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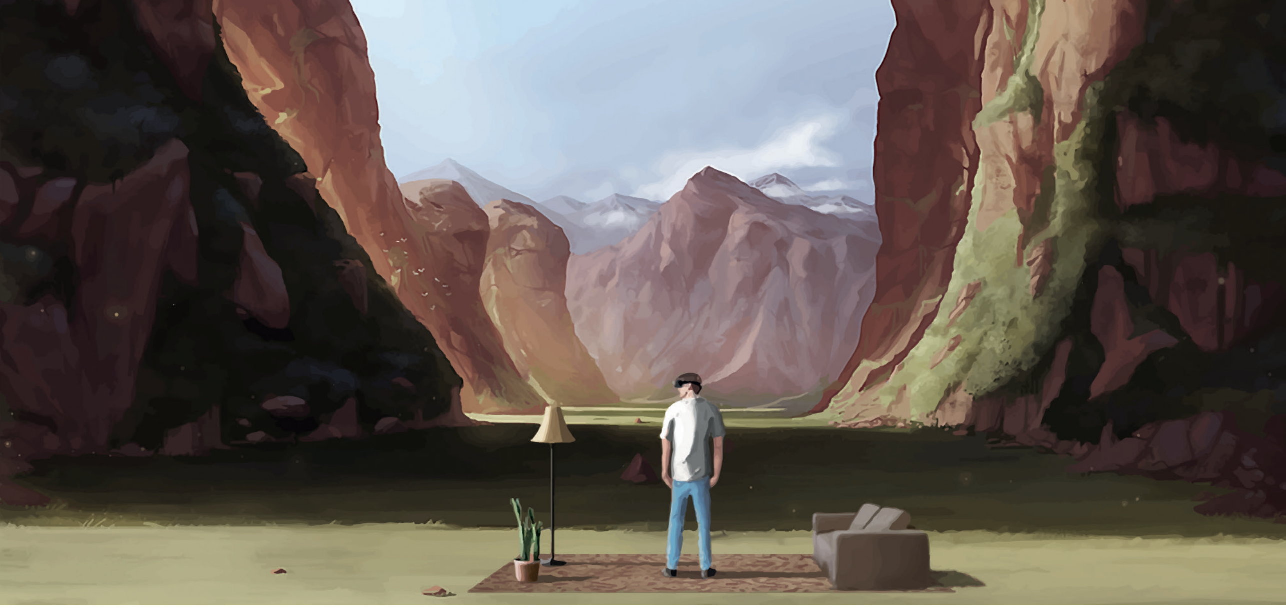

WALKING WITHOUT MOVING

AN EXPLORATION OF FACTORS INFLUENCING THE PERCEIVED NATURALNESS OF WALKING-IN-PLACE TECHNIQUES FOR LOCOMOTION IN VIRTUAL ENVIRONMENTS

BY
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DENMARK

PhD Dissertation

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To Elliot, Vincent and Camilla,
for making me cherish today and look forward to tomorrow.

Author CV

Niels Christian Nilsson received his BSc and MSc in Medialogy from Aalborg University Copenhagen in 2008 and 2010. Until starting the PhD in the spring of 2012, he worked as a research assistant at the same university where he was affiliated with the Multisensory Experience Lab.

Abstract

Recent technological advances may soon bring immersive virtual reality (IVR) out of the laboratory and into the homes of consumers. This means that IVR systems will be deployed in settings where the physical interaction space is very limited in size. If users wish to navigate virtual environments on foot, these spatial constraints are problematic since they make real walking infeasible. Walking-in-Place (WIP) techniques constitute a convenient and inexpensive approach to facilitating walking within virtual environments. When relying on WIP techniques for virtual locomotion, the user performs stepping-like movements that serve as a proxy for real steps and enable movement through the virtual world while the user remains (relatively) stationary with respect to the physical environment. However, additional work is arguably needed in order to make WIP techniques a more viable approach to virtual walking.

This thesis focuses on the factors influencing the degree of perceived naturalness of WIP locomotion; i.e., the degree to which the user's experience of walking through a virtual environment using WIP locomotion is mistakable for the experience of real walking. I take the degree of correspondence between the sensorimotor loops of real walking and WIP locomotion as my point of departure, and explore how to facilitate perceptually natural actions (steps in place) and natural self-motion perception (virtual walking speeds). The primary contributions of the presented work are the findings of ten studies and two meta-analyses documented in the seven papers making up the main body of the thesis.

The first two studies explored alternative gestural input for WIP locomotion and found that gestural input based on more subtle leg movements was perceived as more natural. Presumably because these gestures better matched real walking in terms of perceived exertion. Moreover, it was found that gestural input based on arm movements, rather than explicit leg motion, was comparable to the traditional WIP gesture in terms of perceived naturalness. However, the applicability of this type of gestural input is limited since it makes hand-based interaction impossible while walking. A potential limitation of WIP locomotion is that users wearing a head-mounted display

(HMD) while walking tend to physically drift in the direction they are heading within the virtual environment. This drift was formally documented for the first time, and measures to assess this phenomenon were proposed. It was found that both gestures involving subtle or no leg movement significantly reduces the amount of user drift. The third study explored different types of feedback for minimizing users' drift during WIP locomotion. The results suggested that passive haptic feedback in the form of a circular carpet was the most effective at reducing user drift, and this type of feedback was perceived as the most helpful and least disrupting.

The final seven studies related to the perception of virtual speeds during WIP locomotion. It was demonstrated that WIP locomotion is accompanied by a perceptual distortion similar to the one occurring during treadmill-mediated virtual walking. Specifically, it was found that individuals tend to underestimate visually presented walking speeds during WIP locomotion; i.e., they tend to find realistic walking speeds too slow. Moreover, it was found that there appear to exist a range of speeds that are perceived as natural while walking in place at a given step frequency. Four studies exploring the influence of visual display properties found that both the size of the display field of view and the size of the geometric field of view were inversely proportional to the degree of underestimation, but no significant effects were found for increased HMD weight or varying degrees of peripheral occlusion. Another study found that high step frequencies may be accompanied by an increased underestimation of the visually presented walking speeds during treadmill and WIP locomotion. The two meta-analyses suggested that individuals tend to find slightly higher speeds natural when walking on a treadmill compared to when they are walking in place. Finally, a study revealed that methodological differences may influence what speeds the walker perceives as natural.

Hopefully the contributions documented in this thesis will help bring WIP locomotion one step closer to facilitating perceptually natural walking experiences.

Resumé

Nylige teknologiske fremskridt vil muligvis snart medføre, at immerive virtual reality (IVR) vil blive tilgængelig for brugere. Dette vil bevirke, at IVR systemer bliver taget i brug i omgivelser, hvor der er meget begrænset plads til at interagere med teknologien. Hvis brugerne ønsker at bevæge sig rundt i de virtuelle verdener til fods, er den pladsmæssige begrænsning et problem, da den ikke tillader reel gang. Walking-in-Place (WIP) teknikker udgør en praktisk og billig måde at muliggøre gang i virtuelle verdener. Brugeren går på stedet uden fysisk at bevæge sig fremad og genererer på den måde bevægelse i den virtuelle verden. Der er dog behov for mere research, hvis WIP skal blive en meningsfuld tilgang til virtuel gang i omgivelser med begrænset plads.

Denne afhandling fokuserer på undersøgelser af de faktorer, der påvirker, i hvor høj grad en bruger finder WIP teknikker naturlige, dvs. de faktorer der er med til at bestemme, om brugerens oplevelse af at gå på stedet føles ligesom reel gang. Der tages afsæt i graden af overensstemmelse mellem brugerens sensoriske og motoriske oplevelse af gang på stedet og virkelig gang og undersøges, hvordan det vil være muligt at støtte handlinger og virtuelle hastigheder, så de føles naturlige. De primære bidrag er resultaterne af ti studies og to meta-analyser, som er dokumenteret i de syv vedlagte artikler, der udgør hovedparten af afhandlingen.

De første to studier undersøger alternative former for gestikulatorisk input til WIP teknikker og indikerer, at input, som involverer mere subtile benbevægelser, bliver opfattet som mere naturligt, muligvis fordi dette input stemmer bedre overens med de fysiske anstrengelser, der er forbundet med reel gang. Ydermere ser det ud til, at input baseret på armbevægelser kan blive opfattet som værende lige så naturligt som det input, der traditionelt bliver brugt i forbindelse med WIP teknikker. Det skal dog bemærkes, at nytten af denne type input er begrænset, da den forhindrer brug af hænderne, mens brugeren går. Et potentielt problem forbundet med brugen af WIP teknikker sammen med et head-mounted display (HMD) er, at brugeren har en tendens til fysisk at bevæge sig fremad, når pågældende forsøger at gå på stedet. Denne uhensigtsmæssige bivirkning er formelt dokumenteret, og mulige måder at kvantificere den på, er præsenteret. Det har vist sig, at både gestikulatorisk input baseret på subtile benbevægelser og armbevægelser mindsker problemet. Det tredje studie undersøger forskellige andre måder at mindske problemet på via forskelligt feedback. Det har vist sig, at passivt haptisk feedback i form af et cirkulært tæppe er mest effektivt, og deltagerne i studiet synes, at denne type feedback er mest behjælpelig og mindst forstyrrende.

De sidste syv studier omhandler opfattelsen af virtuel fart og demonstrerer, at gang på stedet er ledsaget af en perceptuel forvrængning, der minder om den, der ledsager virtuel gang på et løbebånd. Mere specifikt har det vist sig, at folk har en tendens til at underestimere visuelle hastigheder, når de går på stedet. Med andre ord har folk en tendens til at opleve realistiske ganghastigheder som værende for langsomme. Derudover har det vist sig, at der findes en række hastigheder, som føles naturlige, når man går på stedet i en bestemt takt. Fire studier er udført med henblik på at undersøge, hvordan forskellige faktorer forbundet med visuelle displays påvirker opfattelsen af fart. Resultaterne indikerer, at en forøgelse af størrelsen på displayets field of view samt det geometriske field of view reducerer graden af underestimering af virtuelle hastigheder. Der er ingen effekt fundet i forbindelse med en forøgelse af vægten på HMD'et eller forskellige grader af afdækning af det perifere synsfelt. Endnu et studie har vist, at en øget step-frekvens muligvis medfører forøget underestimering af de virtuelle hastigheder. De to meta-analyser indikerer, at folk ved gang på et løbebånd i højere grad underestimerer virtuelle hastigheder sammenholdt med gang på stedet. Endelig viser et studie, at metodiske forskelle kan påvirke hvilke hastigheder, der opfattes som naturlige.

Forhåbentlig vil bidragene beskrevet i denne afhandling hjælpe med at gøre oplevelsen af at gå på stedet gennem virtuelle verdener endnu mere naturlig.

Preface

In the wake of Facebook's acquisition of Oculus VR, Professor Henry Fuchs gave an inspiring keynote at the 2014 IEEE Virtual Reality conference. When discussing what future this recent turn of events might lead to, he asked the audience to imagine a world with millions of virtual reality users. Incidentally, the work detailed in this thesis was largely motivated by a challenge that is likely to follow if virtual reality becomes a common household item: If these (hopefully) millions of users wish to explore virtual worlds on foot, then we need to develop inexpensive, convenient, and perceptually natural techniques for virtual travel. What follows is my contribution to the incremental development of techniques intended to address this challenge. Particularly, the thesis is based on a series of studies exploring the factors influencing the perceived naturalness of Walking-in-Place locomotion.

Thesis Roadmap

The thesis is organized into two main parts: an introduction and a collection of papers.

The introduction itself is divided into six chapters: The first chapter of the introduction opens with a few remarks on my personal motivation for working with walking in virtual environments, before presenting an overview of existing methods for virtual travel. Based on this overview, I conclude the chapter by motivating my choice of focusing on Walking-in-Place locomotion. Subsequently the chapter *Walking-in-Place Locomotion* outlines existing research on Walking-in-Place locomotion and uses this research as a basis for the argument that the perceived naturalness is worthy of more explicit attention during the development and evaluation of Walking-in-Place techniques. Since the perceived naturalness of Walking-in-Place techniques is intrinsically tied to expectations derived from our everyday experience of walking, the chapter *Perceived Naturalness of Virtual Walking* introduces the biomechanics and perception of human walking as well as the notions of interaction, display, and simulation fidelity. The chapter is concluded with a description of perceived naturalness that serves as a bridge to the following chapter that outlines the research questions forming the basis for the performed work. The two last chapters of the introduction summarize the included papers and present conclusions and potential future work.

The second part of the thesis presents a collection of seven papers that make up the bulk of the presented work. Papers A and B deal with the perceived naturalness of gestural input for Walking-in-Place techniques. Paper C details a study exploring different approaches to reducing the positional drift accompanying Walking-in-Place locomotion. Papers D, E, and F present studies documenting that users underestimate virtual walking speeds while walking in place as well as some of the factors influencing the degree of underestimation. Finally, Paper G presents two meta-analyses of the findings of the previous three papers.

Acknowledgments

First and foremost, I wish to thank my two supervisors Rolf Nordahl and Stefania Serafin. Rolf Nordahl generously made the PhD possible, and throughout the process, he has given me the freedom to pursue lines of research that I was passionate about. Stefania Serafin has helped me in more ways than I can count with everything from mundane questions about hyphenation rules to advice on how to deal with life as a PhD student and a new parent. Always accessible, always interested, and always in high spirits. Thank you!

Besides from my supervisors, there are a few people who made tangible contributions to the presented work. Morten Havmøller Laursen, Kasper Søndergaard Pedersen, and Erik Sikström helped implement the Walking-in-Place algorithm, and create the virtual environment and soundscape used for the study described in Paper A. Besides from their practical contributions, my discussions with the three also spurred ideas that eventually led to some of the performed studies. Stefano Baldan provided me with valuable advice on how to implement the gesture detection used for the studies documented in Papers B and C, and Bob Sturm commented on the manuscript that eventually became Paper D. Moreover, I wish to thank Dr. Ryan McMahan for providing me with feedback on my thoughts about the relationship between fidelity and perceived naturalness, and Thomas Wievegg for allowing me to use his artwork which I adapted for the cover image. I am grateful for the help offered by the administrative staff at Aalborg University in general and Lene Rasmussen in particular. Finally, I owe a big thanks to the many people who took part in my, sometimes painfully boring, studies.

On a personal note, I wish to thank my fellow PhD students for adding humor and “hygge” to the daily office humdrum. I am particularly thankful to Jon Ram Bruun-Pedersen for his friendship and our many cathartic discussions. I would like to express my gratitude to my parents for giving me an upbringing I can only hope to give my own children and for the sub-

tle nudges that ultimately led to me consider studying at a university. I am thankful to my Finnish family-in-law for giving me what feels like a second home up north and for making July the best month of the year, and to my friends (you know who you are) for providing welcome distractions and for understanding that life as a PhD student and a new parent does not allow for quite as much camaraderie as one would have liked. Finally, the biggest thank of all goes to Camilla and our two boys, Elliot and Vincent, for supporting me throughout the process and making every day a better one.

