked individual differences between the best transfer functions and significant benefits in user experience for the best functions. These results can serve as prior models for future research on evaluating or optimizing transfer functions for walking in VR. We encourage future work to further explore the application of optimization to VR locomotion and suitable goodness functions.

Based on previous work, we expected users to lower their walking velocity due to being exposed to disturbing acceleration effects [100, 281]. So, apart from user experience, we also optimized for performance by including the time-to-target component in our fitness function. Although we did not compare our results to out-of-VR walking, we found no evidence that users significantly changed their walking speed during the experiment or individual trials. On the contrary, we found that users walked faster on average compared to previous work: 1.25 m/s compared to 1.0 m/s in [100]. This result is encouraging since this is close to the preferred walking speed for real-world walking: 1.2–1.25 m/s [175].

Although we did observe some gait disturbances during the experiment, we believe that the six traversals were indeed enough to adapt and prevent measurable effects on walking velocity. When participants were trying the technique for the first time, we observed stumbling, swaying, and inconsistent steps. However, after the ten practice trials, all participants felt confident in their ability to walk with a high gain. Previous work has suggested that users may take smaller but more frequent steps when walking in VR to compensate for unbalanced gait (e.g., [169, 168, 218]). In our case, it may be that the walking velocity was unaffected, but the participants' gait was. Although we also performed some exploratory analysis on step size, we could not find evidence of this.

In the user study, we used only one *average gain* value and one physical distance to maximize the number of optimization rounds to ten while keeping the study duration and sickness effects under control. We can speculate that a longer physical distance or lower gain values can use smaller $\alpha$ values. There may not be a difference for larger gain values, but for smaller distances, it will depend on the distance, the gain, and the task requirements. For example, a gain of 20 on a distance of one meter would require more than just optimized $\alpha$ values. In this work, we found that the ability to slow down in time and thus stop in a controlled and comfortable manner is an essential user requirement. We expect this to translate to other travel tasks. Future work should investigate the requirements for starting and stopping acceleration in more depth, particularly for different travel tasks. Finally, the particular transfer functions in our results should not be applied directly in future applications. Instead, we propose calibrating the transfer function to an individual as the preferred approach.

## 9.7 Conclusions

In this work, we have presented the steps required to design good transfer functions for walking with a high gain in Virtual Reality. We discussed how we could vary the acceleration and deceleration curves of a transfer function to generate distinct, asymmetric configurations. In a user study, we evaluated these configurations while optimizing for user experience and task performance. We found that we can successfully predict the user's best configuration. Furthermore, the predicted best configurations for users are individual, asymmetric, and much better in terms of usability and quality of walking. Finally, we have collected and analyzed qualitative data on the quality of VR walking, and we propose that the following qualities matter most to users: Naturalness, Enjoyment, Difficulty, Comfort, Effort, and Control. Our work shows that good transfer functions can feel like natural walking, even for high gain values.

# 10 Doorways Do Not Always Cause Forgetting

This chapter presents the paper "Doorways Do Not Always Cause Forgetting: Studying the Effect of Locomotion Technique and Doorway Visualization in Virtual Reality" [291]. At the time of writing the paper was accepted for revision at CHI '24 with encouraging reviews.


## Abstract

The "doorway effect" predicts that crossing an environmental boundary affects memory negatively. In virtual reality (VR), we can design the crossing and the appearance of such boundaries in non-realistic ways. However, it is unclear whether locomotion techniques like teleportation, which avoid crossing the boundary altogether, still induce the effect. Furthermore, it is unclear how different appearances of a doorway act as a boundary and thus induce the effect. To address these questions, we conducted two lab studies. First, we conceptually replicated prior doorway effect studies in VR using natural walking and teleportation. Second, we investigated the effect of five doorway visualizations, ranging from doors to portals. The results show no difference in object recognition performance due to the presence of a doorway, locomotion technique, or doorway visualization. We discuss the implications of these findings on the role of boundaries in event-based memory and the design of boundary interactions in VR.

**Title:**
Doorways Do Not Always Cause Forgetting: Studying the Effect of Locomotion Technique and Doorway Visualization in Virtual Reality.

**Authors:**
*Thomas van Gemert*, Sean Chew, Yiannis Kalaitzoglou, and Joanna Bergström.

**Venue:**
The 2024 CHI Conference on Human Factors in Computing Systems.

**What was the role of the PhD student in designing the study?**
The student designed the first study and part of the second study.

**How did the PhD student participate in data collection and/or theory development?**
The student carried out the data analysis and had a majority part in theory development.

**Which part of the manuscript did the PhD student write or contribute to?**
The student wrote and contributed to the entire manuscript.

**Did the PhD student read and comment on the final manuscript?**
Yes.


Figure 10.1: A scenario depicting the doorway effect in a virtual reality (VR) game: A VR user wants to read a book of spells, so they head to the library (left). To reach the library, they walk through a portal, which acts as an environmental boundary (middle). However, after appearing in the library, they cannot seem to remember what they came looking for (right).

## 10.1 Introduction

The *doorway effect* is the phenomenon that people are more likely to forget things when crossing an environmental boundary (e.g., a doorway) as they move from one location to another, compared to remaining within the same environment (e.g., moving within a single room) [206, 207]. Virtual reality (VR) research addresses how to design virtual environments and move around in them, often in non-realistic ways. VR typically includes more environmental boundaries than real life due to the design of small, separated spaces due to compute power limitations or the use of locomotion techniques that rely on such boundaries for redirection (e.g., doorway redirection [93], foldable spaces [79], or impossible spaces [267]). Furthermore, VR locomotion techniques often feature unrealistic ways of moving around in order to make VR more usable (e.g., teleportation, see [54, 167] for an overview). Therefore, VR designs can manipulate both aspects involved in inducing the doorway effect: the crossing of a boundary and the boundary itself. However, at the moment, it is unclear whether the doorway effect itself is present in VR experiences.

The doorway effect has been investigated in both real [208, 161] and virtual environments [207, 161, 201, 200, 199]. The former used physical doors and curtains as boundaries in combination with walking through real rooms. The latter used simplistic but realistic virtual environments, navigated with keyboards and joysticks [207, 201] on desktop PCs with large screens, or natural walking and passive movement in immersive head-mounted VR displays [161, 86]. While the doorway effect appears to be robust in desktop PC-based virtual environments, it remains unclear whether immersive VR-based environments can induce the doorway effect. For example, Helvoort et al. [86] found a doorway effect using VR, while McFadyen et al. [161] did not. McFadyen et al. speculated that their use of passive locomotion in VR aided memory performance and thus prevented the doorway effect from occurring, although earlier work found the doorway effect when passively crossing doorways [199]. As a whole, it remains unclear whether immersive VR with active locomotion can induce a doorway effect.

Previous work on the doorway effect has used relatively realistic virtual environments, but virtual reality (VR) research often considers environments and interaction designs that are non-realistic. First, locomotion techniques such as teleportation offer the benefit of long-range mobility, but may bypass environmental boundaries (e.g., doors) altogether. However, it is unclear whether teleportation can induce a doorway effect through just the shift in location, or whether an environmental boundary is additionally required. Second, the doorway effect has been demonstrated with various environmental boundaries (e.g., transparent walls [200] and even imagined doorways [132]). However, it is unclear whether non-realistic boundaries (e.g., portals) can induce the doorway effect.

We present two lab studies investigating the doorway effect in virtual reality (VR). The first study (N=40) investigates whether VR locomotion techniques influence the doorway effect by comparing teleportation to natural walking. The second study (N=20) investigates whether five different doorway visualizations, from a realistic door to a portal, are more or less reliable in inducing the doorway effect. In both studies, we use natural walking through realistic doors in VR as a baseline, and conceptually replicate the original doorway effect experiments. The results show no difference in error rate due to the presence of a doorway, locomotion technique, or doorway visualization; we discuss these findings with respect to previous work and possible limitations. Finally, we discuss whether it is likely that a doorway effect existing in VR, and what implications this has for environment and interaction design in VR.

## 10.2 Background

In this section, we first summarize the theory behind the doorway effect. We then review previous studies that have shown the doorway effect, and the conditions in which it was found. Finally, we discuss the factors that may influence the effect, in particular in relation to characteristics of virtual reality.

**Theory Behind the Doorway Effect.** The Event Horizon Model (EHM) is a framework that formulates how memory is organized according to separate event models [206]. Radvansky and Zacks [206] elaborate on the five principles that constitute the EHM. First, incoming information is segmented into events based on how predictive items in the current event model are for upcoming events: “When important situation features change, such as new movements, *spatial location*, objects, etc, ... the current event model is updated and this is experienced as an event boundary.” [206] Second, information in the current event model is more readily available than information in previous event models, which are stored in long-term memory. Third, events that are causally connected are better remembered. Fourth, information retrieval in a non-competitive manner (i.e., the opposite of the task in “doorway studies”) is aided by the information being present in multiple events. Finally, the fifth principle is illustrated by previous work that found the doorway effect: retrieval interference occurs when information is stored in multiple events but only the information from one event is needed. For example, when a person carrying an object in their pocket crosses an environmental boundary like a door, this signals a shift in location, triggering event segmentation and leading to the object being present in both the current event model of the new room and the event model of the previous room. When the person tries to remember what object they are carrying right now, retrieval interference occurs, leading to forgetting.

**Findings from Doorway Effect Studies.** In the earliest doorway effect experiment, Radvansky and Copeland [207] investigated whether the availability of entity information (an object being picked up) would vary as a result of a spatial shift. In a virtual environment, the participant had to pick up an object (after which it would disappear) and bring it to the other side of the room, where they would then answer a memory probe about the object. In some trials, the participant would walk through a doorway (spatial shift) that halved the room into two smaller ones. The authors reported significantly higher error rates after a spatial shift ($M = 0.14 \pm 0.12$) than when participants stayed within the same room ($M = 0.04 \pm 0.14$); they coined this the "location updating effect", which was subsequently termed the "doorway effect". This effect has since been demonstrated in related work using imaginary doorways [132], transparent walls [200], different travel and observation times [201], recall and recognition memory probes [202], active and passive interaction [199], smaller and bigger screens [208], real environments [208], and more. These works all used highly similar methodologies. It was not until recently that the doorway effect was investigated using immersive virtual reality (VR) [161].

**The Doorway Effect and Virtual Reality.** A recent study by McFadyen et al. [161] failed to find the doorway effect in multiple experiments using virtual reality (VR) and real environments. In the VR experiments, with and without an additional memory load, the authors aimed to strictly control the study design to only measure the effect of a door on memory error. Nevertheless, they were unable to find significant differences and argued that this may be due to their use of passive locomotion, which can improve object memory performance. Furthermore, the visualization and positioning of the door were near-identical in their experiments; the authors speculated that a more salient environmental boundary could have triggered an event segmentation. Finally, Helvoort et al. [86] implemented two museum rooms in VR to investigate how spatial boundaries and physically travelled distance affect painting recognition performance. The authors proposed that there was a "spatial boundary effect" because paintings encoded in the same room were better remembered than those encoded across rooms. Their study design was different from the previously discussed oeuvre of doorway effect studies, suggesting that the effect exists outside the original experimental paradigms. Most notably, they were able to find a doorway effect using natural walking in an immersive VR environment, a feat previously unaccomplished. In this work, we extend the line of investigation by McFadyen et al. [161] to address the questions of whether the doorway effect is present with different (active) locomotion techniques in virtual reality and with different visualizations of the environmental boundary.

## 10.3 Study 1: Locomotion Techniques

In the first study, we investigate the doorway effect with a locomotion technique that avoids doorways altogether: teleportation. The study conceptually replicates the original experiment by Radvansky and Copeland [207] and the VR experiment by McFadyen et al. [161]. In the experiment, the participant collects and carries six objects in a box to the other side of a room (Figure 10.2), whereby they either pass through a door or not, and use natural walking or teleportation to move (Figure 10.3). On the other side of the room, they answer a series of object recognition probes.

This is a mixed-design lab study with two independent variables: “Door presence” is a within-subjects variable with two levels: either there is a doorway separating two different rooms (Door condition), or there is only one larger room without a doorway (No-Door condition). These conditions are called “Shift” and “No Shift” in previous work. The second independent variable is locomotion technique as a between-subjects factor: either a participant uses natural walking or teleportation.

As our dependent variables, we measure object recognition performance through error rate and response time. For error rate, we use associated (object was picked up in this trial) and negative (object was not picked up in this trial) probes that ask the user whether a [colour] [shape] object is in the box. Based on their Yes/No responses, we calculate the error rate (ratio of No to Associated and Yes to Negative probes). We measure the response time for each probe from the moment the probe appears to the user pressing a response button. Based on Pettijohn and Radvansky [201]’s work, we do not include dissociated probes, as they are typically unaffected by the doorway effect, whereas associated probes reliably are.

We assign each participant one locomotion technique and 40 trials containing both Door and No-Door conditions. The condition order is pseudo-randomized: we ensure that the same door presence condition cannot appear more than three times sequentially to even out the spread of the conditions. In each trial, there are six probes: four associated and two negative. This results in 160 associated probe responses, and 80 negative probe responses. Negative probes are created from combinations of color and shape that were not present in the trial.

Based on the previous work and a pilot study, we hypothesize the following with respect to a participant’s ability to correctly remember what objects are in the box:

**H1:** In the “Walking” condition, error rate will be higher in the “Door” condition than in the “No-Door” condition due to the presence of an environmental event boundary.

**H2:** In the “Teleportation” condition, there will be no difference in error rate for the “Door” and “No-Door” conditions, due to the lack of an environmental event boundary.

**H3:** In the “Teleportation” condition, error rate will be higher than in the “Walking” condition, because the teleportation animation effect always acts as an event boundary.

The experiment was pre-registered at the Open Science Foundation.[1] We expand on the pre-registration mainly by conducting additional (Bayesian) analysis on the data. We additionally add more details about the study design, and slightly improve the study procedure. In case of conflicting information, the current work is leading.

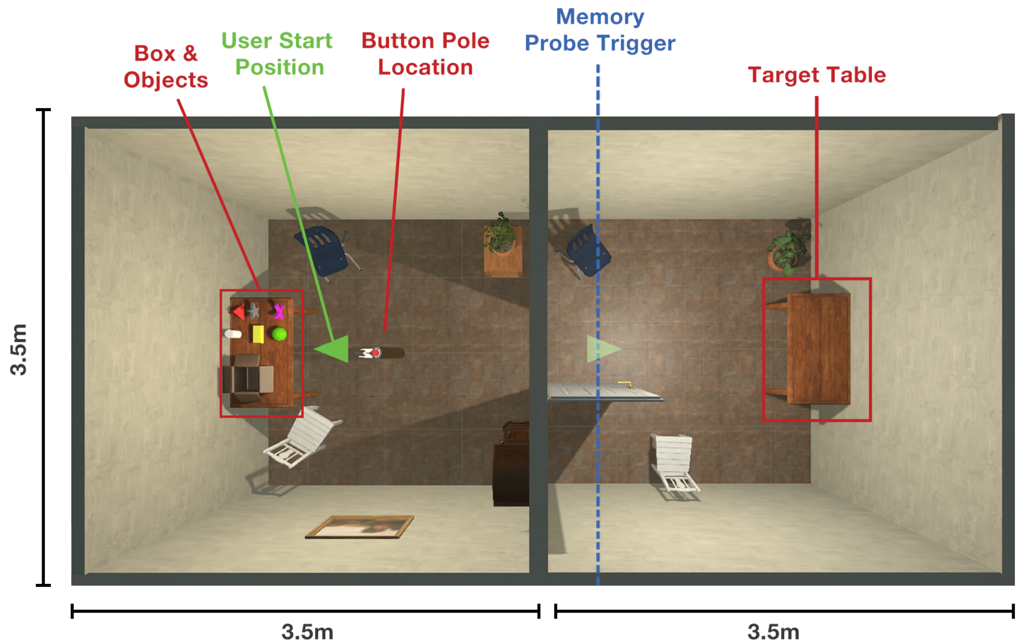



Figure 10.2: A birds-eye view of the virtual environment of the door condition, containing randomized furniture sets. The no-door condition will not have the wall and door in the middle, and will be furnished as a large room instead of two smaller ones. Note that the button pole only appears in teleportation conditions; the teleport destination is displayed as a translucent green triangle.

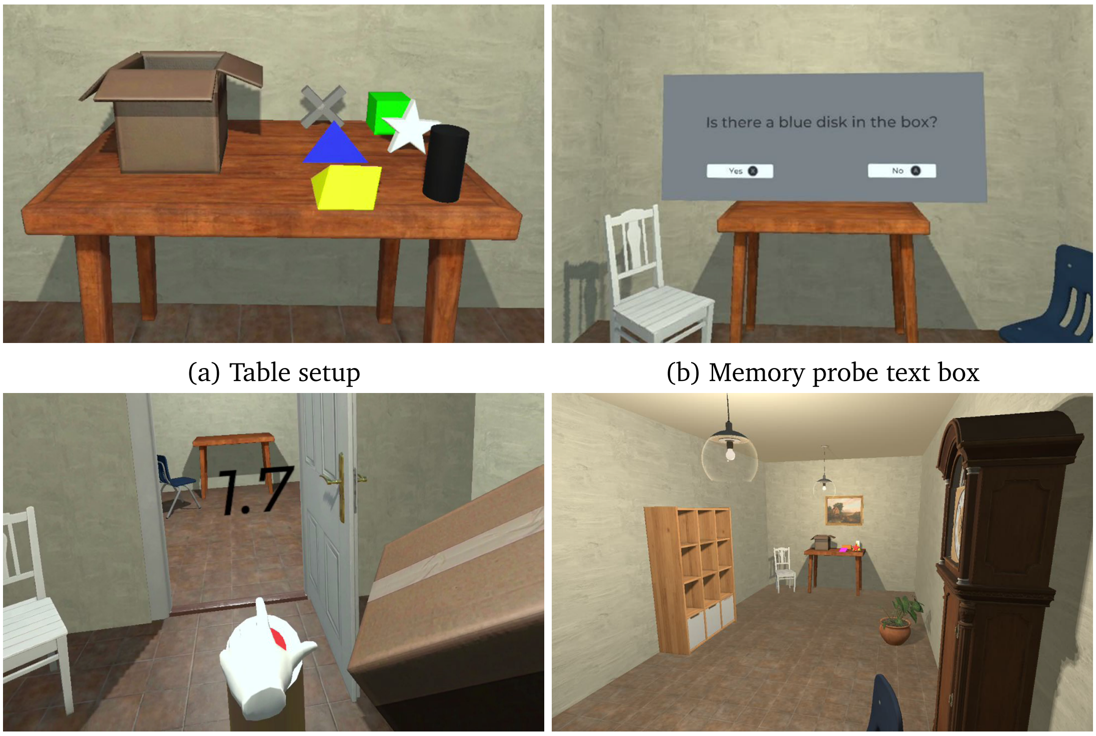
**Task.** At the start of a trial, participants face a table with an open cardboard box on the left and six unique objects on the right (Figure 10.3a). The participant's task is to (i) put the objects in the box, (ii) carry the box to the other side of the space, and (iii) put the box down on the next table. At a point shortly after the participant passes through a door or the midpoint of the space, the object recognition probes appear (Figure 10.3b).