Niels Christian Nilsson
Copenhagen, May 26, 2015

Thesis Details

Thesis Title: Walking Without Moving: An exploration of factors influencing the perceived naturalness of Walking-in-Place techniques for locomotion in virtual environments

PhD Student: Niels Christian Nilsson

Supervisors: Assoc. Prof. Rolf Nordahl, Aalborg University
Prof. Stefania Serafin, Aalborg University

The main body of this thesis consist of the following papers.

[A] N. C. Nilsson, S. Serafin, M. H. Laursen, K. S. Pedersen, E. Sikström, and R. Nordahl, "Tapping-in-Place: Increasing the Naturalness of Immersive Walking-in-Place Locomotion Through Novel Gestural Input", *Proceedings of the 2013 IEEE Symposium on 3D User Interfaces*, pp.31–38, 2013.

[B] N. C. Nilsson, S. Serafin, and R. Nordahl, "The Perceived Naturalness of Virtual Locomotion Methods Devoid of Explicit Leg Movements", *Proceedings of 2013 ACM Motion in Games*, pp. 155–164, 2013.

[C] N. C. Nilsson, S. Serafin, and R. Nordahl, "A Comparison of Different Methods for Reducing the Unintended Positional Drift Accompanying Walking-in-Place Locomotion", *Proceedings of the 2014 IEEE Symposium on 3D User Interfaces*, pp. 103–110, 2014.

[D] N. C. Nilsson, S. Serafin, and R. Nordahl, "Establishing the Range of Perceptually Natural Visual Walking Speeds for Virtual Walking-in-Place Locomotion", *IEEE Transactions on Visualization and Computer Graphics*, vol. 20, no. 4, pp. 569–578, 2014.

[E] N. C. Nilsson, S. Serafin, and R. Nordahl, "The Effect of Visual Display Properties and Gain Presentation Mode on the Perceived Naturalness of Virtual Walking Speeds", *Proceedings of 2015 IEEE Virtual Reality*, pp. 81–88, 2015.

[F] N. C. Nilsson, S. Serafin, and R. Nordahl, "The Influence of Step Frequency on the Range of Perceptually Natural Visual Walking Speeds During Walking-in-Place and Treadmill Locomotion", *Proceedings of the 20th ACM Symposium on Virtual Reality Software and Technology*, pp. 187–190, 2014.

[G] N. C. Nilsson, S. Serafin, and R. Nordahl, "The Perceived Naturalness of Virtual Walking Speeds During WIP locomotion: Summary and Meta-Analyses", *PsychNology*.

In addition to the main papers, the following publications have been made.

[1] N. C. Nilsson, S. Serafin, and R. Nordahl, "The Effect of Head Mounted Display Weight and Locomotion Method on the Perceived Naturalness of Virtual Walking Speeds", *Proceedings of 2015 IEEE Virtual Reality*, pp. 249–250, 2015.

[2] N. C. Nilsson, S. Serafin, and R. Nordahl, "A Comparison of Four Different Approaches to Reducing Unintended Positional Drift During Walking-in-Place Locomotion", *Proceedings of 2014 IEEE Virtual Reality*, pp. 101–102, 2014.

[3] R. Nordahl and N. C. Nilsson, "The Sound of Being There: Presence and Interactive Audio in Immersive Virtual Reality", *The Oxford Handbook of Interactive Audio*, Oxford University Press, 2014.

[4] E. Sikström, N. C. Nilsson, R. Nordahl, and S. Serafin," Preliminary Investigation of Self-Reported Emotional Responses to Approaching and Receding Footstep Sounds in a Virtual Reality Context", *Audio Engineering Society Conference: 49th International Conference: Audio for Games*, 2013.

[5] E. Sikström, N. C. Nilsson, R. Nordahl, A. De Götzen, and S. Serafin, "Perceived Spatial Positioning of Self-footstep Sounds in Three Surround Sound Speaker Setups for Immersive Virtual Reality", *Proceedings of the 10th International Symposium on Computer Music Multidisciplinary Research*, pp. 1004–1016, 2013.

[6] N. C. Nilsson, S. Serafin, and R. Nordahl, "Unintended Positional Drift and Its Potential Solutions", *Proceedings of 2013 IEEE Virtual Reality*, pp. 121–122, 2013.

[7] S. Serafin, N. C. Nilsson and D. Skaarup, "Influence of auditory and haptic feedback on a balancing task", *International Journal of Autonomous and Adaptive Communications Systems*, vol. 6, no. 4, pp. 366–376, 2013.

[8] S. Serafin, N. C. Nilsson, E. Sikström, A. De Götzen and R. Nordahl, "Estimation of Detection Thresholds for Acoustic Based Redirected Walking Techniques", *Proceedings of 2013 IEEE Virtual Reality*, pp. 161–162, 2013.

[9] L. Turchet, N. C. Nilsson, and S. Serafin "Inside the Boundaries of the Physical World: Audio-Haptic Feedback as Support for the Navigation in Virtual Environments", *Haptics: Perception, Devices, Mobility, and Communication*, vol. 7282, pp. 577–588, 2012.

[10] N. C. Nilsson, R. Nordahl, E. Sikström, L. Turchet, and S. Serafin, "Haptically Induced Illusory Self-motion and the Influence of Context of Motion", *Haptics: Perception, Devices, Mobility, and Communication*, vol. 7282, pp. 349–360, 2012.

[11] N. C. Nilsson, R. Nordahl, L. Turchet, and S. Serafin, "Audio-Haptic Simulation of Walking on Virtual Ground Surfaces to Enhance Realism", *Haptic and Audio Interaction Design: 7th International Conference*, vol. X, no. X, pp. 61–70, 2012.

[12] N. C. Nilsson, S. Serafin, and R. Nordahl, "The Fwobble: continuous audio-haptic feedback for balance control", *Proceedings of the 2012 IEEE Symposium on 3D User Interfaces*, pp. 153–154, 2012.

[13] N. C. Nilsson, S. Serafin, and R. Nordahl, "Gameplay as a Source of Intrinsic Motivation for Individuals in Need of Ankle Training or Rehabilitation", *Presence: Teleoperators and Virtual Environments*, vol. 21, no. 1, pp. 69–84, 2012.

[14] R. Nordahl, N. C. Nilsson, L. Turchet and S. Serafin, "Vertical illusory self-motion through haptic stimulation of the feet", *Proceedings of 2012 IEEE VR Workshop on Perceptual Illusions in Virtual Environments*, pp. 21–26, 2012.

[15] R. Nordahl, S. Serafin, N. C. Nilsson, and L. Turchet, “Enhancing realism in virtual environments by simulating the audio-haptic sensation of walking on ground surfaces”, *Proceedings of 2012 IEEE Virtual Reality*, pp. 73–74, 2012.

[16] R. Nordahl, S. Serafin, L. Turchet, and N. C. Nilsson, “A multimodal architecture for simulating natural interactive walking in virtual environments”, *PsychNology*, vol. 9, no. 3, pp. 245–268, 2011.

[17] S. Serafin, L. Turchet, R. Nordahl, and N. C. Nilsson “Presence studies in multimodal augmented floors”, *Deliverable 6.1 Natural Interactive Walking (NIW) Project*, FET FP7, 2011.

[18] N. C. Nilsson, S. Serafin, and R. Nordahl, “Comparison of a Commercial and Two Low-cost Interfaces for Virtual Skiing”, *PsychNology*, vol. 13, no. 1, pp. 57–74, 2015.

This thesis has been submitted for assessment in partial fulfillment of the PhD degree. The thesis is based on the submitted or published scientific papers that are listed above. Parts of the papers are used directly or indirectly in the extended summary of the thesis. As part of the assessment, co-author statements have been made available to the assessment committee and are also available at the Faculty. The thesis is not in its present form acceptable for open publication but only in limited and closed circulation as copyright may not be ensured.

Contents

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Part I

Introduction

Background

> *"Suppose evil scientists removed your brain from your body while you slept, and set it up in a life-support system in a vat. Suppose they then set out to trick you into believing that you were not just a brain in a vat, but still up and about, engaging in a normally embodied round of activities in the real world."* [32]

Thus begins philosopher and cognitive scientist Daniel Dennett's book *Consciousness Explained* [32]. He goes on to describe that in a moment of kindness the evil scientists might choose to fool you, the disembodied brain, into believing that you just woke up on a sandy beach. For starters they hold of visual information, but flood your sensory nerves with just the right auditory and vestibular stimulation to make you feel as if you are lying down on the beach. However, once they lift the paralysis and you become free to touch the sand with your hands, the scientists are faced with the staggering challenge of making available the huge number of possible sensory experiences that may result from the different ways in which you can choose to inspect the grains of sand.

By opening his book with this tale of the brain in a vat—a contemporary alternative to Descartes's evil demon [33]—Dennett seeks to probe our intuitions about what kinds hallucinations we are susceptible to. This thesis is not about hallucinations or consciousness for that matter, but user's experience of walking within virtual environments. Thus, I chose to begin with this tale for two different, albeit not entirely unrelated, reasons.

First, I believe that many researchers and practitioners who study and develop *immersive virtual reality* (IVR) share the ambition of Dennett's evil scientists; namely, to fool users into believing that they are in some place other than the one where they are physically located. In line with the recommendation made by Frederick P. Brooks Jr. at a 2010 IEEE VR panel discussion on the nature of virtual reality [64], I use the designation IVR to describe systems relying on high fidelity tracking and displays in order to facilitate natural perception and action within a computer generated environment; i.e., IVR supports a sensorimotor loop similar to that of the real world, thus enabling users to interact and perceive as they would during unmediated experiences. The experience of "being there" in an artificial or remote environment is sometimes referred to as *telepresence* [81], *virtual presence* [111], *physical presence* [58], *spatial presence* [156], or just *presence* [119]. IVR's capacity for eliciting compelling illusions of presence was one of the primary reasons why I found myself drawn to this burgeoning medium.

Second, Dennett's version of the brain in the vat is centered on how our perception of the world and ourselves is susceptible to illusions and the efforts it requires take advantage of these propensities. Particularly, his description makes references to the haptic perception of sand. My first compelling IVR experience did not involve transportation to a beach, but I did experience an illusion of sand under my feet thanks to a pair of sandals augmented with actuators and pressure sensors [92]. I had this experience when participating in a study run in the Multisensory Experience Lab at Aalborg University Copenhagen. The lab where I for two years worked with multisensory feedback for natural interactive walking and eventually ended working on the PhD. Thus, the story of the evil scientists resonated with me in more than one way.

The dream of visiting virtual worlds, which initially spurred my interest in IVR, has been central to IVR research since its infancy. In 1965 Sutherland described the ultimate display as *"[...] a room within which the computer can control the existence of matter. A chair displayed in such a room would be good enough to sit in. Handcuffs displayed in such a room would be confining, and a bullet displayed in such a room would be fatal."* [133]. Three years later Sutherland had designed and constructed what he called a head-mounted three-dimensional display [134]. This display could not control the existence of matter, but two small CRTs allowed the wearer to observe a computer-generated environment in stereo and an elaborate mechanical setup made it possible to change the virtual viewpoint through head movements. We have yet to see a display comparable to Sutherland's ultimate display, but IVR has come a long way since he created one of the earliest head-mounted displays (HMDs). A particularly exciting prospect of recent advances within display and tracking technology is that IVR is becoming increasingly widespread and soon may become a common household item.

During our everyday lives, we routinely move about the physical environments we inhabit on foot or aided by humanly propelled or motorized vehicles. For the most part, we are able to do so with relative ease and without assigning explicit attention to the act of walking or controlling the vehicle. Thus, it seems likely that virtual travel will become a central activity for the users who (hopefully) will be able to enjoy IVR within the near future. Indeed, virtual travel is already considered to be one of the most common and universal activities occurring during users' interaction with three-dimensional (3D) computer-generated environments [12].

This thesis is focused on a specific approach to virtual travel, namely, Walking-in-Place (WIP) techniques. When relying on WIP techniques for virtual locomotion, the user performs stepping-like movements that serve as a proxy for real steps and enable movement through the virtual world while the user remains (relatively) stationary with respect to the physical environment [151]. The aim of this chapter is to answer the question *"Why focus on WIP techniques?"* by positioning this approach within the wider category of virtual travel techniques. Initially, the concept *navigation* and its constituent parts will be introduced (Section 1), then a taxonomy of virtual travel techniques is presented (Section 2), and finally the different dimensions of the taxonomy are discussed in relation to consumer IVR (Section 3).

1 Traveling Through Virtual Worlds

When discussing interaction techniques for most common 3D interaction tasks, Bowman et al. [12] highlight the importance of *navigation*; i.e., *"[...] movement in and around an environment."* [12] Particularly, the authors describe that it is possible to subdivide navigation into the two components *wayfinding* and *travel*.

Wayfinding—the cognitive component of navigation—involves higher level processes, such as path planning and decision making. Thus, wayfinding amounts to orienting oneself in the environment and determining the path to a desired location, and may rely on natural and artificial aids such as landmarks, maps and signs.

Travel—the motor component of navigation—involves lower level actions, such as controlling the orientation and position of the virtual viewpoint, and movement velocity. Examples of the travel component in the real world could be the physical acts of walking or manipulation of steering wheel and throttle of a vehicle [12]. Notably, Whitton and Razzaque [149] favor the term *locomotion* over *travel*, as the latter connote movement over greater distances. Throughout following I use the two interchangeably. While the distinction between wayfinding and travel techniques generally is useful, Bowman et al. [12] note that it is possible for an interaction technique to combine the two. This implies that the choice of travel technique may influence wayfinding and some travel techniques necessarily do a better job at supporting wayfinding than others. This thesis is concerned with how users experience the lower level actions necessary to move from one place to another within the virtual environment. Thus, the primary focus is on virtual travel.

2 A Taxonomy of Virtual Travel Techniques

Several taxonomies classifying and categorizing interaction techniques for virtual travel have been proposed. Indeed, Bowman et al. [12] describe the categorization and classification of interaction techniques as a common theme within 3D interaction research. Notably, none of these taxonomies can in isolation be considered superior because each taxonomy offers a more or less unique perspective on the space of possible travel techniques [12].

Bowman et al. [10] distinguish between techniques that are *active* (user-controlled movement), *passive* (system-controlled motion), or *route planning* (a combination of the two). Bowman et al. [12] introduce another orthogonal level of description, namely, the distinction between *physical* techniques, where viewpoint translation or rotation is accomplished through the user's physical translation or rotation, and *virtual* techniques where the virtual movement of the viewpoint happens while the user remains stationary.

Different travel techniques have also been classified based on the involved subtasks [11], level of control [10], and interaction metaphor [12]. To exemplify, Whitton and Razzaque [149] describe that virtual locomotion types may be categorized in terms of the three dominant metaphors: *Real-walking-style systems*, *Vehicle-style interfaces*, and *Magic-style interfaces*. The first two metaphors involve so-called *mundane* interaction (they imitate real-world interactions) while the latter is *magical* interaction (it does not comply with the rules that govern real-world interactions) [120, 149]. The distinction between *natural* and *magical* 3D interaction techniques have similarly been used to separate techniques intended to preserve interaction fidelity[1] from ones that are intended to increase usability and enhance performance by allowing for physically impossible interactions [14].