Participants can grab and move the objects and box using the grip buttons of the controllers. When an object enters the box, it disappears, and when all six objects have entered the box, it closes automatically, signalling that collection is complete.

In the teleportation condition, there is a pedestal with a button behind the participant (Figure 10.3c). Upon pressing it, a countdown starts (2 seconds) after which the participant is teleported (1-second fade-out, fade-in effect) to the other side of the space, where the probes appear after 0.5 seconds to allow the participant to look around for a moment. The countdown time was designed to match the average travel time in the walking condition. In the walking condition, the participant simply turns around and walks to the target table (either passing through a door or not, depending on the condition). The first probe appears when the user enters the teleport target location, approximately half a meter after the door or the midway point.

The object recognition probe is a screen in VR. Participants need to answer "Yes" (X

[1]https://osf.io/ezct2/?view_only=80917ad685974cc58e3a322d6014c274




(a) Table setup

(b) Memory probe text box

(c) Teleport button in the door condition

(d) No door condition

Figure 10.3: Screenshots from the experiment application that show the table with the box and 6 objects (a), an object recognition probe (b), the teleport button with an active countdown (c) and a view of a room in the No-Door condition (d).

button) or "No" (A button) by pressing a button on their left- or right-hand controller. The probes are a sequence of six questions in text format: "Is there a [colour] [shape] in the box?" After the last probe, the text box disappears and participants are able to continue to the target table.

When the participant drops the box on the target table, the environment resets: the new box and objects spawn on the target table, and the next trial starts in the other direction.

**Environment.** The experiment took place in a physical space of 8mx5m. The virtual environment was designed isometrically and comprised a large 7m by 3.5m room (No-Door condition) or two smaller 3.5m x 3.5m rooms connected by a door (Door condition). Each room had the same wallpaper and a pseudo-random selection and positioning of furniture. We aimed to create a more ecologically valid scenario than previous work, so the rooms were designed to look like living rooms. The furniture presets are comprised of generic household furniture such as potted plants, paintings, chairs, side tables, vintage clocks and wooden shelves. Two ceiling lamps are present in both layouts to provide lighting. We randomized the visualization and layout of these furniture items to prevent confounding effects on object recognition performance. In the case of two smaller rooms, different furniture layouts are generated for each one.

The participant starts facing a table with the empty box and six objects on it. Behind the participant, the door (if present) is closed and prevents erroneous movement to the other room. When the box closes, the door opens automatically. When the participant puts the closed box down on the target table, the room(s) immediately reset to a new configuration. The majority of this happens out of sight of the participant. Between the teleportation and walking conditions, the only environmental difference is the addition of the teleport button on a pedestal behind them.

**Materials.** The environment was developed in Unity version 2020.3.30f1. The experimental application is provided in the supplementary materials.[2] We used a Meta Quest 2 virtual reality headset for this experiment.

**Participants.** A power analysis based on the effect sizes reported in previous work (see pre-registration) suggested a minimum of 40 participants. We recruited 42 participants from a university environment via a mailing list, word-of-mouth, noticeboard advertising, and social media. Prior experience with VR was not required, although participants with known color blindness, visual impairment, memory or mobility limitations were rejected. Participants were thanked for their participation with  $20 worth of drinks, chocolates, and/or sodas. Three participants were excluded due to technical difficulties and undisclosed health issues: 39 participants were included in data analysis before outlier removal; 22 males and 17 females.

**Procedure.** After obtaining informed consent, the experimenter measured the participant's inter-pupillary distance (IPD) and adjusted the headset. For participants who used glasses, we attached the glasses bracket to the Quest 2 headset. The participant was then assigned a locomotion technique (the between-subject variable), and given a document with the task- and object descriptions. Participants were further instructed that they should spend less than 30 seconds on memorizing the objects. We additionally encouraged participants to be as accurate as possible, and that they could opt-in to submitting their error rates to a leaderboard. Furthermore, we explained that the task is intentionally difficult and that the participant cannot ask questions during the experiment.

Before the first trial, the participant completed a practice round to become familiar with the locomotion technique, the object interaction, and answering the probes. During the practice round, the experimenter verbally instructed and supported the participant.

After the practice round, the experimenter answered any remaining questions, provided final instructions, and placed the participant at the starting location. When the participant was ready, they could press a "Start" button in VR by pressing a button on their controllers to start the first trial. The experiment concludes automatically after 40 trials by showing the participant a text message in VR.

**Analysis.** We exclude trials that took longer than mean+3SD for each participant or less than 10 seconds: On a distance of 5 meters and considering a walking speed of 1

[2] https://osf.io/kdtxn/?view_only=d651c0d98b5e439da4a572f9ecb5a329

m/s a user could reasonably rush through the task in 5–10 seconds. We assume any such trials resulted from a software or user fault and constitute an invalid trial. There were no such trials in our data. Trial time includes memorization time, probe time, and travel time. We exclude probes with a response time > mean+3SD of the full participant sample, or < 250ms (considered an accidental button press, similar to [161]). If a subject is missing more than 2 responses in a trial according to these criteria or a data collection fault, that trial will be removed. Furthermore, if a subject has more than 2 missing trials according to the exclusion criteria above, the participant is excluded from analysis. After data processing, we included 36 participants in data analysis, leading to 18 observations per condition. The details can be found in the supplementary materials.

We estimate the effects of locomotion technique and door presence in a Bayesian regression model. We model a posterior binomial distribution of Error with a probability that is given by a combination of Participant and Condition. The model is implemented in STAN using the *rethinking* package [159]. We assessed the convergence and stability of the Markov Chain Monte Carlo sampling with R-hat, which should be lower than 1.01 [296] and the Effective Sample Size (ESS), which we expect to be greater than 1000. The model is shown below in mathematical form:

$$E_i \sim Binomial(1, p_i)$$

$$logit(p_i) = \alpha_{P[i]} + \beta_{C[i]}$$

$$\alpha_j \sim Normal(0, 1.5)$$

$$\beta_k \sim Normal(0, 0.75)$$

Where E indicates the 0/1 variable of whether a probe was answered incorrectly, P stands for the participant ID, and C indicates one of four conditions. In other words, the probability of making an error is estimated with a coefficient for each participant and each condition. The implementation, the causal model, and the prior distributions are detailed in the accompanying R notebook in the supplementary material.

For completeness' sake and comparability to previous work, we also include ANOVA results generated with JASP 0.17.3.[3]

## 10.4 Results

**Error.** Descriptive statistics (mean error rate $\pm$ standard deviation) show a marginal difference in error rate between the locomotion techniques Walking ($M = 0.176 \pm 0.381$) and Teleportation ($M = 0.218 \pm 0.413$). However, there appears to be no difference between the Door and No-Door conditions for either Walking (No-Door: $M = 0.179 \pm 0.384$ vs. Door: $0.172 \pm 0.377$ (Door) or Teleportation (No-Door: $0.219 \pm 0.414$ vs. Door: $0.217 \pm 0.412$).

Table 10.1 displays the total effects of each condition on error probability (note that these values are log-odds). All conditions have a negative effect on error probability, as expected, and walking has indeed a slightly more negative effect. A more negative effect

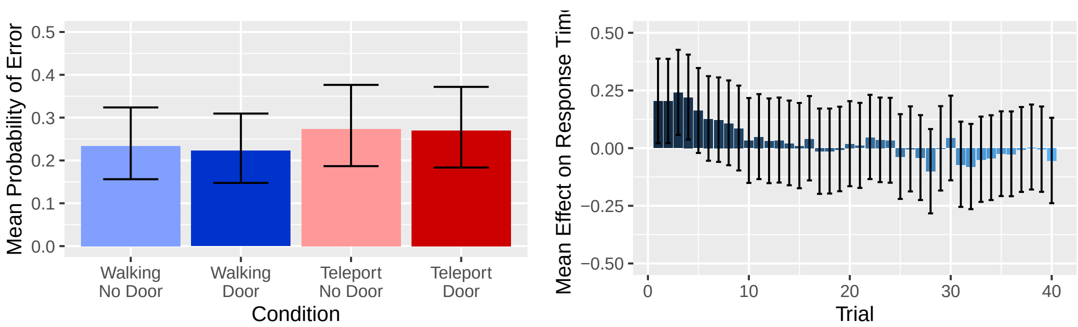
[3]`https://jasp-stats.org`

Table 10.1: Total effects of each of each condition on Error probability. Note that these effects are log-odds. W=Walking, T=Teleportation, ND=No Door, D=Door. The table includes the 89% credible value interval, the number of effective samples (n_eff) and Rhat statistic for MCMC chain convergence.

| Condition | Mean | SD | 5.5% | 94.5% | n_eff | Rhat4 |
|---|---|---|---|---|---|---|
| **W-ND** | -1.216 | 0.303 | -1.704 | -0.735 | 2012 | 1.001 |
| **W-D** | -1.279 | 0.304 | -1.768 | -0.796 | 2059 | 1.001 |
| **T-ND** | -1.004 | 0.298 | -1.471 | -0.529 | 2159 | 1.001 |
| **T-D** | -1.023 | 0.298 | -1.492 | -0.546 | 2139 | 1.001 |