Different classification schemes also focus on describing the space of possible travel techniques at different levels. The description provided by Suma [131] is centered around three sub-categories of active techniques; Hollerbach's taxonomy [54] describes interfaces for user self-propulsion involving repetitive limb movement; Wendt [146] presents a taxonomy focused on walking interfaces; and finally, Steinicke et al. [123] and Suma et al. [128] present taxonomies focused on a subset of these walking techniques, namely, redirected walking techniques.

The taxonomy presented throughout the following divides existing virtual travel techniques into dichotomous categories based on three of the attributes that shape, and are shaped by, the type of application and the context where it is used. The general division into three orthogonal classifications was inspired by the taxonomy of redirected walking techniques proposed

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[1] Bowman et al. [14] define the interaction fidelity, or naturalism, of a user interface (UI) *"[...] as the objective degree with which the actions (characterized by movements, forces, or body parts in use) used for a task in the UI correspond to the actions used for that task in the real world."*

by Suma et al. [128], while the individual classifications were inspired by existing categorizations of travel techniques. The taxonomy organizes virtual travel techniques in terms of *user mobility*, *virtual movement source*, and *metaphor plausibility*. The taxonomy is illustrated in Figure 1.

User mobility simply relates to whether physical translation is required in order to perform virtual movement; i.e., whether the user is *mobile* or *stationary*. This is crucial since the size of the physical interaction space necessarily constrains the amount of movement the user can perform which in turn may limit the scenarios that can play out within the IVR. Notably, the walking interface taxonomy described by Wendt [146] relies on a similar dimension. While it is meaningful to think of this dimension as dichotomous, it is possible to map the amount of physical user movement along a continuum because techniques may require varying degrees of physical movement.

The second classification *virtual movement source* relates to whether the form of travel being simulated is *body-centric* or *vehicular*. Body-centric locomotion involves generation of movement through direct exertion of forces to the environment; i.e., when walking, swimming, or flying, forces are applied to the ground, water, or the air, respectively [57]. Contrarily, when relying on vehicular travel, the user indirectly produces movement through interaction with the interface of a vehicle [12]; i.e., when pressing the throttle and turning the steering wheel, it is the engine and steering mechanisms, not the driver, controlling the forces propelling the car in the desired direction at the desired speed. At first glance, this distinction may appear similar to the classification of manipulation techniques along a continuum ranging from indirect to direct manipulation [73]. However, the division is not dependent on how the user's real actions are mapped to their virtual counterparts. Instead the dividing line is drawn based on the type of virtual travel technique being simulated; thus making this division similar to the classification in terms of travel metaphors [12, 149].

Finally, the separation in terms of *metaphor plausibility* is adopted from Slater and Usoh [120] who use it to distinguish between different types of body-centered interaction. A travel technique is considered *magical* if it relies on a metaphor for virtual movement that is not limited by real-world constraints, such as the ones imposed by the laws of physics, biological evolution, or the current state of technological development. A technique is considered *mundane* if it relies on a metaphor adopted from real-world travel. This necessarily, implies that the travel techniques that currently qualify as magical over time may become mundane as technological strides are made and new vehicles and body augmentations become reality.

Throughout the following, I provide examples of travel techniques belonging to the eight categories of the taxonomy. Note that I, for the sake of brevity, have chosen to omit virtual travel accomplished using traditional peripherals (e.g., using a game controller as input for a racing game).

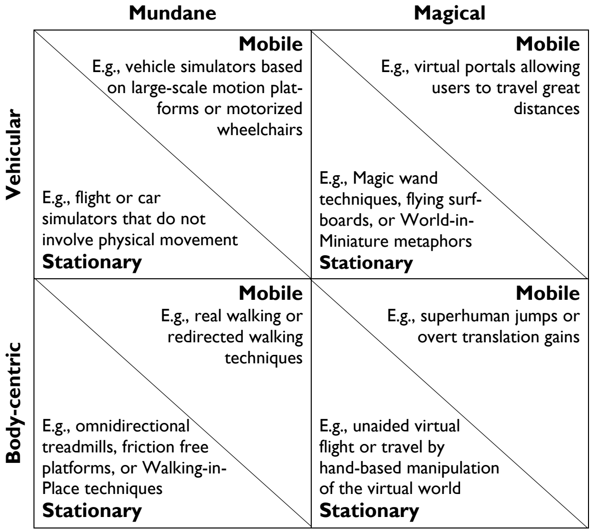

Fig. 1: Taxonomy of virtual travel techniques. The vertical axis subdivides the techniques based on the virtual movement source. The horizontal subdivides the techniques based on the metaphor plausibility. The division of each cell represents the degree of user movement relative to the physical environment.

2.1 Vehicular Techniques

Mobile mundane vehicular techniques: This category includes virtual travel techniques that enable users to travel using virtual, yet plausible, vehicles while physically moving within the interaction space. With exception of large-scale motion platforms used for advanced vehicle simulators (e.g., NASA Ames' Vertical Motion Simulator [1]), such techniques are relatively rare. Interestingly, Nybakke et al. [93, 94] used motorized wheelchairs as part of a study investigating if physical motion facilitates spatial updating.[2]

Stationary mundane vehicular techniques: There exist numerous examples of virtual travel techniques that allow stationary users to experience real-world vehicular travel. Indeed, one of the earliest multisensory systems, Heilig's *Sensorama* from 1962 [53], allowed users to passively experience the sensation of riding a motorcycle through the streets of New York [49]. This category of virtual travel techniques is central to vehicular simulation. Particularly, flight simulators have been used extensively for pilot training and certification [71]. Besides from allowing users to pilot virtual airplanes, IVR technology has been used to simulate a range of different motorized and

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[2] The process of keeping a mental record of where one is located relative to the parts of the environment that are out of view [94].

humanly propelled vehicles. Amongst other things users have been able to steer merchant ships [17], drive cars, heavy trucks, and busses [40], and pedal through virtual environments on a bicycle [22]. This category also includes leaning-based travel techniques, such as the Joyman [75], insofar as they can be viewed as virtual versions of the Segway—a self-balanced, two-wheeled vehicle that is partially controlled through leaning. Previously, it has been argued that vehicle simulators, at least in the past, provided some of the most compelling IVR experiences [17]. A likely explanation is the indirect nature of the interaction. The system has to handle neither the forces exerted by the user on the environment in order to generate movement nor provide the user with somatosensory stimulation during direct contact with the environment. Instead, the user exerts manageable forces on the interface and perceives the environment indirectly through the vehicle. Moreover, even though a stationary travel technique does not provide the user with vestibular motion cues, an illusory sensation of self-motion, also known as vection, can be induced using visual, auditory, and vibrotactile feedback [87, 106, 140].

Mobile magical vehicular techniques: When using travel techniques belonging to this category, virtual movement is achieved by means of an implausible vehicles that requires the user to physically move about the interaction space. Virtual portals are one approach that meets these requirements. The basic idea is that the user is able to enter a door somewhere in the virtual environment and exit somewhere else within the same or another environment. Steinicke, Bruder, and colleagues [122] used virtual portals to transport walking users from a transitional environment (a replica of the physical laboratory) to the virtual environment and found that it positively influenced the users' sensation of presence. The authors also applied this technique as part of the *Arch-Explore* user interface for architectural walkthroughs [20]. More recently, Freitag et al. [45] proposed an approach allowing users to position the destination portal at a visible location within the environment. In addition to facilitating virtual travel, this approach prevented users from colliding with the walls of a CAVE-like system.[3]

Stationary magical vehicular techniques: The fourth category comprises travel techniques performed indirectly through a virtual interface that does not currently exist outside virtual worlds. Since the designs of the virtual interfaces are only constrained by the imagination of their creators, the category includes a great variety of techniques.

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[3] CAVE is short for *Cave Automatic Virtual Environment*. The first CAVE system was proposed by Cruz-Neira et al. [29] and consisted of a room surrounding the user with images of the virtual world through wall, floor, and ceiling projections while ensuring a viewer-centered perspective through tracking of the user's position in the room.

Some techniques are based on metaphors that appear inspired by science fiction and fantasy. The *magic wand* technique [27] literally relies on a magical interaction metaphor. The user assumes the role of wizard that interacts with the virtual environment by casting spells that are achieved by swinging the magic wand (pointing) and chanting (voice commands). Virtual travel is commenced by pointing in a given direction and saying "fly". Notably, the magic wand technique is not the only technique that relies on a wand for interaction with the virtual environment (e.g., [16, 26, 28]). Wang and Lindeman [143] describe the *Silver Surfer* system which is a leaning-based surfboard interface that allows users to navigate virtual environments using a flying surfboard. Cirio et al. [28] introduce the *Virtual Companion*, a virtual bird that warns the user about proximity to the walls of a CAVE-like system and enables travel by pulling the user who controls the bird using virtual reins.

Other techniques are based on less familiar metaphors. To exemplify, Bowman et al. [12] describe three different techniques that they collectively refer to as *Route-Planning Techniques*. First, path drawing techniques do, as the name implies, enable users to specify the desired path by drawing it either directly on the virtual environment [56] or by drawing it on a 2D or 3D map of the environment [12]. Second, the user can similarly define the path by placing markers in the virtual environment or on a map of the environment [10]. The third type of route-planning technique described by Bowman et al. [12] involves manipulation of a virtual representation of the user; e.g., when relying on the World-in-Miniature (WIM) metaphor [127], the user might change position and orientation by moving a virtual version of herself around a miniature version of the environment.

2.2 Body-centric Techniques

Mobile mundane body-centric techniques: Body-centric locomotion does, as suggested, involve generation of virtual movement through direct exertion of forces to the environment. Bowman et al. [12] has described physical walking as *"[...] the most direct and obvious technique for traveling in a 3D world."* One of the advantages of real walking is that the physical movement produces vestibular self-motion information, which aids the walker's understanding of the size of the environment and improves spatial understanding [12]. However, in order to rely on a one-to-one mapping between real and virtual movement, the virtual environment should be smaller than the physical tracking space. Thus, in order to deploy this method safely, you either need a very large tracking space or else you will have to limit the size of the virtual world. Alternatively, you might employ one or more so-called redirection techniques; i.e., a collection of techniques that makes it possible to discretely or continuously reorient or reposition the user through overt or subtle manipulation of the stimuli used to represent the virtual world [128]. Since subtle redirection techniques are designed to be imperceptible, these allow users to walk naturally through the virtual environment without noticing the manipulation. For example, it is possible to introduce subtle mismatches between the user's physical and virtual movement (i.e., translation, rotation, or curvature gains) that will cause the user to unconsciously adjust the walking path and thereby stay within the tracked space (e.g., [18, 59, 101, 102]). An alternative to this form of subtle redirection is manipulations of the virtual architecture (e.g., changing the position of doors) that remain unnoticed by the user due to change blindness [129]. This method is necessarily limited to environments with architectural features that can be manipulated in a meaningful way [128].

Stationary mundane body-centric techniques: If we disregard abstract mappings between user actions and virtual walking (e.g., game controllers, mouse and keyboard, or techniques like *Finger Walking in Place* [68]), we are able to distinguish between at least two general approaches to facilitating walking experiences on behalf of stationary users: repositioning systems and system that take alternative gestures as input.

Repositioning systems essentially counteract the forward movement of the user and thereby ensure that the user remains at a relatively fixed position. Examples include unidirectional [42, 66, 98] and omnidirectional treadmills [31, 62, 91, 121] motorized floor tiles [60], human-sized hamster balls [79], cancellation of steps through strings [61], and friction-free platforms that prevent the forces generated during each step from moving the user forward [3, 24, 55, 63, 135, 142].

The second type of system requires the user to perform an alternative gesture serving as a proxy for actual steps. The most common approach is WIP techniques that as previously described involve the user performing stepping-like movements on the spot in order to generate virtual movement [21, 41, 118, 147]. It has also been proposed that the user might perform gestures devoid of explicit leg movement; e.g., Terziman et al. [138] proposed a technique requiring users to sway their heads from side to side in order to move within the virtual world. A type of interface that arguably lie somewhere between the two sub-categories just described is the Sarcos Uniport that was designed for infantry training and resembles a unicycle [12]. The user sits on the seat and the foot movements used to pedal serve as a proxy for real steps.

Mobile magical body-centric techniques: This category comprises techniques that allow users to travel through virtual environments using superhuman abilities that are somehow mapped to their physical movement within the interaction space. Bolte et al. [6, 7] have proposed the *Jumper Metaphor* that combines real walking with the ability to travel greater distances through superhuman jumping. To be exact, a target location is defined based on the user's viewing direction and in order to travel to that location the user physically jumps forward. Another instance of virtual superhuman travel involving physical movement is redirected walking based on noticeable translation gains [59].

Stationary magical body-centric techniques: The final category also comprises techniques that grant the user superhuman abilities to move within the virtual world; however, no physical translation is required. For example, Rosenberg et al. [109] performed a study where participants were able to control virtual flight by using their arms in a manner similar to how Superman moves about the sky. Bowman et al. [12] describe that techniques similar to the ones used for virtual manipulation also have been used to accomplish virtual travel. Particularly, they describe that the user may be able to move through the virtual world by grabbing and pulling any point in the environment—including a point in mid-air [144]. The world will move as if being manipulated, but to the user it will appear as if the virtual viewpoint is being moved. Alternatively, the user might rotate the viewpoint around a selected object in the environment using hand movements [80].

3 Walking in Room-Scale Virtual Reality

IVR has for a long time had scientific, military, and industrial applications, but high prices have made it unavailable to consumers and smaller companies and public institutions [3]. However, recent technological developments, partially fueled by a new generation of entrepreneurs and crowd-funding campaigns [82], have the potential to change this. The systems that may help bring IVR into the homes of consumers include, but are not limited to, the relatively inexpensive head-mounted display developed by Oculus VR,[4] Sony's project Morpheus,[5] and HTC's Vive headset, powered by SteamVR.[6] Considering how central virtual travel is to interaction with digital games and virtual environments in general, it is necessary to identify virtual locomotion techniques that are meaningful in relation to consumer IVR systems.

Most of the approaches to virtual travel cited throughout the previous section represent a meaningful way of enabling a user to get from one point to another within a virtual environment. Thus, the aim of the current section is not to criticize or praise the specific implementations used as examples of

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[4] www.oculusvr.com

[5] www.playstation.com

[6] htcvr.com and store.steampowered.com

the eight subcategories of the taxonomy. Instead, I contrast the more general categories of travel techniques and discuss their relevance to consumer IVR.

Regarding metaphor plausibility, there are some important differences between travel techniques that qualify as either magical or mundane. Particularly, Bowman et al. [14] describe that magic interaction techniques may be designed purposely to favor task performance and usability over the familiarity accompanying techniques that mimic real-world interactions. If you were to traverse great distances within the virtual environment, it would be much faster and less straining to get there by teleporting or walking through a virtual portal instead of walking or driving. Moreover, if you were to find your way around a complex scene, then you might be more efficient if you used a WIM technique, or if you were to closely inspect a large virtual object, then a technique that allowed you to rotate the viewpoint around the object using hand gestures might be favorable. With that being said, the familiarity of a mundane technique may in some cases have a positive influence on usability, which may include factors like learnability and memorability [108]. Moreover, the scenario itself may demand a technique based a on real-world metaphor; e.g., during virtual training or narrative experiences depicting events unfolding in a world limited by real-world constraints.