Table 10.2: Total effects of each of each condition on log response time (seconds). W=Walking, T=Teleportation, ND=No Door, D=Door. The bottom part shows the estimated effects of each probe on response time. The table includes the 89% credible value interval, the number of effective samples (n_eff) and Rhat statistic for MCMC chain convergence.

| Condition | Mean | SD | 5.5% | 94.5% | n_eff | Rhat4 |
|---|---|---|---|---|---|---|
| **W-ND** | 0.292 | 0.341 | -0.255 | 0.826 | 1652 | 1.002 |
| **W-D** | 0.315 | 0.340 | -0.232 | 0.850 | 1644 | 1.002 |
| **T-ND** | 0.364 | 0.344 | -0.181 | 0.919 | 1860 | 1.004 |
| **T-D** | 0.345 | 0.344 | -0.199 | 0.903 | 1863 | 1.003 |
| **Probe 1** | 0.428 | 0.258 | 0.025 | 0.842 | 2113 | 1.001 |
| **Probe 2** | 0.204 | 0.258 | -0.200 | 0.618 | 2107 | 1.001 |
| **Probe 3** | 0.163 | 0.257 | -0.240 | 0.577 | 2113 | 1.001 |
| **Probe 4** | 0.134 | 0.258 | -0.270 | 0.548 | 2113 | 1.001 |
| **Probe 5** | 0.142 | 0.258 | -0.262 | 0.557 | 2111 | 1.001 |
| **Probe 6** | 0.107 | 0.258 | -0.297 | 0.521 | 2109 | 1.001 |




(a) Posterior probability of error (b) Effect of trial on response time

Figure 10.4: Figure of (a) the estimated posterior probability of object recognition, and (b) the total effect of each trial on response time (log scale). Intervals are 89% credible-values intervals.

Table 10.3: Total effect of travel time on error, while adjusting for Technique. Values are in log-odds scale.

| Condition | Mean | SD | 5.5% | 94.5% | n_eff | Rhat4 |
|---|---|---|---|---|---|---|
| **Walking** | -1.605 | 0.446 | -2.327 | -0.892 | 1279 | 1.005 |
| **Teleport** | -1.363 | 0.472 | -2.108 | -0.614 | 940 | 1.006 |
| **Travel Time** | 0.057 | 0.129 | -0.147 | 0.261 | 1842 | 1.001 |

indicates a lower error probability. However, the credible intervals[4] largely overlap, signalling that there is no meaningful difference between any conditions. For a more intuitive interpretation, we have plotted the estimated posterior error probabilities for each condition in Figure 10.4a.

A repeated-measures ANOVA with Door Presence as the within-subjects factor and Technique as the between-subjects factor showed no significant effect on error rate of the presence of a door ($F(1, 34) = 0.287, p = 0.595, \eta \approx 0.0$) nor the locomotion technique used ($F(1, 34) = 1.119, p = 0.298, \eta = 0.03$). The interaction was also not significant ($F(1, 34) = 0.062, p = 0.804, \eta \approx 0.0$).

**Response Time.** For response time, we include probe (Pr) and trial (Tr) numbers to check whether participants changed their answering behavior over time or between probes. We modified the model slightly to estimate the response time as sampled from a normal distribution with a mean determined by probe number, trial number, technique, and door presence. Before analysis, we did a log transformation on the response times.

Descriptive statistics (mean±std.dev) show a marginal difference in response time (seconds) between the locomotion techniques Walking ($M = 0.176 \pm 0.381$) and Teleportation ($M = 0.218 \pm 0.413$). However, there appears to be no difference between the Door and No-Door conditions for either Walking (No-Door: $M = 0.179 \pm 0.384$ vs. Door: $0.172 \pm 0.377$ (Door) or Teleportation (No-Door: $0.219 \pm 0.414$ vs. Door: $0.217 \pm 0.412$).

Table 10.2 shows the estimated effects of condition and probe on response time. We observed a similar pattern in the effect of condition on response time as on error. Teleportation leads to marginally higher response time than walking, but the credible intervals overlap almost perfectly. For the Door condition, the credible intervals overlap perfectly. For probe number, we see a larger effect for the first probe compared to the rest. This is to be expected, as the participant needs additional time to stop and look at, attend to, and respond to the first probe. The other probes have very similar effects, as expected. Finally, Figure 10.4b shows the estimated posterior probabilities of each trial on response time. As participants progress in the experiment, they respond faster, but this stabilizes somewhat after trial 15. This could indicate that participants took some time to become comfortable with the task, or that they lost motivation or concentration over time.

[4]An 89% credible interval indicates that, given the data, the model specification, and the prior belief, there is a 89% probability that the true estimate lies within the given range.

**Travel Time.** We suspected that a difference in travel time could lead to some locomotion techniques allowing more time to forget objects than others. To test whether this was the case in our study, we modelled the effect of log travel time on error using a similar model to the one described in section 10.3. Travel time was calculated from the moment the box closed to the moment the first probe appeared.

Descriptive statistics show $M = 20.088, CI = [14.064, 27.661]$ seconds for Walking and $M = 23.925, CI = [17.237, 34.496]$ for Teleportation. Travel using teleportation took $\approx 3$ seconds longer than walking. Despite our efforts to align travel time between walking and teleportation, participants walked more slowly on average than we anticipated. The estimated effects are shown in Table 10.3. The relative effects of walking and teleportation are similar to what we found earlier in this section (see Table 10.1). Importantly, the effect of travel time is nearly zero, with a nearly symmetric credible interval around 0. This means that is unlikely that travel time affected error rate. This harmonizes with previous work by Pettijohn and Radvansky [201], who found no effect of travel time on the doorway effect.

## 10.5 Study 2: Doorway Visualization

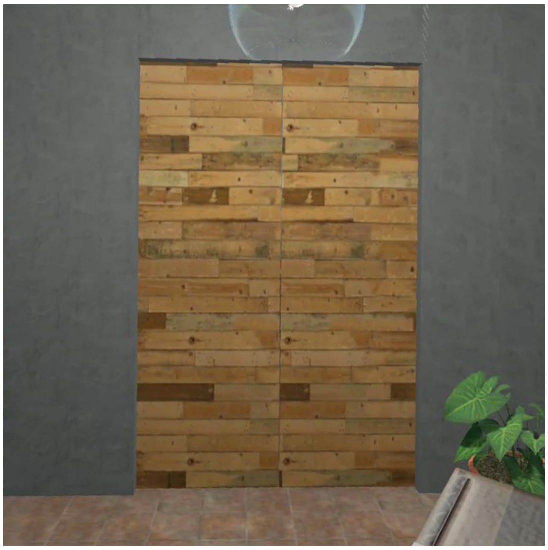
In Study 1, we observed a small increase in error rate when teleportation was used instead of walking. As we did not find evidence of other factors (e.g. travel time) confounding this result, we speculated that this difference may be due to the appearance of the boundary between the two locomotion conditions: When walking, the open door may not be interpreted as an event boundary, but during teleportation, the fade-in, fade-out animation could be interpreted as a boundary instead. In this study, we investigate this by focusing on how different doorway representations affect object recognition performance.

Study 2 is a within-subjects lab study with one independent variable, doorway Visualization, spread across five levels (depicted in Figure 10.5): No door (N), Ordinary Door (O), Transparent Sliding Door (T), Opaque Sliding Door (S), and Portal (P). We imagine the 5 visualizations in an increasing degree of environmental boundary salience. The No Door and Ordinary Door conditions are identical to Study 1's conditions. Transparent Sliding Door and Opaque Sliding Door are made to resemble sliding doors one would encounter in real life, with the latter blocking the view to the next room. We decided to use sliding doors because the task of turning a door handle on an ordinary door could introduce confounding effects. Finally, the Portal is a sci-fi element that does not show the next room and causes a full-screen flash when the user walks through it; this is expected to introduce a highly salient environmental boundary. The order of the conditions is pseudo-randomized akin to Study 1, being randomly assigned with the condition so that the same condition cannot appear more than 3 times in a row. In total, there are 12 trials per condition, resulting in a total of 60 trials per participant.

Our dependent variable is object recognition performance. Similar to Study 1, this is operationalized by error rate and response time on associated and negative probes. We used two associated and two negative probes to limit the duration of the experiment, the order of which is randomized. Our single hypothesis is as follows:

(a) **O**rdinary door

(b) **T**ransparent sliding door



(c) Opaque **S**liding door

(d) **P**ortal

Figure 10.5: This figure shows the different doorway visualizations we used in Study 2. The **N**o Door condition is similar to Study 1. In the experiment, the walls had different colors which are not shown here.

**H4:** Boundaries that are more salient are positively associated with error rate, because they are more readily interpreted as an event boundary.

**Task, Environment, Materials, Apparatus, and Procedure.** The design and implementation of Study 2 are largely identical to Study 1. Here we describe the differences between Study 2 and Study 1.

All participants use natural walking to move through the environment. Additionally, we made some changes to the task to simplify and shorten the experiment. In Study 1, several participants complained that they got bored, fatigued and distracted toward the end. Participants also complained that the task was too difficult; This was intentional, as previous work suffered from ceiling effects. Despite this, error rates in Study 1 were still rather low, indicating that the perceived difficulty did not translate to the observed results. Therefore, while we kept the task the same, we reduced the number of objects and memory probes to 4 each and allowed participants a 5-minute break halfway through the experiment.