For most people, walking is the default way of getting from one point to another. Generally, this body-centric form of locomotion is effortless and largely unconscious. However, with practice the controls of a vehicle can obviously also become second nature, and consumer IVR applications based on vehicular travel has great potential, as exemplified by the anticipated immersive game *Eve: Valkyrie*[7] that invites the player to pilot spaceship and engage in dogfights. Nevertheless, walking is considered a natural and promising approach to virtual travel [126], and it seems likely that a great deal of the virtual travel taking place in the homes of future IVR users will be performed on foot.

However, one of the greatest impediments to natural walking experiences within IVR is, as suggested, the potential difference in size between virtually limitless virtual worlds and finite physical interaction spaces [132]. Redirection techniques constitute a promising solution to this problem since they preserve the vestibular motion information accompanying real walking. However, work by Steinicke et al. [123] suggests that a very large tracking space is necessary (40m×40m) in order to enable unlimited walking along a straight line in the virtual environment while being redirected along a circular arc in the real world. Moreover, recent evidence suggests that such manipulations demand additional cognitive resources, and increasing the degree of manipulation also increases the needed resources [19]. The interaction spaces available to consumers are not likely to meet the require-

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[7] www.evevalkyrie.com

ments for unconstrained virtual locomotion using redirected walking. Thus, it seems meaningful to consider travel techniques where the user mobility qualifies as stationary rather than mobile. In principle repositioning systems, such as omnidirectional treadmills, might be useful to consumers. However, most of these systems cannot be considered a feasible alternative within a foreseeable future [6]. It is worth noting that more affordable repositioning systems based on friction-free platforms have been developed (i.e., Cyberith's *Virtualizer*[8] and the *Virtuix Omni*[9]). However, while less expensive than previous omnidirectional treadmills, these solutions are not cheap,[10] and they do require the user to allocate space for a relatively large platform.

WIP techniques are an inexpensive and practical alternative that already is achievable using commercial hardware, such as Microsoft's *Kinect*[11] [130] and Nintendo's *Wii Balance Board*[12] [153]. In their current form, WIP techniques do not rival real walking in terms of simplicity, straightforwardness, and naturalness [139]. However, studies suggest that these techniques may elicit a stronger sensation of presence than techniques where users have to push a button in order to propel themselves forward [118]. Moreover, Slater et al. [117] describe that a primary advantages of their original WIP technique [115] is that the gestural input generates proprioceptive feedback similar, albeit not identical, to the one resulting from real walking. Also, Williams and colleagues [153] found that walking in place on the Wii Balance Board was as effective as physical walking in a simple spatial orienting task. Combined, these potential benefits suggest the need for finding the best possible WIP technique.

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[8] www.cyberith.com

[9] www.virtuix.com

[10] The Virtuix Omni currently sells for $699.00 (April 2015)

[11] www.microsoft.com

[12] www.nintendo.com

Walking-in-Place Locomotion

WIP techniques are, as suggested, not the only viable approach to facilitating relatively natural walking experiences when the interaction is constrained by a limited physical space, and steps in place cannot compete with real walking techniques in terms of the afforded control and naturalness. However, the convenience and cost-effectiveness of WIP techniques have been highlighted as factors making the lower levels of control and naturalness worthwhile tradeoffs [41]. The current chapter provides an overview of existing WIP techniques and the accompanying evaluations (Section 4), before introducing a relevant direction for future research on WIP locomotion (Section 5).

4 Existing WIP Techniques

Whitton and Razzaque [150] describe three essential characteristics of WIP locomotion interfaces: (1) *"Users are standing."* (2) *"Users move their feet in an up–down fashion similar to really walking."* (3) *"Users are (reasonably) stationary in the laboratory space."* Notably, it would appear that most WIP techniques take more or less the exact same gesture as input; i.e., the user alternately lifts each foot as if climbing a flight of stairs or marching on the spot. Similar user movement notwithstanding, WIP techniques have been implemented using markedly different hardware and step detection algorithms.

Generally it is possible to divide WIP techniques into two categories based on whether the steps in place are registered by a physical interface or a by some form of motion tracking system. Strictly speaking, the physical interfaces also perform primitive gesture tracking since manipulation of the physical interface is used to register that a step has been performed. However, such interfaces commonly detect discrete gait events (e.g., impacts between the feet and the ground) as opposed to proper motion tracking systems that enable continuous detection of positions or velocities of body parts.

4.1 Physical Interfaces

One physical interface detecting discrete gait events is the *Walking Pad* [8]. This interface uses 60 iron switch sensors embedded on a 45cm×45cm plexiglass surface to detect the user's steps in place. Processing of the binary values provided by the switches enables the system to detect the orientation of the user's feet when these are grounded, and based on this information, the direction of heading is determined. Bouguila et al. [8] performed a small-scale evaluation (*n=5*) of the Walking Pad where they asked participants to walk through a virtual maze. The authors report overall good performance (no collisions with the walls) and all participants reported that they found the system easy to use, but three found the size of the pad too small.

Richard et al. [104] describe a between-subjects study (*n=12*) comparing the Walking Pad with a mouse-based navigation technique. The participants were asked to walk as fast as possible through a virtual maze with a number of posters on the walls while memorizing what they encountered during the walk. Subsequently, the participants filled out a questionnaire regarding their experience of the travel technique, the number of encounter posters, and their contents. The results revealed that the participants completed the task faster when using mouse-based navigation, but the participants found WIP more intuitive and immersive,[13] and information recall was better for WIP.

Bouguila et al. [9] describe a platform that facilitates foot-based locomotion through four embedded load sensors. Notably this interface can reorient users towards a visual display since the platform also serves as a mechanical turntable. Additionally, this device is capable of simulating surface inclines and declines via three air cylinders mounted underneath the turntable. The evaluation of the interface suggested that 43 in 50 participants mastered the task of walking through the virtual maze, and from a sub-sample of 10 participants, they found that 8 were able to walk straight to the goal. However, lack of methodological details and statistical analyses make it hard to draw any reliable conclusions based on the findings.

Williams et al. [153] combined the Wii balance board, which is embedded with four pressure sensors, with an orientation sensor. Their *WIP–Wii* algorithm detects how rapidly the user applies weight to each corner of the board and translates the viewpoint accordingly. The orientation sensor is used to determine the direction of heading. Williams et al. [153] performed a within-subjects study (*n=12*) comparing this WIP technique to joystick locomotion and real walking in a simple spatial orienting task. The results suggest that WIP and walking are superior to joystick navigation in terms of both turning error, while WIP and walking performed similar in terms of both turning er-

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[13] The authors appear to be interested in some form of psychological immersion (e.g., [157, 77, 39]). However, they do not make this explicit or specify if they simply asked the participants how immersive they found the systems or if they relied on an existing questionnaire.

ror and object localization times. Similarly, Filho et al. [44] have proposed a WIP technique based on a combination of two Wii balance boards that is able to derive both the walking speed and orientation based on the data obtained from the boards. The authors do not present an evaluation of the proposed technique.

4.2 Motion Tracking

Slater et al. [115] describe one of the earliest implementations of a WIP technique, dubbed the *Virtual Treadmill*. This technique does not explicitly rely on tracking of leg movements. Instead it detects whether users are walking in place via a neural network recognizing patterns in head tracking data. Based on a personal correspondence with Slater, Feasel et al. [41] describe that the viewpoint displacement used for the original virtual treadmill was discrete rather than continuous; i.e., when the neural network registered a step, the viewpoint abruptly jumped a full step length forward. Moreover, this algorithm may have been perceived as somewhat unnatural since movement was not instigated until four steps in place were detected, and it would not terminate the movement unless no steps were detected for two full cycles.

Slater et al. [118] performed a between subjects study (*n=16*) comparing a version of this WIP technique with push-button-flight along the ground plane (the participants would point in the direction they wanted to go and click to move). The participants' sensation of presence was assessed using the original three-item Slater-Usoh-Steed (SUS) questionnaire, and the extent of their association with the virtual body was also assessed using self-reports. The results suggested that participants who experienced a strong identification with their virtual body reported stronger sensations of presence, if they had been walking in place rather than using push-button-flight.

Usoh et al. [139] performed a between-subjects study (*n=33*) relying on a similar method as the one used by Slater et al. [118]. This study included the same conditions (WIP locomotion and push-button-flight) but also included real walking. The results replicated the findings of Slater et al. [118]; i.e., the participants reported experiencing a stronger sensation of presence during WIP than push-button-flight. Moreover, the results indicated that real walking elicited the highest sensations of presence.

Whitton et al. [152] performed a within-subjects study (*n=32*) that also involved a WIP technique relying on detection of head movement tracked using an accelerometer. The study compared five conditions: three conditions where the user wore a HMD (WIP, joystick, and real walking) and two where the user did not (real walking with natural vision and real walking with restricted field of view[14] [FOV]). The participants walked through a

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[14] In regards to vision, field of view refers to *"[...] the angular extent of the observable world that is visible from a particular point in a single direction."* [25]

simple maze where they encountered five targets on the walls that they had to approach and stop once they were as close as possible. The authors employed three motion path measures, three measures of task performance, and self-reported measures of perceived performance. The results indicated variation in the performance between locomotion techniques; i.e., the motions pertaining to WIP and joystick did not correspond to those of real walking. However, the authors note that the poor results pertaining to the WIP technique may in part be ascribed to less-than-optimal detection of steps.

Feasel et al. [41] describe a technique referred to as *Low-Latency, Continuous-Motion Walking-in-Place* (LLCM-WIP). This technique controls the viewpoint displacement based on the speed of the user's vertical heel movement and promises low starting and stopping latency, smooth motion between steps, within-step control of the speed, and turning on the spot without erroneous forward movement. The authors present two types of evaluations of the system: technical evaluations of the systems performance and a usability study. The technical evaluation (*n=5*) quantified performance in terms of starting and stopping latency and the effectiveness of virtual-locomotion-drift suppression. The results suggested that the longest starting latencies were present during slow-paced walking, but no difference was found in terms of stopping latency, and a mean virtual-locomotion-drift of 3 cm was identified. The within-subjects usability study (*n=8*) compared five conditions: real walking (no HMD), real walking (no HMD, restricted FOV), real walking (with HMD), WIP (with HMD), and joystick (with HMD). The participants traveled through a maze while hiding behind shelter to avoid incoming fire. Their performance was assessed based on time required to train to competence, time in safe-zones, and length of head trajectories during gunfire. The results indicated that the participants' performance did not vary considerably across the WIP and joystick condition, but they were better during the three real walking conditions.

Wendt et al. [147] have proposed the *Gait-Understanding-Driven Walking-in-Place* (GUD WIP). This technique similarly takes the vertical speed of the heel as an input. However, it sets itself apart from its predecessors in that it is informed by gait principles and thereby produces walking speeds that correspond better with those of real walking. To be exact, the virtual velocity is controlled by a biomechanics-inspired state machine that can estimate the step frequency multiple times during each step. Moreover the technique relies on a biomechanics-inspired method for estimating the walking velocity. Wendt et al. [147] describe a within-subjects study (*n=8*) comparing GUD-WIP, LLCM-WIP, and real walking. The participants were asked to walk in sync with a metronome at four different step frequencies for both real walking and stepping in place. They did so with an unobstructed view of the real world. The results showed that the speeds generated from both real walking and GUD-WIP were consistent with changing step frequencies.

Moreover, GUD-WIP produced output speeds that were smoother and had a higher step-frequency-to-walk-speed consistency than LLCM-WIP.

Bruno et al. [21] developed a WIP technique called *Speed-Amplitude-Supported Walking-in-Place* (SAS-WIP) that enables users to control the virtual walking speed using footstep amplitudes registered using an optical motion capture system. The authors performed informal observations of participants (*n=N/A*) who were asked to represent slow, moderate, and fast virtual walking speeds using the height of their steps while walking in place. The observations suggested that foot height and vertical speed might be the most important metrics for controlling virtual speeds during WIP locomotion. Moreover, Bruno et al. [21] ran a formal exploratory study (*n=5*) requiring the participants to perform a similar task while their foot movement was recorded using an optical motion capture system. The results indicated that the participants expected footstep amplitudes to influence virtual walking speeds. The detected amplitudes informed the design of the SAS-WIP technique. Finally, Bruno et al. [21] performed a within-subjects study (*n=20*) comparing SAS-WIP with GUD-WIP. For each WIP technique, the participants were asked to walk as fast as they could along nine paths with different distances while stopping at predefined target locations. WIP technique performance was measured based on effectiveness (target overshoot frequency), precision (distance between stopping and target location), efficiency (number of steps), and mean speed. Questionnaires were used to evaluate each technique based on the factors fun, ease of use, fatigue, precision of control, naturalness, and global appreciation. The results indicated that for long distances SAS-WIP was more efficient and faster than GUD-WIP and for short distances SAS-WIP was more effective and precise. The subjective measures suggested that the participants preferred SAS-WIP and found this technique less strenuous, more fun, and easier to control.

Kim et al. [69] have proposed a technique dubbed *Sensor-Fusion Walking-in-Place* (SF-WIP), which relies on the acceleration and magnetic sensors embedded within two smart phones in combination with a magnet to produce WIP locomotion from any walking-like movement performed by stationary users. In order to test the validity of their approach, Kim et al. [69] performed an evaluation (*n=N/A*) of three different sensor-based approaches: an acceleration sensor, a magnetic sensor, and sensor-fusion. The participants walked along a path divided into three sections where they had to walk at three different step frequencies resulting in slow, normal, or fast speeds. The results indicated that the sensor-fusion based technique could detect varying walking speeds with low starting and stopping latencies.

Wilson et al. [155] describe another WIP technique based on commercially available hardware, namely, Microsoft's Kinect (*WIP–K*). Particularly, the authors combined the skeletal data from two Microsoft Kinects in order to avoid potential occlusion problems. The authors performed a within-subjects study (*n=12*) comparing WIP-Kx2 (two Kinects), WIP-K (one Kinect), and with joystick-controlled virtual translation. The study task required the participants to learn the positions of six virtual objects placed within a 50m×50m open virtual environment and subsequently identify the location of the objects by facing them. From this task, turning errors and object localization times were derived. The results indicated that WIP-Kx2 did not perform better than the other conditions. Nevertheless, the authors describe that the result were consistent with previous work by Williams et al. [153] (see subsection 4.1); i.e., in regards to spatial orientation, WIP locomotion was superior to the joystick condition.