In Study 1, it was possible for participants to derive a pattern in the probes and perform better: The colours and shapes of associated probes would never show up in negative probes; Therefore, it was possible for participants to answer probes correctly by only memorising either colour or shape. Without knowledge of the experiment's purpose, it is unlikely that participants used this, but we prevent this in study 2 by allowing negative probes to share features with associated ones as long as the **combination** is different. For example, if "red cube" is associated, it is now possible for "red sphere" or "blue cube" to be negative prompts, unlike before.

The No Door and Ordinary Door conditions are implemented similarly to study 1's No-Door and Door conditions. Both sliding doors open automatically when the participant comes within 0.2 metres of the doors with a full box. The Portal acts as a textured, animated wall separating the two rooms, necessitating the user to walk through. When they do, a full-screen flash plays for 1.5 seconds. The probes appear a short distance after passing through the doors. When participants place their boxes on the target table, they will immediately be teleported to a different room with a red button in front of them. They need to press this button by pushing it with one of their hands, which will then trigger a fade teleport transition to the starting position of the next trial. This transitional environment was implemented to further separate and reduce cross-over effects between trials.

In original doorway experiments, each room had a different pattern on the wall to emphasise a change in location. In our first study, we followed the design by McFadyen et al., so the wall was the same in every room [161]. In order to further visually separate the rooms and maximize the chances of a doorway effect, rooms in Study 2 were pseudo-randomly assigned one 1 of 10 possible wall colors: green, yellow, purple, red, light blue, black, pink, grey, brown and dark blue. When there were two rooms, we ensured that the colors picked were different.

**Participants.** Participants were recruited from social and professional circles via word-of-mouth and advertising on university pages. 20 participants successfully completed

Table 10.4: Total effects of each of each condition on Error probability. Note that these effects are log-odds. The conditions are **N**o door, **O**rdinary door, **T**ransparent sliding door, opaque **S**liding door, and **P**ortal. The table includes the 89% credible value interval, the number of effective samples (n_eff) and Rhat statistic for MCMC chain convergence.

| Condition | Mean | SD | 5.5% | 94.5% | n_eff | Rhat4 |
|---|---|---|---|---|---|---|
| **N** | -0.737 | 0.245 | -1.135 | -0.345 | 1202 | 1.002 |
| **O** | -0.862 | 0.245 | -1.253 | -0.466 | 1212 | 1.002 |
| **T** | -0.814 | 0.244 | -1.208 | -0.419 | 1209 | 1.002 |
| **S** | -0.661 | 0.244 | -1.054 | -0.265 | 1200 | 1.002 |
| **P** | -0.906 | 0.246 | -1.302 | -0.509 | 1221 | 1.002 |

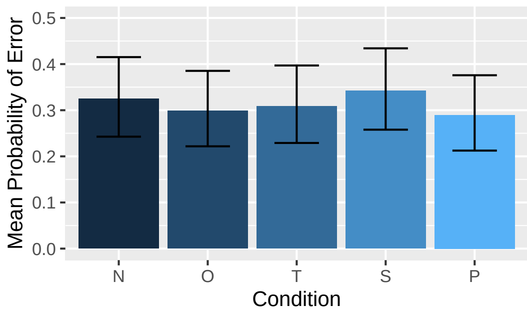



Figure 10.6: Figure of (a) the estimated posterior probability of object recognition error by doorway visualization. The conditions are **N**o door, **O**rdinary door, **T**ransparent sliding door, opaque **S**liding door, and **P**ortal. Intervals are 89% credible-values intervals.

the experiment. Data from 4 additional participants was discarded due to technical difficulties. 17 participants were students in higher education, 2 were researchers in Human-Computer Interaction, and 1 was a student in secondary education. Half (10) were male and half were female, with an age range of 23-35 (M=25.7, SD=3.6). The experiment took approximately an hour, with the main experiment taking around 40 minutes. Participants were thanked for their participation with \$20 worth of drinks, chocolates, and/or sodas.

**Analysis.** We use the same outlier removal strategy as in Study 1, except that we do not test for travel time since we already showed it to have no effect, and since the locomotion technique in this study was not varied. No participants were removed; after data processing, we still had 20 participants left. The Bayesian model for parameter estimation is essentially the same as in section 10.3, but with five levels for the Door parameter and no Technique parameter.

## 10.6 Results

Descriptive statistics (mean error rate$\pm$ standard deviation) show an error rate of $M = 0.194 \pm 0.396$ when there is no door, $M = 0.0.175 \pm 0.380$ when there is an ordinary door,

$M = 0.183 \pm 0.387$ for the transparent sliding door, $M = 0.208 \pm 0.406$ for the sliding opaque door, and $M = 0.170 \pm 0.376$ for the portal.

Table 10.4 displays the total effects of each doorway visualization on error probability (note that these values are log-odds). All conditions have a negative effect on error probability, as expected: A more negative effect indicates a lower error probability. However, the credible intervals overlap greatly and there appears to be no meaningful difference between the estimated effects. For a more intuitive interpretation, we have plotted the estimated posterior error probabilities for each condition in Figure 10.6.

A repeated-measures ANOVA with Visualization as the within-subjects factor showed no significant effect on error rate ($F(4, 76) = 0.814, p = 0.46, \eta = 0.046$).

## 10.7 Discussion

In this work, we set out to show that walking through a doorway in virtual reality negatively affects memory; in other words, the doorway effect. We investigated the effect of teleportation and doorway visualization. We found no evidence that error rates or response times are higher as a result of travelling through a doorway, teleporting to another room, or walking through different types of doorways. In this section, we discuss possible explanations.

**Presence of an Event Boundary.** By definition, the occurrence of the doorway effect relies on an event boundary triggering event segmentation, leading to retrieval interference. A possible explanation of our findings is that neither the doorways nor the teleportation were interpreted as an event boundary. It is possible that the task or user motivation led to both rooms being interpreted as part of the same event: The current and next rooms were critical parts of the same task in which participants walked back and forth. In Study 1, the door was open and the wall colors were the same. In Study 2, the wall colors changed and we aimed for salient doors. We also instructed participants to be as accurate as possible. Therefore, the high user motivation to remember the objects and the relations between the task elements may have prevented event segmentation. However, our task was conceptually similar to those in previous work, and previous work has demonstrated the doorway effect in real, virtual glass, and imaginary doorways. The doorways in our study, in particular in Study 2, were arguably more salient than the simple doors in previous work, so we believe that the spatial boundaries in our studies should have led to event segmentation.

**Effects of Travel and Response Times.** We considered two other possible explanations: the differences in travel time between the locomotion techniques or the limited time to interpret the next room before answering the memory probes. We found a difference in travel time between walking and teleportation, but including this in the model showed no effect of travel time on error rates. This dovetails with previous work that found no effect of travel time on the doorway effect [201]. Similarly, we speculated that because the probe appeared quickly after entering the next room, there was not enough time for the cognitive processes to finish interpreting the next room as a separate event. However, our setup is again similar to previous work, and Pettijohn and Radvansky [201] showed that time spent observing the next room before the probe has no effect.

**The Object Recognition Task.** We speculate that the most likely explanation is that the objects in our studies were dissociated instead of associated. Previous work has demonstrated the doorway effect only for associated objects when using recognition probes [207, 201] (although [202] show a doorway effect for dissociated objects when using a recall probe). What counts as an associated or dissociated object is somewhat unclear, but Radvansky and Copeland [207] provide the following example: "A story protagonist could either put on a sweatshirt (associated) or take it off (dissociated) and then go running." In previous work, the participant picked up an object that disappeared, walked through a doorway, and then answered a probe about the object they had just picked up (associated) or set down in the preceding trial (dissociated). Instead, our participants put several objects in a box that then automatically closed. It is possible that this may have caused the objects to become dissociated from the participant. If so, the objects would not be present in the current event model, and thus event segmentation due to the doorway would have no effect on retrieval error. On the other hand, post-experiment chats with the participants suggest that many used active strategies to remember the objects. It seems unlikely that the objects could be absent from the current event model in that case. This question requires more investigation, specifically to determine and control what makes an object associated or dissociated.

**Virtual Reality and the Doorway Effect.** Virtual reality has a number of unique characteristics that are relevant to this investigation. In section 10.1 we discussed how virtual reality environments may offer relatively *more* doorways than real life and use locomotion techniques that rely on environmental boundaries for travel. We cannot be certain that there is *no* doorway effect: If the task design or user characteristics caused both rooms to be interpreted as part of the same event, or if the objects being carried were treated as being dissociated, the doorway and the visualization thereof (including teleportation) would have no effect. There is ample previous work demonstrating the effect in various scenarios, and the event horizon model of memory that predicts it has received increasing empirical support, meaning that by all accounts we should have found a doorway effect. However, some recent work using VR failed to find evidence of a doorway effect, indicating that the prerequisites for the effect to occur are more nuanced than we initially assumed. In sum, we suspect that virtual reality research and design may be susceptible to degraded memory performance due to the presence of a doorway effect. However, many questions remain: we need future work to continue this line of investigation while carefully considering the (dis)associated status of the objects, the design of spatial boundaries, and the use of interaction techniques.

## 10.8 Conclusions

In this work, we investigated how common locomotion techniques in virtual reality (VR) and non-realistic environment designs can cause the doorway effect. We discussed the Event Horizon Model that predicts that the doorway effect occurs as a consequence of crossing an environmental boundary, resulting in “forgetting.” While several previous works have demonstrated the doorway effect in desktop environments, its causes and effects in immersive virtual reality were unclear. Therefore, we conducted two VR lab studies to investigate how walking and teleportation as well as different doorway visualizations impact the doorway effect. Our results showed no difference due to crossing different doorway visualizations using either walking or teleportation. This came as a surprising finding considering previous work, and we discussed how the lack of a doorway effect may have been caused by how participants interact with the objects or how they move through boundaries. In conclusion, we believe more work is required to investigate the causes and effects of the doorway effect in virtual reality, particularly in relation to the design of different locomotion techniques, virtual environmental boundaries, and how users interact with objects requiring memorization.