4.3 Backward and Lateral Virtual Movement

Many WIP techniques have been focused on enabling forward virtual movement. However, exceptions do exist. Zielinski et al. [160] proposed *Shadow Walking*—a WIP technique that also facilitates lateral movement through the virtual environment. This technique used a camera to track the shadows cast by the users' feet onto the floor of an under-floor projection system within a six-sided CAVE. While the gesture used for forward locomotion seemingly correspond to the one commonly used for WIP techniques, sidestepping is achieved through a pinch gesture similar to the one used with touch screen devices. Zielinski et al. [160] do not present a formal evaluation, but based on their own experience, they report that the technique appear easy to use and natural. Moreover, the authors compared the tracking data from their system with the data of an Intersense IS-900 head tracker and report the mean ground-plane location error and the mean yaw error.

An early approach to WIP locomotion proposed by Templeman et al. [136] (the *Gaiter*) allowed both forward, backward, lateral, and diagonal movement. Gaiter allows the user to control the movement through different gestures tracked using a combination of force sensors embedded in shoe insoles and magnetic [136], or optical motion [112, 137] capture. Thus, this technique relied on a combination of a wearable physical interface and motion tracking. Particularly, the user's knee movements were tracked, and the foot-ground contact was used to separate knee movements occurring during steps from movements occurring while the feet were grounded as well as detection of knee positions when a step begins or ends. Forward movement was performed by walking in place (the knees were swung forward and then backward). Lateral movement was accomplished by changing the movement of one leg; e.g., in order to perform rightward movement, the user swung the right leg to the right and back. Backward movement was performed either by bending the knees and swinging the feet backward and then forward, or by swinging the whole leg backward. Forward or backward diagonal movement was performed by rocking the knees or feet diagonally.

Sibert et al. [112] performed an evaluation of the Gaiter (*n=10*) where the participants were asked to walk along different paths marked on the floor of a virtual building, and perform rotations while either wearing the HMD or not. The participants were wearing a harness during the walks that helped prevent them from drifting forward while walking in place. The performance of the participants was assessed based on accuracy (the ability to stop and stay on the path), rate of movement (virtual velocity), and rotation error. Simulator sickness was measure using the *Simulator Sickness Questionnaire* (SSQ) [67], and the participants' sensation the presence was assessed using the *Presence Questionnaire* (PQ) [157]. Based on the results pertaining to performance, the authors conclude that the Gaiter allowed participants to complete the walks in a controlled manner as they would during real walking. Moreover, it was observed that the harness interfered with the participants' ability to perform the gestures. Simulator sickness was relatively low and the PQ yielded mediocre scores suggesting room for improvement.

Moreover, Templeman et al. [137] performed a between-subjects study (*n=24*) comparing the Gaiter to two joystick conditions (rifle-mounted joystick and desktop joystick). The study involved three different path integration tasks: pointing to the starting location after walking through a maze, walking to the position of visual targets that were no longer visible, and turning for a predefined number of degrees without visuals being displayed. Based on the results, Templeman et al. [137] concluded that the participants perform well using the desktop joystick when visual cues are presented, but when visuals are omitted, proprioceptive and kinesthetic feedback may positively influence performance.

4.4 Steering During WIP Locomotion

By involving the whole body during turns, the user is supplied with additional proprioceptive and kinesthetic feedback which, according the study performed by to Templeman et al. [137], may provide an advantage on blind rotation tasks. However, there exist more than one way of mapping physical turns to the user's movement during virtual steering.[15]

Williams et al. [154] describe that WIP techniques may rely on at least two body parts for determining the walking direction. Gaze-directed steering involves translation of the user in the direction they are looking which prevents the user from looking around the environment while walking [153]. Alternatively, torso-directed steering allows the user to define the walking direction using the orientation of the torso [41]. While this permits the user to orient themselves while walking, Williams et al. [154] speculate that this might be disorienting. In order to compare the two approaches, Williams

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[15] In relation to virtual travel, *steering* refers to *"[...] continuous control of the direction of motion by the user."* [12]

et al. [154] performed a within-subjects study (*n=12*) based on an earlier version of the WIP-K technique (see subsection 4.2). The participants were tasked with learning the positions of six virtual objects placed in a 6m×6m virtual room and subsequently point to their position without seeing the objects. The participants' performance was assessed based on turning error and object localization time. The results suggested that the participants were equally fast when using the two steering techniques, but gaze-directed steering led to the lowest mean angular error and this type of steering was also preferred by the participants.

Razzaque et al. [100] tackle another problem related to steering within virtual environments. When relying on a CAVE-like system with a missing back wall, the user's field of regard[16] (FOR) is limited. Thus, if a WIP technique is used for virtual locomotion, then the user cannot steer using full body turns without facing the empty back wall. In order to circumvent this problem Razzaque et al. [100] have proposed *Redirected Walking Walking-in-Place* (RWP). The technique ensured that the user always faced the back wall by subtly rotating the virtual world around the user. The amount of rotation was dependent on whether the user was stationary, walking in place, or turning. Razzaque et al. [100] performed a between-subjects study (*n=28*) comparing the redirection-based turning afforded RWP with manual turning using a hand-controller. The participants were asked to find and read four signs within a virtual environment and then revisit them in alphabetical order. The authors measured how often the participants saw the back wall (it came within 40° FOV of the participants), the amount of head and torso rotation, and the amount of physical movement within the CAVE. Additionally, self-reported measures of presence and simulator sickness were used, and the participants were asked to report if they noticed the room rotating. The results revealed that RWP did not reduce the frequency of looks towards the back wall and the participants more frequently noticed that the world was rotating when using RWP. Moreover, the results suggested that noticing the back wall was associated with a decreased sensation of presence. The two conditions did not differ in terms of simulator sickness.

4.5 Alternative Gestural Input for In-Place Locomotion

While most WIP techniques rely on the same gesture for generating forward movement, alternative types of gestural input has been proposed. For example, both the Gaiter technique [136] and Shadow Walking [160] allow the user to perform alternative gestures in order to generate virtual movement in other directions than forward (see subsection 4.3). Techniques that do not rely on explicit leg movements do not qualify as WIP techniques in the tra-

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[16] Field of Regard refers to *"[...] the amount of the physical space surrounding the user in which visual images are displayed."* [12]

ditional sense. Nevertheless, examples of these have been included as they produce virtual motion from gestures inspired by the movements performed during real walking.

Terziman et al. [138] proposed an alternative technique named *Shake-Your-Head* (SYH). When using this technique, the user performed explicit head gestures such as lateral head oscillation for walking and vertical head movement for jumping. An interesting implication of this is that the technique also can be used by seated users. Terziman et al. [138] performed a within-subjects study ($n=12$) involving four conditions: (1) SYH while standing in front of a large back-projected screen. (2) SYH while seated in front of a laptop monitor. (3) Joystick controls while standing in front of the back-projected screen. (4) Keyboard controls while seated in front of the laptop monitor. The participants had to navigate through a series of gates, and the four conditions were compared in terms of task completion time, percentage of cleared gates and the participants' subjective experience of fun, easiness of use, intuitiveness, accuracy, presence, walking realism, fatigue, cybersickness, and global appreciation. The results suggested that while seated SYH required a short learning period in order to outperform the keyboard. The participants found the joystick and keyboard easier to use, more precise, and less tiring. However, SYH led to higher ratings in terms of fun, global appreciation, presence, and walking realism.

Unlike much of the reviewed work, Figueiredo et al. [43] did not evaluate a high-fidelity prototype of a novel WIP technique. Instead, they ran a study ($n = 10$) aimed at exploring the space of possible gestures for virtual navigation through participatory design; i.e., the participants were asked to both evaluate existing and propose new gestures for forward, backward, and lateral virtual locomotion. The participants were asked to navigate along a predefined path in a virtual environment displayed using a projector, and the gestures were translated into virtual movement using the *Wizard of Oz* method.[17] The performance of the gestures was evaluated in terms of task completion time and path precision, and the participants were asked to rate each gesture in terms of accuracy, velocity, ease of use, sensation of walking, tiredness, enjoyment, sense of security, and screen view obstruction. The authors present results pertaining to six gestures: *Hand as Joystick* (the user indicated the direction of movement as if holding an invisible joystick); *Equilibrium* (the user changed the direction of movement by changing the center of gravity and turned by rotating the shoulders); *Taxi Driver* (the user pointed in order to indicate the direction of movement and an open hand terminated the movement); *Supermarket Cart* (movement was performed by stretching the arms forward as if pushing a shopping cart, turns were performed by

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[17] When using the Wizard of Oz method, the user interacts with a system with limited functionality while another person simulates the missing functionality, thus creating the illusion that system is functional [108].

retracting one arm slightly during movement and completely while stationary); *Thumb-based* (movement was controlled by using the thumb to touch the leftmost (left turn) middle (forward) and rightmost (right turn) phalanges of the index finger); and *Tapping-in-Place* (the user alternately tapped each heel against the ground in order to move and right and leftward head rotations were used to turn). Tapping-in-Place, which was the only WIP technique, served as a control and was inspired by the work described in Paper A. The recorded paths through the virtual environment indicated that the users were the most precise when using Equilibrium and Thumb-based movement, while Supermarket Cart and Tapping-in-Place appeared harder to control. Tapping-in-Place did on average lead to the fastest completion times, the lowest perceived physical effort, and scored the highest in regards to walking sensation together with Equilibrium. Based on the quantitative data and semi-structured interviews, the authors highlight Thumb-Finger and Taxi Driver as being the most promising.

The novelty of applying the Wizard of Oz method in relation to virtual travel is notable and the findings are also interesting in their own right. With that being said, a necessary limitation of the study, besides from the lack of statistical analyses, is that the gestures used for steering are confounded with the ones used for velocity control. Thus, the findings are not generalizable beyond the specific tasks and gesture-sets. Notably, confounding factors are a common limitation of practical fidelity evaluations involving comparisons of systems that differ drastically from each other [78]. Moreover, since the study involved a screen-based virtual environment, the findings need not apply when users are wearing a HMD affording a larger FOR.

5 A Direction for Future Research

The majority of the work cited throughout the previous section involves descriptions of implementations, and often evaluations, of novel WIP techniques. The novelty of the individual techniques often derives from the particular hardware or algorithms used to enable virtual movement, and the evaluations usually involve comparisons with existing WIP techniques or approaches to virtual locomotion. In order to provide a general impression of what has been the focus of the presented evaluations, Table 1 presents a simplistic categorization of the measures employed in the reviewed studies. Particularly, the measures have been organized into three objective measures and seven subjective measures. The categories of objective measures are: *system performance* (e.g., starting and stopping latency [41]); *task performance* (e.g., turning error and object localization times [153]); and *user behavior* (e.g., foot movement characteristics [21], behavioral correlates of presence [139], or degree of verisimilitude between real and virtual behavior [152]). The categories

Table 1: Simplistic overview of the objective (O) and subjective (S) measures used in the reviewed studies (Section 4).

Author(s)	WIP Technique	System performance (O)	Task performance (O)	User behaviour (O)	Usability (S)	Presence (S)	Naturalness (S)	Simulator sickness (S)	Fatigue (S)	Enjoyment (S)	Other (S)
Bouguila et al. [8]	Walking Pad		x		x						
Bouguila et al. [9]	N/A		x		x						
Bruno et al. [21]	SAS-WIP		x	x	x		x		x	x	x
Feasel et al [41]	LLCM-WIP	x	x								x
Figueiredo et al. [43]	N/A		x		x		x		x	x	x
Razzaque et al. [100]	RWP			x		x		x			
Richard et al. [104]	Walking Pad		x		x						x
Sibert et al. [112]	Gaiter		x			x		x			
Slater et al. [118]	Virtual Treadmill			x	x	x	x	x			x
Templeman et al. [137]	Gaiter		x								
Terziman et al. [138]	SYH		x		x	x	x	x	x	x	x
Usoh et al. [139]	Virtual Treadmill			x	x	x	x				
Wendt et al. [147]	GUD-WIP	x									
Whitton et al. [152]	N/A		x	x	x						x
Williams et al. [153]	WIP–Wii		x								
Williams et al. [154]	WIP-K		x								x
Wilson et al. [155]	WIP–K		x								x
Zielinski et al. [160]	Shadow Walking	x									

of subjective measures are: *usability* (e.g., ease-of-use [21], intuitiveness [104], and perceived performance [9]); *presence* (e.g., the SUS questionnaire [118]); *naturalness* (e.g., self-reported measures of walking realism [138], walking sensation [43] and naturalness [21]); *simulator sickness* (e.g., the SSQ [67]); *fatigue* (self-reported measures of perceived exertion [21]); *enjoyment* (self-reported measures asking about positively valenced affect [43, 138]); and *other* (other self-reported measures that were used in less than three of the cited studies).

A common thread through many of the presented studies is that they are concerned with how WIP techniques influence the user's perceived and actual performance on various tasks. The focus on usability is apparent from the large number of studies involving objective measures of task performance and self-reported measures pertaining to usability. This hardly comes as a surprise considering that virtual travel more often than not will be secondary to some other task, such as exploration, search, or maneuvering. Thus, the usability of travel techniques is essential in order to allow the user to focus cognitive resources elsewhere [12]. This need for a high level of usability is also reflected in the objective measures of system performance related to starting and stopping latency. Notably, Whitton and Peck's [151] description of the primary technical challenge in WIP systems also seem to reflect this need. The authors describe that it is central to provide users with the ability to control virtual velocities in a manner that is both responsive and smooth. Naturally, the distinction between the factors that positively influences usability and naturalness is not always an easy one to make; e.g., if a system is able to reduce stopping and starting latencies to a point where they are indistinguishable from those experienced during real walking, then this will arguably contribute to the WIP technique being perceived as more natural.

Indeed, aside from usability, self-reported measures of presence and naturalness were used repeatedly in the described studies. Again this is to be expected since it is a goal in its own right to ensure a compelling illusion of "being there" in the virtual environment. Since WIP techniques from the outset are meant as an alternative to real walking, it is meaningful that researchers have been interested in knowing if their novel WIP techniques actually were perceived as natural. An important caveat is that the cited authors rarely make it clear what they mean by naturalness,[18] or if they ensured that the participants had a consistent view of what it means for interaction to be perceived as natural. Nevertheless, I grouped measures of naturalness with measures of walking realism and walking sensation since naturalness often is viewed as an expression for the degree of correspondence between real and virtual actions [14, 78, 113]. Despite the use of naturalness as a (possibly ambiguous) metric for evaluating novel implementations of WIP techniques, it would appear that little work has explicitly addressed how to make WIP locomotion feel even more like the real thing.

In the opening paragraph of this chapter, it was mentioned that the convenience and cost-effectiveness of WIP techniques might make the lower levels of control and naturalness worthwhile tradeoffs [41]. Addressing the technical challenge highlighted by Whitton and Peck [151] will help bring the level of control closer to that of real walking. This thesis is motivated by a different, albeit connected, challenge; namely, the challenge of uncovering the factors that influence the perceived naturalness of WIP locomotion and thereby help bring the experience of WIP locomotion a bit closer to the experience of real walking.

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[18] In relation to gestural interaction, the notion "natural" has also been used rather ambiguously to mean intuitive, easy to use, or easy to learn [96], which necessarily makes it hard to draw the distinction between the experience of usability and naturalness in the sense that it is advocated here.