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# A Appendices

## A.1 Extended Qualities of Walking

This section presents the results from the 15–20 minute semi-structured interview that we conducted with all participants at the end of the study in "Step On It" [71]. Our aim is to explore and describe the *qualities of VR walking* with variations of transfer functions.

To analyze the interview data, we first transcribed all the participant statements from audio files into text snippets. Two of the authors then started organizing the text snippets into categories describing different qualities or features of walking through a 2.5-hour affinity diagramming session. The categories were adjusted with edits, additions, and deletions during the session. The rest of the snippets were later labeled into categories on a digital sheet (some with many labels) by one author. We found the participants describing their experiences in terms of six qualities: Naturalness, Enjoyment, Difficulty, Comfort, Effort, and Control. Next, we provide insights into the six qualities.

**Naturalness.** During the interview, participants often described their experience as "feeling natural" or "feeling like normal walking." Rokso said "[It] was based on a feeling of whether it felt like good walking, more natural in a way, or felt kind of off." After trying out their predicted best configuration, another participant, Ximeno, said: "I guess I would say it just feels like normal walking," and when comparing their best configuration to another: "The first one was also fine in the sense that I was like, comfortable and everything but I could tell that the second one was better, actually: an even more natural feeling." In contrast, they described more negative experiences often as "unnatural," "weird," or "a bit off."

The moment of starting and stopping to walk is related to a "natural" feeling. For example, the sudden start was sometimes referred to as a "glitch" or "strange." Tara compared the experience of a slow starting acceleration to starting to run, noting that "in real life, if you start running, the speed increases, [but] it's not that at some point [it will suddenly increase]. So I think that's the feeling that just puts me off a little bit." When talking about their experience in the `stop` condition, Mukesh said that "… they all felt very, very good. Or a couple were completely natural. And you didn't have to think at all." On the other hand, during the experiment Dana exclaimed "I'm not doing what feels natural, [I'm] just trying to compensate for the sensitive finish line" when walking with $\alpha_{stop} \approx 0.95$ (sudden stop).

A couple of participants indicated a positive correlation between how "natural" or "normal" a configuration feels and the degree to which they feel present or immersed in the virtual environment. Specifically, a negative configuration such as the sudden stop, could "… break the illusion" (Dana). Similarly, Silvestre commented "It was the feeling of like, virtual and not real. The others were very real. Even the fast walk." regarding the sudden stopping. One other comment highlights the potential relationship quite well: when inquired about what "feeling a bit off" meant, Rokso responded by saying:

> In some of the walks, you're made very aware that you're in a VR headset, and it just doesn't feel like the normal way of walking. Whereas in some others it feels more natural: even though you're walking very fast and stuff, you kind of forget that you're in a headset.

**Enjoyment.** Almost all participants thought walking in VR with high-gain was fun or said they enjoyed it. Some configurations in particular may have been more fun than others. For example, during the experiment Arni exclaimed "I need an 'extra fun' category; that was nice!" when walking with a slow start of $\alpha_{start} = 0.4$. Bellatrix was very enthusiastic overall and said "I definitely had fun!" and used "fun" as one of their main descriptors: "… when the finish line was suddenly upon you, and you just had no chance to react basically. I mean, that took a bit of the fun of it out of it, …" On the other hand, Kane did not have a negative feeling, but felt it was "fine" and "a bit boring" (Kane). Some participants felt that a configuration would be "annoying" if it did not behave as desired. For example, both a very slow stop ($\alpha_{stop} \approx 0.65$) and a very fast stop ($\alpha_{stop} \approx 0.95$) were regarded as annoying by Terah and Arni respectively, saying: "The thing that's annoying me is that I have to stop before taking my last step." and "The annoying one was when it did not slow down in the end, and you really had to stop." Notus also referred to both the starting acceleration and the velocity or acceleration in the stopping moment like this: "But like when you slow down, it almost comes as a shock almost every time when it's like, too fast. And it always causes annoyance when it's too slow." Bellatrix (paraphrased) nicely illustrates a possible difference between a configuration being easy to use and it being enjoyable:

> The requirements question was: how much did I like it? But the second one, easy-to-use, was much more subjective: it could be easy to use, meaning whether I felt like I hit the finish line, but, I did not necessarily enjoy it. So, to me easy-to-use was enjoyment.

**Difficulty.** The task in the experiment required users to stop on the target mark as accurately as possible. The UMUX-Lite questionnaire contains a question asking how "easy to use" the configuration is. It is thus no surprise that many participants commented on configurations being "easier" or "harder." It seems that there is a desire to be accurate, and that being accurate becomes more difficult in certain configurations. Parnel interpreted the requirements question as relating to accuracy and later added that another relevant question could have been "more or less precise." They said that when given enough time to slow down "… it felt like I could be more accurate."

Perhaps the difficulty arises from some expectation of the user regarding the deceleration towards the target, as is illustrated by Flora's comment: "… when I messed up it was because it didn't stop. And I was expecting it to, like, slow down right before the end. This is further supported by the fact that none of our participants felt that the `start` condition was difficult. In the experiment, Bogomil drew the short straw and received `stop` configurations with the fastest decelerations first. As they walked through $\alpha_{stop} = 0.85, 0.95, 0.75$ we could see them stumbling, swaying, and struggling to stop smoothly. Then, when going through $\alpha_{stop} = 0.75, 0.65$, they exclaimed: "I feel like it's getting easier and easier!"

**Comfort.** A large portion of participants used "comfort" to describe their experiences. They would say that the overall experience, or a particular configuration would feel "comfortable." For example, Dana said: "I think comfort was my biggest requirement, right? Actually feeling that I trusted the system, but also feeling that I felt comfortable walking in the space." For Haizea, "comfort" was more related to a feeling of control over their movements, saying: "I think I just felt maybe more comfortable when like, I could also feel like I can control my walking." When asked about what specifically influences their comfort level, they responded: "[Whether] I felt, like, safe walking, and [that I'm] not gonna, like, fall, or trip or lose my balance." Most participants reported that they felt comfortable, or even "very comfortable" (Bellatrix) during the experiment. However, some conditions were reported as being "uncomfortable," particularly the fast start and sudden stop configurations ($\alpha_{start} < 0.05$ and $\alpha_{stop} > 0.95$). Kasey explained that the fast starting speed was "not difficult, but uncomfortable," while others also found the overall speed to be "not that comfortable" (Flora), or complained about sudden stops: "… the ones where the deceleration was very abrupt; that was the most uncomfortable" (Ximeno). Sometimes participants could not or did not explain what they meant by "comfortable/uncomfortable," but they often reported "feeling comfortable" as being part of their assessment of the requirements and easy-to-use parts of the UMUX-Lite questionnaire.

**Effort.** The participants referred to both physical and mental effort of VR walking with gain functions in their statements. As an example of physical effort, some participants (e.g., Notus, Mukesh) felt that a good configuration would allow them to land on the target with their final step. That is, not requiring additional effort, half steps, or walking velocity adjustment. Some participants went one step further and directly related their required effort to their gait, or the way they (had to) control their steps. Notus felt that it was "… almost a natural walk when the configuration was right," and that it would be very easy to use: "I hit the target perfectly without having to think about [having to] adjust my step or anything. It just comes.. fluidly."

Others also mentioned such mental effort of "thinking." For example, Mukesh said: "None of them required conscious thinking, but a couple of them made you revise your expectations about what a step does. So I guess the ones that I didn't rate very easy to use, [are so] because it made me think twice about what a step is." Bellatrix preferred to "have time to get your bearings, and you know, figure, okay, this is where I want to go, instead of just, you know, having to adjust very suddenly." Other participants also felt like they had to explicitly think about their steps in some configurations; Colomba summarizes this effect nicely:

> Sometimes I had to, like, be careful about the step before it stopped. I had to time it a bit or take a bigger step to get there, or else I would have to take another step or something like that. And sometimes it stopped a bit before: like, it slowed down a bit before the red line, and then I had to take the decision whether I would take a couple more steps or just take a bigger step to get onto it.

**Control.** In several instances, the participants reported that the system responded in an unexpected way. This happened in all three parts of the traversal: the starting, the middle, and the stopping. For the starting moment, a low $\alpha_{start} \approx 0.05$ causes the amplified movement to begin immediately, for even the smallest head movement. Both Emiliya and Silvestre believed it to be some sort of glitch, whereas Flora said: "First, when I didn't expect it, I felt like falling. Because I was like, 'Oh, no, no, the ground [is] being removed.'"

Mostly, the comments relating to what might be a "feeling of control" related to the moment of stopping, or the perceived virtual speed while approaching the target. Either the participant felt that they had to, and could, control their physical walking speed to adjust the virtual speed to stop on the target, or that they were not in control of their speed. In particular, several participants noted that a very slow stop (low $\alpha_{stop}$) would feel like they were being stopped before the target, and that they had to take additional steps to arrive. For example, Kane said that "the times where I got annoyed with that, I had to walk so much further in the end. Because it's, I mean, I know I had to walk the same distance, but it felt like I had to walk further." In contrast, the sudden stops were difficult to use (as discussed previously), and some participants reported that they felt like they had to consciously and physically slow down to compensate. For example, Ximeno had to "slow down my physical walking speed to get to the to stop at the right place. Or at least it felt like it." A more gradual stop also allowed for another aspect of locomotion, perhaps related to motor control planning or navigation. For example, Haizea wanted to be "… in control of their walking" and Kasey said that "it's more important to have the possibility to choose how and where I stop."

The functions with low/high $\alpha$ values, resulting in sudden acceleration, often received negative comments both during the study and interview: participants found these "constant gain" configurations difficult to use and uncomfortable, especially when stopping. Kane said about the sudden conditions: "The one that stopped really.. suddenly, it was a rated low because I found it difficult to stop." Other participants reported similar difficulties and said it may be because they did not have enough time to stop normally, or because the sudden stop caused them to lose their balance. We often saw participants stumble or almost fall forward when they first encountered a sudden stop, and most continued struggling to stop smoothly on the target. However, some participants did not mind it too much, for example: Bellatrix struggled to stop as well, but later said: "… I had fun doing it, even if, if sometimes the finish line would just, you know, be there all of a sudden." Only a couple of users reported that they found the sudden start disturbing, saying it felt like a "glitch," or "… that the walls start moving before me."

## A.2 Search Queries

This section presents the detailed search queries used to discover relevant literature in the systematic review "Sicknificant Steps" [292].

We used the following query for ACM Digital Library with a filter for "Research Article" (there is an implicit OR between individual terms in ACM DL). We added a term "virtual environment(s)" because some authors with relevant papers (e.g., Janeh et al. [100]) refer to "virtual environments" instead of "virtual reality" in the abstract, otherwise leaving those papers out of the ACM DL search results. This is no problem in other databases because they have a more reliable ability to do metadata- and full-text search to find the base keywords.

```
[[Abstract: "virtual "reality vr "virtual "environment "virtual
   "environments]] AND [All: sickness cybersickness] AND [All:
   locomotion walking] AND [Publication Date: (01/01/2016 TO
   12/31/2021)]
```

We used the following query for IEEE Xplore with filters for "Journals," "Conferences," and years "2016–2021":

"

```
(All "Metadata":virtual "reality OR "All "Metadata:vr) AND "(Full
   Text & "Metadata":"sickness OR "Full Text & "Metadata":
   "cybersickness) AND "(Full Text & "Metadata":"locomotion OR "Full
    Text & "Metadata":"walking)
```

We used the following query for Elsevier ScienceDirect with a filter for "Research articles":

```
Title, abstract, keywords: "(virtual "reality OR vr); Articles with
   terms: (sickness OR cybersickness) AND (locomotion OR walking);
   Year(s): 2016-2021
```

Springer Link's advanced search is limited, so we used four individual searches with filters for "Conference Paper" and "Article" using both "sickness" or "cybersickness," and "locomotion" or "walking" respectively and removed the duplicates.

```
sickness AND locomotion AND "virtual "reality; between 2016--2021

cybersickness AND locomotion AND "virtual "reality; between
   2016--2021

sickness AND walking AND "virtual "reality; between 2016--2021

cybersickness AND walking AND "virtual "reality; between 2016--2021
```

## A.3 Literature Search Results

The following section presents the summaries of all included studies in "Sicknificant Steps" their grouping [292]. The walking papers are presented in Table A.1, resetting papers in Table A.2, scene manipulation papers in Table A.3, repositioning papers in Table A.4, and reorientation papers in Table A.5 and Table A.6.

Studies with multiple relevant conditions are listed with one line per condition. The empty rows describe studies that are included in the systematic review but not in the meta-analysis, because SSQ total score data was not available. "*Number of observations*" refers to the sample number included in the mean score presented in each paper, "*Mean SSQ-TS*" is the mean total SSQ score with "*standard error*." "*Taxonomy grouping*" refers to the groups in our extension of [184]'s taxonomy (see Figure 8.2). "*Independent?*" describes whether several conditions were included in one study that might have produced carry-over and, thus *not independent*, effects.

Table A.1: Papers Walking

| Study name | Number of observations | Mean SSQ-TS | Standard error | Taxonomy grouping | Independent? |
|---|---|---|---|---|---|
| McFadyen2018 [160] | 10 | 0.23 | 0.38 | Isometric walking | Not independent |
| Mousas2021 | 64 | 2.03 | 0.07 | Isometric walking | Not independent |
| Selzer2022 | 22 | 6.80 | 1.75 | Isometric walking | Independent |
| Schmitz2018 | 9 | 8.31 | 4.17 | Isometric walking | Independent |
| Mayor2021 | 48 | 9.35 | 2.02 | Isometric walking | Not independent |
| Pala2021kids | 30 | 10.47 | 1.98 | Isometric walking | Independent |
| Fiset2020 | 10 | 10.85 | 4.81 | Isometric walking | Not independent |
| Feigl2019 | 34 | 11.22 | 2.27 | Isometric walking | Not independent |
| Wozniak2020 | 20 | 11.41 | 2.88 | Isometric walking | Independent |
| Monteiro2018 | 16 | 12.39 | 4.80 | Isometric walking | Independent |
| Cmentowski2021 | 15 | 12.55 | 0.98 | Isometric walking | Independent |
| Buhler2019 | 13 | 13.81 | 2.34 | Isometric walking | Independent |
| Deb2017 | 26 | 14.07 | 3.14 | Isometric walking | Independent |
| Buhler2018 | 12 | 14.65 | 2.46 | Isometric walking | Independent |
| Besha2022 | 12 | 15.00 | 4.56 | Isometric walking | Independent |
| Nguyen2021 | 24 | 15.42 | 4.64 | Isometric walking | Not independent |
| Shin2016 | 15 | 16.21 | 3.69 | Isometric walking | Independent |
| Sayyad2020 | 16 | 16.83 | 4.82 | Isometric walking | Not independent |
| Feigl2020 | 21 | 16.92 | 3.20 | Isometric walking | Not independent |
| Born2018 | 17 | 17.16 | 3.14 | Isometric walking | Independent |
| Vincent2021 | 19 | 18.80 | 4.92 | Isometric walking | Not independent |
| Pastel2022 | 20 | 19.45 | 4.95 | Isometric walking | Independent |
| Feigl2020 | 21 | 19.59 | 3.64 | Isometric walking | Not independent |
| Wilson2018 | 40 | 19.92 | 2.94 | Isometric walking | Not independent |
| Feigl2020 | 21 | 20.12 | 3.34 | Isometric walking | Not independent |
| Janeh2019 | 18 | 20.14 | 5.11 | Isometric walking | Independent |
| Born2018 | 19 | 20.67 | 4.31 | Isometric walking | Independent |
| Born2018 | 15 | 21.94 | 5.70 | Isometric walking | Independent |
| Pala2021kids | 26 | 23.88 | 3.02 | Isometric walking | Independent |
| Kim2022 | 16 | 24.27 | 5.99 | Isometric walking | Not independent |
| Cmentowski2021 | 15 | 25.68 | 1.92 | Isometric walking | Independent |
| Kim2022 | 16 | 28.81 | 5.26 | Isometric walking | Not independent |
| Borrego2016 | - | - | - | Isometric walking | Not independent |
| Min2020 | - | - | - | Isometric walking | Not independent |
| Feigl2019 | - | - | - | Isometric walking | Not independent |
| Sohre2017 | - | - | - | Isometric walking | Independent |
| Pala2021HMD | - | - | - | Isometric walking | Independent |
| Bindschadel2022 | - | - | - | Isometric walking | Independent |
| Rubo2019 | - | - | - | Isometric walking | Independent |
| Wang2022 | - | - | - | Isometric walking | Independent |
| Kwon2022 | - | - | - | Isometric walking | Independent |

Table A.2: Papers Resetting

| Study name | Number of observations | Mean SSQ-TS | Standard error | Taxonomy grouping | Independent? |
|---|---|---|---|---|---|
| Zhao2021 | 16 | 4.63 | 1.19 | Resetting | Independent |
| Wu2022 | 16 | 9.14 | 1.98 | Resetting | Independent |
| Wu2022 | 16 | 9.40 | 2.65 | Resetting | Independent |
| SUKwon2022 | 36 | 10.34 | 1.76 | Resetting | Not independent |
| Wu2022 | 16 | 11.11 | 1.30 | Resetting | Independent |
| Wu2022 | 16 | 11.55 | 2.05 | Resetting | Independent |
| Wu2022 | 16 | 12.07 | 2.05 | Resetting | Independent |
| SUKwon2022 | 36 | 15.71 | 2.79 | Resetting | Not independent |
| Wu2022 | 16 | 17.66 | 2.58 | Resetting | Independent |
| Simeone2020 | 19 | 18.70 | 4.94 | Resetting | Not independent |
| Ueda2017 | 8 | 20.57 | 5.37 | Resetting | Independent |
| Ueda2018 | 10 | 23.19 | 6.25 | Resetting | Not independent |
| Han2020 | 20 | 31.00 | 8.21 | Resetting | Not independent |
| Han2020 | 20 | 41.40 | 12.10 | Resetting | Not independent |
| Min2020 | - | - | - | Resetting | - |
| Sra2018 | - | - | - | Resetting | - |
| Gao2022 | - | - | - | Resetting | - |
| Paris2022 | - | - | - | Resetting | - |