Perceived Naturalness of Virtual Walking

I concluded the previous chapter by arguing that, even though "naturalness" has been used repeatedly as a (sometimes ambiguous) metric when evaluating WIP techniques, it is worthy of more explicit attention. Particularly, I am advocating that it is worth assigning explicit attention to the degree of perceived naturalness of virtual walking experiences; i.e., the extent to which the user's experience of walking through a virtual environment using a particular locomotion technique is mistakable for the experience of real walking. Natural interaction and the accompanying experience of perceived naturalness will be the subject of this chapter which is divided into three sections: Initially, Section 6 introduces the perception and biomechanics of human walking—the activity WIP techniques serve as a proxy for. Subsequently, Section 7 introduces the notions of interaction, display, and simulation fidelity that can be used to describe the extent to which a system is able to produce sensory stimuli and afford interactions equivalent to their real-world counterparts. Finally, Section 8 elaborates on the notion perceived naturalness and describes how it relates interaction, display, and simulation fidelity.

6 Human Walking at a Glance

In the foreword to the book *Human Walking in Virtual Environments* [126], Steinicke et al. describe that human walking can be seen as serving two primary purposes: *"[...] those of movement and of sensory awareness, i.e., of action and perception"* [125]. This section briefly outlines the biomechanics involved in the act of walking and the ways in which the perceptual system informs the walker about the environment and the act of walking itself.

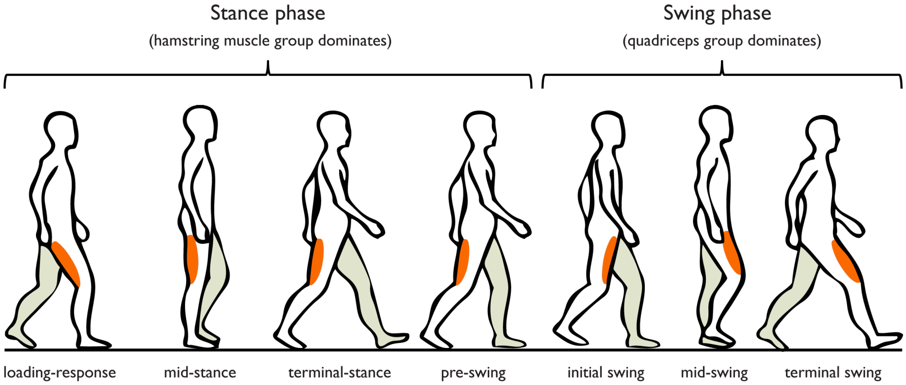

Fig. 2: Illustration of the two general phases of the gait cycle. The dominant muscle groups are highlighted with orange.

6.1 Biomechanics of Walking

We are generally able to describe the act of walking in terms of repeated gait cycles—the period from initial contact of one foot until the same foot makes contact again. Each gait cycle is normally divided into the two phases: the stance phase (loading response, midstance, terminal stance, and preswing) and the swing phase (initial swing, midswing, and terminal swing) [97]. Multin and Olivier [84] similarly describe walking in terms of strides (the interval between two consecutive heel contacts with one foot). For each stride, the contact phase and the swing phase makes up 60% and 40% of the time, respectively. The double-support phase (the time both feet are grounded) takes up 20% of the total stride time. Increases in speed change the relationship between the duration of the contact and swing phases changes; i.e., as the speed increases the duration of the contact phase decreases. At the point of the walk-run transition, the contact phases makes up 50% and the double-support phase disappears [84]. Walking velocity ($|v|$) can generally be expressed as the product of step frequency (f) and step length (l) [158]:

$$|v| = f \times l \tag{1}$$

During real walking the velocity is increased by jointly increasing the step length and step frequency, and the walk ratio (l/f) is invariant over a wide range of walking speeds [84]. Notably, while walking on a treadmill, a continuous increase in speed will cause the walker to initially increase the step length before increasing the step frequency. Moreover, the walk ratio generally tend to be lower during treadmill walking; i.e., shorter and more frequent steps [37].

The act of walking is sometimes described as controlled falling [72]. Dynamic stability is achieved through a combination of support forces, momentum and inertial forces, and energy is conserved by taking advantage of the forward kinetic energy and the gravitational potential energy of the center of body mass. During the initial phase this moment is primarily provided by the quadriceps muscle group (located on the anterior of the thigh), whereas the terminal phase is dominated by the hamstring group (located on the posterior of the thigh) [5]. Figure 2 illustrates the two general phases of the gait cycle and the dominant muscle groups are highlighted with orange.

Human biomechanics may inform the design of WIP techniques in at least two ways: On the one hand, WIP algorithms may use information about gait characteristics when translating steps in place into virtual walking speeds (the GUD-WIP technique [147] described in Section 4 is a good example of this). On the other hand, information about exertion or time spent in each phase of the gait cycle may be used to refine the gestures for WIP locomotion (Section 7 addresses an approach to objectively describing the degree of correspondence between gestural input and real walking).

6.2 Perception of Walking

Walking is an inherently multisensory activity in that several sources of sensory information become intertwined by experience [35]. These sources of perceptual information include optic flow [48], acoustic flow [110], proprioceptive feedback [51], and vestibular stimulation [52]. While walking our senses provides us with information about at least two things: the environment we are navigating through and the act of walking itself, including, but not limited to, information about our biomechanical movement and the current walking speed. Waller and Hodgson [141] presents a discussion of the sources that supply individuals with sensory information about their place in the environment and distinguish between three *external* (visual, auditory, and somatosensory) and two *internal* (vestibular and kinesthetic) sources.

External sensory information:

Waller and Hodgson [141] describe vision as a *"[...] direct, rich, and precise source of spatial information"*, which even from a stationary vantage point provides the spectator with detailed information about the spatial properties of the environment. However, vision is also crucial to how we perceive our surroundings while walking. Particularly, optic flow[19] helps inform the walker about translational and rotational movement in the environment. Radial optic flow patterns may be indicative of forward motion (expanding flow fields) or backward motion (contracting flow fields), and laminar flow patterns across

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[19] Based on work by Gibson [47], Warren et al. describe optic flow as *"[...] the pattern of visual motion at the moving eye."*[145]

the retina may suggest rotational or sidewards movement. The exact interpretation of optic flow patterns may vary depending on gaze direction and head orientation.

While, vision is the modality that has been researched the most extensively, other external senses may also provide walkers with information about their surroundings [141]. Waller and Hodgson [141] note that audition may help provide information about the scale of the environment and enables localization of objects and events in the environment—provided that they emit sounds of course. Moreover, sound sources moving relative to the listener may also influence the sensation of motion, as apparent from research on auditory self-motion illusions [140]. In a review of the literature on this form of illusions, Väljamäe [140] describe that the three primary cues for discrimination of auditory motion are binaural cues, the Doppler effect, and sound intensity. Briefly put, binaural cues inform the listener about spatial positions of auditory objects through interaural time and level differences at listener's ears. The Doppler effect entails frequency shifts during relative movement between a sound source and listener, and Doppler shifts have been found to be dominant in relation to judgements about the velocity and acceleration of auditory objects. Moreover, Doppler shifts appear to be the most salient sources of information about traveled distances, together with sound intensity, when objects move at speeds below 10 m/s. In addition to dominating perception of traveled distance, intensity also influences perception through intensity changes that inform estimates of time-to-arrival and intensity peaks that indicate the point-of-closest-passage [140].

The third source of external information described by Waller and Hodgson [141] is the one generated by somatosensory pressure receptors that inform the walker about physical contact with objects on the walking path. Moreover, the points of contact with the ground may also inform the walker about acceleration.

Finally, it is conceivable that that other sensory modalities, such as the olfactory or gustatory senses, may provide spatial information. However, during everyday interactions the contribution of such senses is likely to be negligible [141].

Internal sensory information:

Waller and Hodgson [141] describe that internal sensory information originates from three sensory systems: the vestibular system, the kinesthetic/ proprioceptive system, and the somatogravity system.

The vestibular system detects the head's angular and linear acceleration and supports a number of postural and oculomotor reflexes. Moreover, it is believed to play a role in dead reckoning and spatial updating.[20] Moreover,

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[20] Both dead reckoning and spatial updating relate to how an individuals, or animals, orient

vestibular stimulation is also believed to influence self-motion illusions. To be exact, the absence of vestibular stimulation is believed to delay the onset of self-motion illusions [106]; i.e., a stationary perceiver will not experience the illusion right away because there is a mismatch between the artificial stimuli suggesting self-motion and the contradictory signals from the vestibular system.

The kinesthetic/proprioceptive system is responsible for detecting positions, orientations, and movements of musculature. Waller and Hodgson [141] distinguish between information that either is kinesthetic (*"[...] information about the movement of one's limbs or effectors"*) or proprioceptive (*"[...] information about relatively static position or attitude of the musculature"*). Following this distinction, kinesthetic information is what makes the walker able to take steps without visually confirming that the action is being performed as intended, and the proprioceptive sense is what makes an individual knowledgeable of the position of his limbs even in the absence of motion. The authors highlight that particularly proprioceptive information may increase performance in tasks such as heading estimation, turn estimation, distance estimation and spatial updating [141]. Again, it is interesting to note that self-motion illusions may be induced based purely on the leg movement. Riecke and Schulte-Pelkum [107] refer to this phenomenon as *biomechanical vection* and describe that that compelling curvilinear or circular self-motion illusions have been induced in individuals who are deprived of visual stimulation while walking on circular treadmills—the illusion has not been reliably produced using a linear treadmill. Note that I in the ensuring paragraphs and the papers presented in Part II of the thesis use the terms "kinesthetic" and "proprioceptive" interchangeably, as is often done in the literature [141].

Finally, the somatogravity system detects the direction of gravity. Waller and Hodgson [141] do not include a discussion of this system on grounds that relevant research on the topic is scarce. However, it is worth noting that the information generated by the somatogravity system may vary between real walking and WIP locomotion; i.e., the sensation of gravity's pull may vary across the act of controlled falling (walking) and stepping in place.

In addition to external and internal sensory information Waller and Hodgson [141] also discuss the influence of efferent information. The authors do not consider efferent information as "sensory" because it does not provide afferent information from the peripheral to the central nervous system. Particularly, *efference copy* is of relevance to the current discussion. Waller and Hodgson [141] describe efference copy as *"[...] a simultaneous record of the motor commands from the central nervous system to the musculature that enables*

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themselves in an environment. Dead reckoning involves the integration of cues about self-motion over time in order to locate a current position or to return to a starting position [148]. Spatial updating refers to the ability of a moving individual to mentally update the location of a target that was previously perceived from a stationary position [74].

organisms to account for the difference between external stimulation and the stimulation that arises as a consequence of their own actions." It is this knowledge of one's motor commands that makes it possible for a perceiver to determine that the laminar optic flow produced during head turns is indeed indicative of a head turn rather than the environment turning around the observer.

Since the biomechanics of stepping in place differ considerably from real walking, it seems possible that the different efference copies may influence how visual self-motion information interpreted. Indeed, when discussing travel techniques, such as WIP locomotion and omnidirectional treadmills, Waller and Hodgson [141] note that while such systems increase the involvement of efferent information, this information need not be accurate.

7 Interaction, Display, and Simulation Fidelity

When introducing immersive virtual reality in the opening paragraphs of the thesis, I described that IVR systems may be characterized as systems that allow natural perception and action within a computer-generated environment. Thus, an IVR system derives its naturalness from the ability to support a sensorimotor loop similar to the one familiar from everyday, unmediated experiences of the world. McMahan [78] similarly takes the cyclic exchange of information occurring between user and simulation as his point of departure when introducing the notions of *interaction*, *display*, and *simulation fidelity*. Paraphrasing McMahan [78] and using walking in place as an example: Initially the user performs an action (e.g., stepping in place), which is translated into data by an input device, such as a physical interface or a camera. Software is used to interpret this data and derive meaning from it (e.g., translating the timing of feet-ground impacts into a step frequency). Based on model-data and the virtual laws of physics, the simulation determines how to handle this information (e.g., a virtual speed is produced from the step frequency based on knowledge of human biomechanics, combined with information about the inclination at the user's virtual position). Finally, rendering software is used to generate the resulting effects in the virtual world that are displayed using appropriate hardware (e.g., optic flow appropriate to the walking speed displayed on a HMD). Figure 3 details McMahan's version of the user-simulation information loop.

McMahan [78] describes interaction, display, and simulation fidelity as the objective extent to which the system can faithfully reproduce real-world interactions, real-world sensory stimuli, and real-world physics, respectively. Thus, as illustrated in Figure 3, interaction fidelity is associated with the verisimilitude of the input devices and interpretation software, display fidelity is associated with the realism of the display devices and rendering software, and simulation fidelity is associated with the plausibility of the

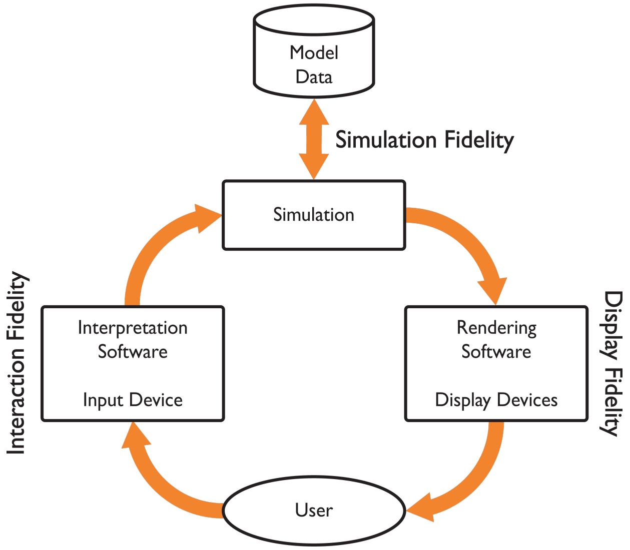

Fig. 3: McMahan's version of the user-simulation information loop. Adapted from [78] with permission from the author.

simulation and the model data.

7.1 Interaction Fidelity

Interaction fidelity, or naturalism, is an expression of the objective degree of exactness with which the physical actions performed by the user in order accomplish a task in the virtual environment are equivalent to those performed when accomplishing the same task in the real world [14]. Motivated by the difficulties involved in objectively analyzing the level of interaction fidelity, McMahan [78] proposed the so-called *Framework for Interaction Fidelity Analysis* (FIFA). FIFA essentially breaks down interaction design into the three general concepts: *biomechanical symmetry*, *control symmetry*, and *system appropriateness* which are summarized in Table 2.

To illustrate how FIFA can be used to analyze interaction within virtual environments, McMahan [78] applies the framework to real walking and three specific virtual travel techniques: (1) The omnidirectional treadmill developed by Darken et al. [31] (two sets of rollers repositions the user walking on the treadmill). (2) The *Seven League Boots* metaphor proposed by Interrante et al. [59] (the user physically walks and the forward movement is scaled to increase the virtual distance traveled for each physical step). (3) The WIP technique described by Slater et al. [118] (steps in place are detected using head tracking and a neural network).

Based on the analysis, McMahan [78] argues that Seven League Boots has

Table 2: Summary of the three concepts making up McMahan's Framework for Interaction Fidelity Analysis [78].