Table A.3: Papers Scene manipulation

| Study name | Number of observations | Mean SSQ-TS | Standard error | Taxonomy grouping | Independent? |
|---|---|---|---|---|---|
| Cao2020 | 16 | 1.50 | 0.67 | Scene manipulation | Not independent |
| Cao2020 | 16 | 1.80 | 0.76 | Scene manipulation | Not independent |
| Cao2020 | 16 | 5.20 | 1.68 | Scene manipulation | Not independent |
| Cao2020 | 16 | 5.20 | 1.68 | Scene manipulation | Not independent |
| Lochner2021 | 25 | 24.91 | 6.71 | Scene manipulation | - |
| Mittal2021 | 10 | 27.30 | 8.00 | Scene manipulation | - |
| Han2022 | 20 | 31.60 | 5.70 | Scene manipulation | - |
| Han2022 | 20 | 32.00 | 8.21 | Scene manipulation | - |
| Simeone2020 | 19 | 39.06 | 9.64 | Scene manipulation | - |
| Stein2022 | 18 | 20.36 | 8.14 | Scene manipulation | - |
| Gao2022 | - | - | - | Scene manipulation | - |
| Vasylevska2017 | - | - | - | Scene manipulation | - |
| Dong2017 | - | - | - | Scene manipulation | - |
| Min2020 | - | - | - | Scene manipulation | - |
| Sun2016 | - | - | - | Scene manipulation | - |
| Neerdal2020 | - | - | - | Scene manipulation | - |
| Koltai2020 | - | - | - | Scene manipulation | - |
| Dong2019 | - | - | - | Scene manipulation | - |
| Serubugo2018 | - | - | - | Scene manipulation | - |
| Dong2017 | - | - | - | Scene manipulation | - |

Table A.4: Papers Repositioning

| Study name | Number of observations | Mean SSQ-TS | Standard error | Taxonomy grouping | Independent? |
|---|---|---|---|---|---|
| Selzer2022 | 22 | 8.33 | 1.83 | Repositioning | Independent |
| Janeh2017 | 19 | 10.24 | 2.80 | Repositioning | Not independent |
| Dong2021 | 19 | 11.61 | 3.21 | Repositioning | Independent |
| Janeh2018 | 21 | 12.64 | 3.99 | Repositioning | Not independent |
| Janeh2018 | 21 | 13.18 | 4.66 | Repositioning | Not independent |
| Selzer2022 | 22 | 17.00 | 3.36 | Repositioning | Independent |
| Dong2021 | 33 | 17.23 | 2.28 | Repositioning | Not independent |
| Wilson2018 | 40 | 18.51 | 3.13 | Repositioning | Not independent |
| Cmentowski2022 | 25 | 20.64 | 4.61 | Repositioning | Not independent |
| Tirado2019 | 17 | 21.42 | 5.17 | Repositioning | Not independent |
| You2022 | 27 | 22.58 | 4.62 | Repositioning | Not independent |
| Wilson2018 | 40 | 23.09 | 3.75 | Repositioning | Not independent |
| Lai2020 | 30 | 24.68 | 4.33 | Repositioning | Not independent |
| Zhang2018 | 15 | 26.68 | 7.18 | Repositioning | Not independent |
| Wilson2018 | 40 | 27.49 | 4.05 | Repositioning | Not independent |
| Kim2022 | 16 | 27.58 | 6.22 | Repositioning | Not independent |
| Kim2022 | 16 | 29.16 | 3.54 | Repositioning | Not independent |
| Kruse2018 | 20 | 31.23 | 7.00 | Repositioning | Not independent |
| Tomar2019 | 36 | 35.22 | 6.14 | Repositioning | Independent |
| Selzer2022 | 22 | 36.38 | 4.26 | Repositioning | Independent |
| Kim2021 | 20 | 40.58 | 7.03 | Repositioning | Not independent |
| Wilson2018 | 40 | 41.42 | 4.78 | Repositioning | Not independent |
| Kim2021 | 21 | 47.20 | 6.45 | Repositioning | Not independent |
| Selzer2022 | 22 | 48.62 | 6.45 | Repositioning | Independent |
| Kim2021 | 20 | 54.98 | 7.39 | Repositioning | Not independent |
| Abtahi2019 | - | - | - | Repositioning | - |
| Williams2019 | - | - | - | Repositioning | - |
| Min2020 | - | - | - | Repositioning | - |

Table A.5: Papers Reorientation Part 1

| Study name | Number of observations | Mean SSQ-TS | Standard error | Taxonomy grouping | Independent? |
|---|---|---|---|---|---|
| Rene2022 | 20 | 3.40 | 1.32 | Reorientation | Not independent |
| Langbehn2018 | 11 | 6.78 | 1.65 | Reorientation | Independent |
| Matsumoto2021 | 24 | 9.69 | 2.32 | Reorientation | Not independent |
| Li2020 | 11 | 10.54 | 1.81 | Reorientation | Not independent |
| Li2020 | 11 | 10.88 | 1.71 | Reorientation | Not independent |
| Chang2021 | 24 | 10.90 | 2.63 | Reorientation | Not independent |
| Chang2021 | 24 | 11.70 | 2.80 | Reorientation | Not independent |
| Li2020 | 11 | 12.24 | 2.67 | Reorientation | Not independent |
| Chang2021 | 24 | 12.40 | 2.96 | Reorientation | Not independent |
| Chang2021 | 24 | 12.40 | 2.96 | Reorientation | Not independent |
| SUKwon2022 | 36 | 13.53 | 1.86 | Reorientation | Not independent |
| Li2020 | 11 | 13.60 | 2.03 | Reorientation | Not independent |
| Li2020 | 11 | 13.60 | 1.84 | Reorientation | Not independent |
| Tomar2019 | 36 | 13.61 | 3.34 | Reorientation | Independent |
| Tomar2019 | 36 | 13.71 | 2.04 | Reorientation | Independent |
| Langbehn2019 | 30 | 15.01 | 2.62 | Reorientation | Not independent |
| Matsumoto2021 | 24 | 16.19 | 2.69 | Reorientation | Not independent |
| Langbehn2019 | 30 | 17.02 | 3.45 | Reorientation | Not independent |
| Li2020 | 11 | 17.34 | 2.03 | Reorientation | Not independent |
| Matsumoto2019 | 22 | 17.60 | 4.15 | Reorientation | Not independent |
| Li2020 | 11 | 17.68 | 2.14 | Reorientation | Not independent |
| Ropelato2022 | 19 | 18.18 | 3.82 | Reorientation | Independent |
| Cao2020 | 16 | 19.20 | 5.46 | Reorientation | Not independent |
| Li2020 | 11 | 20.40 | 2.28 | Reorientation | Not independent |
| Li2020 | 11 | 20.40 | 2.04 | Reorientation | Not independent |
| Sakono2021 | 18 | 20.99 | 5.61 | Reorientation | Not independent |
| Cao2020 | 16 | 22.90 | 6.47 | Reorientation | Not independent |
| Shibayama2020 | 11 | 24.48 | 7.23 | Reorientation | Not independent |
| Sakono2021 | 18 | 25.56 | 6.78 | Reorientation | Not independent |
| Jeon2022 | 30 | 27.19 | 4.08 | Reorientation | Not independent |
| SUKwon2022 | 36 | 28.34 | 4.13 | Reorientation | Not independent |
| Shibayama2020 | 12 | 28.67 | 7.06 | Reorientation | Not independent |
| Jeon2022 | 28 | 29.49 | 4.67 | Reorientation | Not independent |
| Hoshikawa2022 | 12 | 29.60 | 9.56 | Reorientation | Not independent |
| Shibayama2020 | 14 | 29.65 | 6.89 | Reorientation | Not independent |
| Jeon2022 | 28 | 30.20 | 4.64 | Reorientation | Not independent |
| Jeon2022 | 30 | 30.56 | 5.02 | Reorientation | Not independent |
| Shibayama2020 | 11 | 31.28 | 18.17 | Reorientation | Not independent |
| Sakono2021 | 12 | 32.41 | 10.44 | Reorientation | Not independent |
| Dong2021 | 33 | 33.55 | 4.82 | Reorientation | Not independent |
| Shibayama2020 | 12 | 35.22 | 10.39 | Reorientation | Not independent |

Table A.6: Papers Reorientation Part 2

| Study name | Number of observations | Mean SSQ-TS | Standard error | Taxonomy grouping | Independent? |
|---|---|---|---|---|---|
| Jeon2022 | 28 | 35.74 | 5.28 | Reorientation | Not independent |
| Rietzler2020 | 19 | 36.68 | 5.01 | Reorientation | Not independent |
| Shibayama2020 | 14 | 37.67 | 11.57 | Reorientation | Not independent |
| Nguyen2018 | 14 | 41.14 | 10.38 | Reorientation | Not independent |
| Jeon2022 | 30 | 42.65 | 6.92 | Reorientation | Not independent |
| Schmitz2018 | 26 | 48.92 | 9.01 | Reorientation | Not independent |
| Hildebrandt2018 | 40 | 50.05 | 7.08 | Reorientation | Not independent |
| Zhang2018 | 17 | 55.60 | 16.50 | Reorientation | Not independent |
| Liu2021 | - | - | - | Reorientation | - |
| Matsumoto2016 | - | - | - | Reorientation | - |
| Bozgeyikli2016 | - | - | - | Reorientation | - |
| Bozgeyikli2019 | - | - | - | Reorientation | - |
| Bachmann2019 | - | - | - | Reorientation | - |
| Lee2020 | - | - | - | Reorientation | - |
| Lee2019 | - | - | - | Reorientation | - |
| Min2020 | - | - | - | Reorientation | - |
| Sun2018 | - | - | - | Reorientation | - |
| Gao2022 | - | - | - | Reorientation | - |