Biomechanical symmetry:
The degree of symmetry between actions performed during real and virtual tasks may be described by the objective extent to which the physical movements correspond across the two tasks. The movement may be described in terms of:
- *Kinematic symmetry:* The degree to which the real-body motions are reproduced.
- *Kinetic symmetry:* The degree to which internal and external forces are reproduced.
- *Anthropometric symmetry:* The degree to which the body segments used to perform the virtual action corresponds with the ones used when performing the real action.

Control symmetry:
Control symmetry describes the objective extent to which an interaction technique offers the same amount of control as when the task is performed in the real world. McMahan considers the correspondence between three aspects of control across real and virtual actions:
- *Dimensional symmetry:* The degree to which the interaction reproduces control in the same dimensions (e.g., position and orientation).
- *Transfer function symmetry:* The degree to which the translation of input data into output effects is reproduced.
- *Termination symmetry:* The degree to which a virtual action is terminated as it would be in the real world.

System appropriateness:
According to McMahan, it is possible to characterize a system based on how appropriate it is for implementing certain types of interaction based on four factors:
- *Input accuracy:* The degree to which the registered values represent the "true" values.
- *Input precision:* The degree to which the values will be the same across multiple readings under static conditions.
- *Latency:* The amount of temporal delay between the user's action and system response.
- *Form factor:* The shape and size of the input device.

high biomechanical symmetry to walking since it involves the same leg motions (kinematic symmetry), internal and external forces (kinetic symmetry), and body segments (anthropometric symmetry). The same applies for the omnidirectional treadmill, but kinematic symmetry is slightly lower due to the forces imposed by the treadmill belt. Despite having high anthropometric symmetry, the overall biomechanical symmetry of WIP locomotion is moderate since the leg motions differ from real walking (kinematic symmetry) and it does not involve shear ground forces (kinetic symmetry). Moreover, it is worth noting that WIP locomotion differs from real walking in important ways. In Section 6.1 it was described that during walking the forward kinetic energy and the gravitational potential energy of the center of body mass is used to conserve energy. However, since WIP locomotion does not involve physical translation, conservation of energy is not possible in the same way.

In regards to control symmetry, the omnidirectional is believed to resemble real walking the most since the user can control the movement in the same dimensions (dimensional symmetry), steps are translated accurately to virtual movement (transfer function symmetry), and movement is terminated as one would during real walking (termination symmetry). Both Seven League Boots and WIP locomotion arguably has relatively high control symmetry. However, they differ in terms of transfer function symmetry since the WIP technique translates steps in place into positional changes and Seven League Boots translates the user's positional changes into scaled positional changes. It would appear that McMahan [78] does not consider that the viewpoint displacement used for the specific WIP implementation was discrete rather than continuous [41]. This would imply that the translation of input data into output effects differ more considerably from real walking, thus entailing a lower degree of transfer function symmetry.

Finally, McMahan [78] analyzes the system appropriateness of the three specific implementations [31, 59, 118] and concludes that they all have moderate levels or system appropriateness since they rely on head tracking. The latency introduced by the neural network entails that the WIP technique has slightly lower system appropriateness while the omnidirectional treadmills has the lowest system appropriateness due to the latency and form factor of the treadmill belts and the harness used to maintain the user's balance.

McMahan [78] concludes that overall Seven League Boots has the highest level of interaction fidelity since it has the highest biomechanical symmetry, moderate control symmetry, and decent system appropriateness.

It should be stressed that this analysis cannot be generalized to all omnidirectional treadmills, travel techniques involving scaling of user movement, and WIP techniques. To exemplify, different implementations of WIP naturally vary in terms of system appropriateness, they may involve different starting and stopping latencies which influences control symmetry, and subtle differences in the gestures used for a WIP technique may influence biomechanical symmetry.

7.2 Display Fidelity

McMahan [78] describes the display fidelity of an IVR system as the objective degree of exactness with which the sensory displays are able to reproduce real-world sensory stimuli. Thus, while it is possible to talk about the fidelity with respect to one modality, a high level of display fidelity is contingent up the system's ability faithfully reproduce real-world stimuli in multiple modalities (e.g., visually, auditory, olfactory, gustatory, and somatically). McMahan's [78] treatment of display fidelity is focused on the verisimilitude of visual displays. Specifically, McMahan refers to a framework of visual display components proposed by Bowman and himself [13]. The list of components described by McMahan [78] is reproduced in Table 3.

While the list is not exhaustive, it illustrates that visual fidelity may be influenced by display devices and rendering software [13]. Notably, when discussing the original list of components, Bowman and McMahan [13] equate display fidelity with immersion as defined by Slater [119]. In the paper cited by Bowman and McMahan, Slater uses immersion to objectively describe

Table 3: The selection of visual display components listed by McMahan [78].

Refresh rate:	The frequency at which the visual display draws rendered data.
Frame rate:	The frequency at which the display is provided with rendered data.
Display resolution:	The amount of pixels of the visual display.
Display size:	The physical dimensions of the visual display.
Field of view:	The size of the visual field that can be viewed in one direction from a single point.
Field of regard:	The size of the visual field surrounding the user; i.e., the amount of the surroundings where visuals can be displayed.
Stereoscopy:	Presentation of two different images to each eye, depicting slightly displaced views of the virtual scene, and thereby enabling the display of binocular depth and motion cues.

the extent to which the system is able to capture the user's actions through tracking and provide multisensory stimuli in ways that that preserve fidelity. More recently Slater [114] has described that the immersiveness of a system is dependent upon the sensorimotor contingencies that it supports, that is, the range of possible actions the user can perform in order to perceive (e.g., turning one's head in order change viewing direction). Thus, it would appear that following the view advocated by Slater, the immersiveness of a system is dependent upon both the fidelity of the display devices and rendering software (display fidelity) and the fidelity of input device and interpretation software (interaction fidelity).

In relation to WIP locomotion, display fidelity seems particularly important for how users perceive virtual walking speeds. To exemplify, in relation to research on illusory self-motion, it has been described that a primary factor contributing to compelling illusions of movement is the solid angle subtended by the visual motion stimuli, i.e., the FOV [105].

7.3 Simulation Fidelity

Finally, McMahan [78] argues that it also is possible to talk about the fidelity of the simulation and associated model data; i.e., simulation fidelity refers to *"[...] the objective degree of exactness with which real-world physics and characteristics are reproduced in a simulation."* [78] Thus, the fidelity of the simulation relate to the realism of the models based on which the virtual world is generated (e.g., geometric, lighting, or physical models) [15]. Simulation fidelity is arguably relevant to at least two aspects of WIP techniques: the translation of steps in place into virtual movement and appearance of the virtual limb movement accompanying each step. Particularly, simulation fidelity might be said to be higher if external forces, such as the ones impeding when walking up hill or in strong headwind, influences the walking speeds generated by the algorithm. With respect to the control of virtual limb movement a higher degree of simulation fidelity would be achieved if the virtual legs are rendered based on models that accurately reproduce real-world attributes, such as clothing deformations and lighting.

8 Perceived Naturalness

In the opening of this chapter, I described the degree of perceived naturalness of virtual walking experience as the extent to which the user's experience of walking through a virtual environment using a particular locomotion technique is mistakable for the experience of real walking. Thus, an objective description of the verisimilitude of the user-simulation information loop (i.e., fidelity) does not account for the degree of perceived naturalness produced by a given walking technique. Instead perceived naturalness results from the user's continuous experience of this loop. I do not mean to imply that increases in interaction, display, and simulation fidelity will not be lead to increased perceived naturalness. Indeed, that will probably be the case more often than not. To use an extreme example, a user navigating a virtual environment using real walking (high interaction fidelity) should find the walking experience to be more like the real thing than a user traveling by means of a game controller (low interaction fidelity). In a recent study, employing a self-report measure of naturalness, Nabiyouni et al. [85] showed that the participants found walking in the Virtusphere significantly more natural than using a gamepad and less natural than real walking.

While it seems safe to assume that high fidelity IVR systems generally will be experienced as more perceptually natural than low fidelity systems, it is less certain whether this applies if components of interaction, display, or simulation fidelity are limited. Three examples lend themselves well to illustrate this point:

Steinicke et al. [124] describe that in order to ensure an undistorted view of the virtual environment, the *geometric field of view* (GFOV) should be set up to match the *display field of view* (DFOV) of the HMD.[21] A GFOV which is larger than the DFOV will result in *minification*; i.e., the virtual environment will appear minified since more geometry is forced into the projected image. Oppositely, if the GFOV is smaller than the DFOV less geometry will be fitted into the projected image resulting in *magnification*. Interestingly, Steinicke et al. [124] found that participants perceived some amount of minification to be more natural than the undistorted view. Moreover, the authors found that the degree of minification necessary for perceptually natural viewing experiences decreased as the DFOV became large. Thus it would appear that when using a HMD which is imperfect with respect to one component of display fidelity (a DFOV that does not cover the full FOV of the viewer), then it might

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[21] Steinicke et al. [124] define the DFOV as the *"[...] the horizontal and vertical angles subtended by the display"* while the GFOV defines *"[...] the horizontal and vertical boundaries of the virtual viewing volume along with the aspect ratio"* [124].

be necessary to decrease the fidelity of another component (distortion in the form of minifiction) in order to increase perceived naturalness. Granted, one might argue that minifiction need not qualify as a decrease in fidelity. On the one hand minification may be viewed as a decrease in fidelity since the projected image, objectively speaking, does not reproduce the corresponding view of the real world. However, in a sense it also introduces a view of the virtual environment that is more true to the one experienced during perception of the real world by making objects, normally captured by peripheral vision, visible to the user.[22]

The second example relates to the perception of visually presented speeds during treadmill walking. Particularly, it has been demonstrated that if the visual speeds are matched with the speed of the treadmill, then walkers tend to find the visually presented speeds too slow [4, 66, 98]. Thus, it may be necessary to exaggerate the visual speed in order to make it perceptually natural. Unrealistically fast walking speeds arguably reduces interaction fidelity (transfer function symmetry) since the user's input does not translate into a realistic output effect. The degree to which speeds are underestimation appear to be inversely proportional to the DFOV size (see Paper D). Thus, we again find that, when faced with less than optimal display fidelity, it may be necessary to reduce interaction fidelity in order to elicit a perceptually natural experience.

The final example relates to the gestural input used for WIP locomotion. The traditional, marching-like WIP is likely to be more physically demanding than real walking, implying less than optimal kinetic symmetry (component of interaction fidelity). By employing an alternative gesture involving more subtle leg movements without breaking contact with the ground, it might be possible to increase kinetic symmetry since this action will be less strenuous. However, since the walker no longer breaks contact with the ground it would seem that kinematic symmetry (another component of interaction fidelity) is reduced (see Paper A). The IVR systems that will become commercially available in coming years offer much promise, but are unlikely to offer the highest possible levels of fidelity; e.g., limited display resolution and DFOV may make the highest levels of display fidelity unachievable. Moreover, achieving very high interaction fidelity by allowing users to physically walk is not an option when IVR systems are deployed in a limited physical space. The uncertainty of how different components of fidelity will influence the naturalness of walking experiences when faced with technological limitations and physical constraints suggest the need for explorations of how we can make WIP locomotion as perceptually natural as possible.

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[22] Through personal correspondence, Dr. McMahan has confirmed that this interpretation is consistent with his conceptualization of display fidelity; i.e., the decrease in FOV mapping and increase in FOV coverage simultaneously decreases and increases components of display fidelity.

Research Questions

My initial motivation for performing the research documented throughout the included papers (Part II) was rooted in the question: *"How is it possible to increase the perceived naturalness of WIP locomotion?"* At the time I was not aware of McMahan's [78] description of fidelity as the degree to which the user-simulation information loop is able to reproduce real-world stimuli and interactions. Nevertheless, I ended taking a similar idea as my point of departure, namely, the correspondence between the sensorimotor loops of real walking and WIP locomotion. Particularly, the degree to which the user perceives the action of stepping in place as natural should depend on the extent to which this sensation is reminiscent of the perception of walking, and the degree to which the user perceives virtual walking speeds as natural should be contingent upon real-world experiences of the speeds that normally are generated during walking. Consequently, it seemed meaningful to divide the challenge of facilitating natural walking experiences during WIP locomotion into two different, albeit complementary, challenges; i.e., the challenges of facilitating natural actions and perceptions during WIP locomotion. This short chapter details the general research questions forming the basis for the papers making up the bulk of the thesis. The idea of supporting a natural sensorimotor loop did spur additional research questions which are outlined in the final chapter of the introduction (*Conclusions and Future Work*).

9 Perceptually Natural Gestural Input

To the best of my knowledge, most existing WIP techniques rely on the same gesture for input; i.e., a stepping gesture where the user alternately lifts each leg as if climbing a flight of stairs or marching on the spot. However, as discussed in Section 8, it seemed possible that this gesture might be more physically straining than real walking which in turn may lead to a decrease in perceived naturalness. This inspired the first general research question:

Q1: *How is it possible to increase the perceived naturalness of the gestural input used for WIP locomotion?*

During the early stages of the project, it became apparent that the common WIP gesture might be accompanied by undesirable physical movement. While stepping in place users often physically drift in the direction they are headed in the virtual environment. If this drift leads to physical collisions, it may hamper the user's walking experience or in the worst case lead to injuries. Anecdotal evidence of this involuntary movement is presented in the literature along with potential solutions (e.g., verbal or passive haptic warnings and physical constraints) [112, 150, 154]. However, the solutions to this problem had not been formally evaluated. This led to the second general research question:

Q2: *How is it possible to minimize the positional drift occurring during WIP locomotion in a minimally disruptive manner?*

10 Perceptually Natural Virtual Walking Speeds

If one wishes to preserve interaction fidelity (i.e., transfer function symmetry) the WIP algorithm should translate steps in place into realistic walking speeds. However, as suggested in Section 8, it seemed possible to question whether realistic walking speeds necessarily will be perceived as the most natural. The reason being that it has been demonstrated that individuals relying on linear treadmills for virtual locomotion tend to underestimate visually presented speeds. If an accurate visual speed matching the speed of the treadmill is presented, the walker is likely to find it too slow [4, 66, 98]. Establishing what virtual walking speeds that are perceived as natural during WIP locomotion is arguably a prerequisite for facilitating natural walking experiences. Thus, it was deemed relevant to determine if the same perceptual distortion is present during WIP locomotion, which inspired the following general research question:

Q3: *Is WIP locomotion accompanied by an underestimation of visually presented walking speeds similar to the one occurring during treadmill walking?*

Since the initial study revealed that users also underestimate virtual walking speeds during WIP locomotion, it was deemed relevant to further explore what factors that influence speed perception during WIP locomotion. This led to the final general research question:

Q4: *What factors influence underestimations of visually presented walking speeds during WIP locomotion and treadmill walking?*

Summary of Included Papers

The main contribution of the thesis lies in the seven papers presented in Part II. Each paper details one or more empirical studies spurred by the general research questions outlined in the previous chapter. This chapter is divided into two sections: first Section 11 outlines the three papers dealing with perceptually natural gestural input for WIP locomotion and the unintended positional drift occurring during this form of virtual travel. Section 12 summarizes the four papers pertaining to underestimations of virtual walking speeds during WIP locomotion. For each study I briefly outline the motivation, the study design and general method, and the findings.

11 Gestural Input and Positional Drift

Most existing WIP techniques do, as suggested in Section 9, appear to take the same gesture as input. However, it was the belief that this gesture involves at least two drawbacks: (1) It appeared to be more physically demanding than real walking which may decrease perceived naturalness. (2) When used in combination with a HMD, the user tends to physically drift in the direction of heading which may lead to collisions with objects in the physical interaction space. This motivated the work detailed in Papers A, B, and C.

Paper A: Tapping-in-Place: Increasing the Naturalness of Immersive Walking-in-Place Locomotion Through Novel Gestural Input

Motivation: One advantage of the traditional WIP gesture, referred to as *Marching*, is that it provides proprioceptive feedback which is similar to the one generated during real walking. Nevertheless, the biomechanics of this gesture differ considerably from real walking [117]. Particularly, the marcher does not swing the legs, but lifts them vertically. This, combined with the absence of forward physical motion, reduces kinematic and kinetic symmetry and marching is likely to be more physically straining than real walking.

Methods and materials: Motivated by the potential benefits of alternative gestural input for WIP locomotion, the work documented in the paper sought to compare two novel alternatives to the traditional WIP gesture: *Wiping* and *Tapping*. In case of the former, the user generates virtual movement by alternately bending each knee as if wiping the feet on a doormat. This should activate the hamstring muscle group which is activated during the last part of the gait cycle of real walking. When relying on *Tapping*, movement is generated by tapping each heel against the ground without breaking contact with the toes. This gesture should activate the quadriceps muscle group which is dominant during the initial swing phase of real walking. Moreover, this gesture should require less energy to perform and thus provide higher kinetic symmetry with real walking. In order to compare the three gestures, we performed a within-subjects study (n=27) involving a simple walking task which required the participants to walking along a predefined path within a scenic virtual environment. The visuals were presented using a HMD and the user's movement tracked using an optical motion capture system. The gestures were compared in terms of self-reported measures related to perceived naturalness (naturalness, fatigue relative to real walking, self-motion compellingness, and acclimatization) and presence (the original three item SUS questionnaire [115, 116]), and behavioral measures of the amount of unintended positional drift (UPD). Particularly the amount of UPD was assessed in terms of maximum drift (the largest physical distance from the point where the locomotion started), total drift (the total physical distance covered by the user), and the drift/travel ratio (the ratio describing how far the user has drifted in the real world per traveled distance in the virtual world).

Findings: The results suggested that Tapping was perceived as the most natural and corresponded best with real walking in terms of perceived exertion. Moreover, Tapping produced significantly less positional drift than both of the other gestures. No differences were found in terms of reported presence. This led us to conclude that Tapping, or variations of this gesture, might serve as a better form of input for WIP techniques since the proprioceptive feedback and perceived physical strain appear similar to the ones experienced during real walking. Besides from demonstrating the potential benefits of alternative gestural input for WIP locomotion, the contribution of the study also lies in the documentation of UPD. A poster, not included in the thesis, discussing the results pertaining to UPD and potential solutions was also published [88].

Paper B: The Perceived Naturalness of Virtual Locomotion Methods Devoid of Explicit Leg Movements

Motivation: The motivation forming the basis for the work documented in this paper was largely identical to the one described in relation to Paper A. However, considering the issue of UPD, it was regarded as relevant to explore the use of gestural input where the user does not break contact with the ground as this may reduce positional drift.

Methods and Materials: The study compared four different types of input for virtual locomotion: the traditional WIP gesture, two alternative forms of gestural input (*Hip Movement* and *Arm Swinging*) and keyboard input. The hip movement gesture required the user to alternately swing the hip to the right and left while keeping both feet grounded. Since hip movement is an important factor in the normal gait cycle [5], it was the belief that this gesture might generate proprioceptive feedback which to some extent resembles the one produced during real walking while involving some degree of biomechanical symmetry. When using Arm Swinging, virtual movement was generated by swinging both arms back and forth. This gesture was believed to involve some degree of biomechanical symmetry since real walking often involves rhythmic swinging of the arms [159]. Finally, when using the keyboard as input, the user was standing and pressed a button to generate movement. The study relied on a within-subjects design (*n=20*) and involved largely the same task and measures as the study described in Paper A.

Findings: The results suggested that Arm Swinging and WIP were perceived as the most natural. As expected, WIP was perceived as the most physically straining and the keyboard condition the least. Arm Swinging was the gesture that provided the best match with real walking in terms of perceived exertion. WIP led to significantly more drift than the remaining gestures and the keyboard condition led to the least. As in the previous study, no significant differences were found in terms of reported presence. Thus, it would appear that arm swinging might be a meaningful alternative to the traditional WIP gesture. However, an important caveat is that this gesture prevents the walker from using arms and hands during locomotion.

Paper C: A Comparison of Different Methods for Reducing the Unintended Positional Drift Accompanying Walking-in-Place Locomotion

Motivation: The usefulness of WIP techniques is largely contingent upon the user remaining stationary. Consequently, the objective of the study documented in Paper C was to determine how different types of feedback compare in terms of their ability to minimize UPD. Common to the all feedback types was that they were designed to keep the user within a walking area of a fixed size. Moreover, the study also sought to determine the degree to which the feedback disrupted the sensation of being in the virtual environment.

Methods and Materials: The study was based on a within-subjects design (*n=20*) and involved 13 unique types of feedback and a control condition where no feedback was presented. The feedback differed in terms of the *sensory modality* used to provide the stimuli (visual, auditory, audiovisual, or passive haptic feedback). The visual, auditory, and audiovisual conditions also varied in terms of the *feedback onset mode* (sudden or gradual onset) and the *presentation mode* (stimuli external to the virtual environment acting as a warning or deprivation of the stimuli used to present the environment). Passive haptic feedback was delivered using a circular carpet delineating the walking area. The participants were asked to walk through a virtual forest along a predefined path using the traditional WIP gesture. The visuals were presented using a HMD and the users' movements were tracked using an optical motion capture system. UPD was assessed based on behavioral measures of UPD: maximum drift; the percentage of time spent inside a safe zone at the center of the walking area; the percentage of time spent outside the walking area; and the number of times the participants stepped outside the walking area. The participants' experience of the feedback was evaluated using self-reported measures of helpfulness and intrusiveness.

Findings: Generally the results indicated that feedback with a gradual onset and passive haptic feedback were better at limiting UPD to a confined area. Moreover, feedback with a gradual onset was more effective at reducing UPD than feedback with sudden onset. Although no significant differences were found, it is worth noting that four in six of the feedbacks with gradual onset were perceived as more helpful than the ones with sudden onset. Moreover, the second, third, and fourth least disruptive feedback types involved gradual deprivation. Passive haptic feedback was perceived as most helpful and least disruptive. Since carpets of the type used for the study are inexpensive, it was concluded that this form feedback potentially could serve as a meaningful way of minimizing UPD. It is worth noting that similar results were found in another study comparing passive haptic feedback with three combinations of audiovisual feedback. This study is described in a poster which is not included in the thesis [90].

12 Underestimation of Virtual Walking Speeds

Intuitively one might assume that the virtual walking speeds accompanying WIP locomotion should match those of real walking. However, as suggested in Section 10, individuals tend to misperceive visually presented speeds when walking on a linear treadmill. Thus, it seemed possible that WIP locomotion might be accompanied by a similar perceptual distortion. Papers D, E, F and G detail studies exploring the factors influencing misperceptions of visually presented walking speeds during WIP locomotion and treadmill walking.

Paper D: Establishing the Range of Perceptually Natural Visual Walking Speeds for Virtual Walking-in-Place Locomotion

Paper D documents two studies related to perception of speed during WIP locomotion and the influence of gestural input and DFOV.

Study 1 (S1): Gestural Input

Motivation (S1): The objective of the first study was to investigate if WIP locomotion is accompanied by a perceptual distortion of the speed of optic flow similar to the one experienced during treadmill walking.

Methods and Materials of S1: The study was based on a within-subjects design (n=20) and compared four different types of user movement: *Stationary* (the user remained still with both feet on the ground), *Tapping* (the gesture proposed in Paper A), *WIP* (the traditional WIP gesture), and *treadmill walking*. For each movement type, the participants performed 22 walks down a virtual corridor presented via a HMD. The participants were required to sync their steps with a metronome beating at 1.8 steps per second. The virtual speed was varied across the 22 walks per condition. That is, the participants were exposed to 11 different visual gains (scalar multiples of their normal walking speed) ranging from 1.0 to 3.0. Each gain was repeated twice and they were presented in randomized order. The normal walking speeds of the individual participants were estimated based on their heights and the fixed step frequency using an equation described by Wendt et al. [147]. During each walk. the participants were asked to verbally report whether they found the virtual speed *"too slow"*, *"natural"*, or *"too fast"*. This approach was chosen since it makes it possible to identify the lowest and the highest gains perceived as natural [98]. Henceforth I refer to the lower and upper bounds as the minima and maxima, respectively.

Findings of S1: The results pertaining to Tapping and the traditional WIP gesture suggested that the perceptual distortion of walking speeds, known to occur during treadmill walking, also is present during WIP locomotion. Moreover the results revealed that there seemingly exists a range of perceptually natural visual gains applicable to WIP locomotion. No significant differences were found between the four movement types.

Study 2 (S2): Display FOV

Motivation of S2: A primary factor contributing to compelling visually induced self-motion illusions is the size of the DFOV [105], and it has been demonstrated that seated individuals tend to underestimate optic flow speeds (white dots presented on a black background on a screen) for circular DFOVs smaller than 60°[99]. Considering that most HMDs do not occupy the full human field of vision, it was deemed relevant to explore the effects of DFOV size on the perception of speed during WIP locomotion.

Methods and Materials of S2: To meet this aim, a within-subjects study (*n=20*) was performed. The study was based on a 2×4 factorial design and crossed two *movement types* (WIP and treadmill locomotion) and four *DFOV* (the full DFOV of the Oculus Rift DK1 and three constrained views with vertical DFOVs of 25°, 50°, and 75°). The employed method was similar to the one used in the first study of Paper D. However, the normal walking speed was established prior to the first trial by asking the participants to identify the treadmill speed they found most comfortable when walking at the fixed step frequency of 1.8 steps per second used for the study. Moreover, the gains were presented in a different manner. For each condition, the participants were exposed to a series of visual gains which either was commenced with the lowest visual gain (1.0) or the highest (3.0). The gain changed in increments of 0.2 between walks. If the series started with the lowest gain, the gains would gradually increase until the highest possible gain was reached and then decrease until returning to the lowest gain again. If the first gain in the series was the highest possible, then the gains would gradually decrease and then increase.

Findings of S2: Significant main effects were found for both movement type and DFOV. However, the post-hoc analysis did not reveal any significant differences in regards to movement type. Contrarily, significant differences were found for DFOV. These results generally suggested that the size of the display FOV was inversely proportional to the degree of underestimation of the virtual speeds. Interestingly, no difference was found between the largest of the constrained DFOV and the unconstrained DFOV of the Oculus Rift DK1. Thus, it was viewed as plausible that the influence of DFOV size on the degree of underestimation decreases as the FOV becomes larger. Combined, the results of the two studies constitute a first attempt at establishing a set of guidelines specifying what virtual walking speeds WIP gestures should produce in order to facilitate perceptually natural walking speeds.

Paper E: The Effect of Visual Display Properties and Gain Presentation Mode on the Perceived Naturalness of Virtual Walking Speeds

There were differences in the ranges of perceptually natural gains identified in the two studies presented in Paper D. It was the belief that the differences might be attributed to variations in visual display properties or possibly other methodological differences. Moreover, the results of these studies were equivocal with respect to the influence of movement type. This inspired the three studies described in Paper E.

Study 1 (S1): Peripheral Occlusion

Motivation of S1: Work by Jones et al. [65] suggests that the addition of a static white light in the far periphery of a HMD improves the wearer's performance on distance judgement and visual scale tasks. Thus, it was regarded as possible that external peripheral stimulation might also affect judgements of the naturalness of virtual walking speeds.

Methods and Materials of S1: In order to probe this assumption, we performed a within-subjects study (n=20) based on a 2×3 factorial design crossing two *movement types* (WIP and treadmill locomotion) with three *levels of peripheral occlusion* (no occlusion, the standard nVisor SX60 blinders, and deprivation of all peripheral visual information using a cloth shroud). Unlike the previous studies, we asked the participants to perform a gain matching task informed by the method of adjustment; i.e., during each walk the participants would adjust the visual speed using a scroll wheel mounted on the treadmill and indicate when they reached the lowest and highest speeds they found natural. The participants performed four walks down an infinite corridor for each condition and were exposed to gains ranging from 0.1 to 4.0. During one half of the walks, the participants started with the lowest possible gain and increased the speed, and during the other half, the initial gain was the highest possible and the participants had to decrease the speed. All walks were performed at a step frequency of 1.8 and the normal walking speed was established as in S2 of Paper D.

Findings of S1: No significant main effects of movement type or degree of peripheral occlusion were found.

Study 2 (S2): Geometric FOV

Motivation of S2: In order to ensure an undistorted view of the virtual world, one should match the DFOV and GFOV. However, it has been demonstrated that individuals do not necessarily find undistorted perspective projects to be the most natural when wearing a HMD [124]. Moreover, studies have shown that variations in the GFOV influences motion perception during driving simulations [83, 34]. This motivated us to perform S2.

Methods and Materials of S2: The method was identical to the one employed in S1, but the conditions necessarily varied. The study relied on a within-subjects design (*n=20*) and crossed two *movement types* (WIP and treadmill locomotion) and three different *vertical GFOV* (24°, 34°, and 44°).

Findings of S2: Significant main effects of GFOV were found for both minima and maxima, but a significant effect of movement type was only found in relation to minima. With respect to GFOV, the results indicated that the size of the vertical GFOV is inversely proportional to the degree of underestimation of visual walking speeds. The results were equivocal in regards to the effect of movement type.

Study 3 (S3): Gain Presentation Mode

Motivation of S3: The last study of Paper E sought to uncover how different gain presentation modes (specific ways of presenting the visual speeds) used in our own and other's work [98, 66] might influence the range of perceptually natural visual gains.

Methods and Materials of S3: In order to put this assumption to the test, we performed a within-subjects study (*n=20*) crossing two *movement types* (WIP and treadmill locomotion) and three *gain presentation methods* (Randomized Order, Reversed Staircases and User Adjustment). The methods were largely identical to the ones used in the previously presented studies; i.e., Randomized Order and Reversed Staircases resembled the method used in S1 and S2 (Paper D), respectively, and user adjustment corresponded to the method of the first two studies in Paper E. The participants were exposed to gains ranging from 1.0 to 4.0 in case of all gain presentation modes. In case of Randomized Order, the participants performed 30 walks (15 gains, repeated twice). In case of Reversed Staircases, the series of walks was terminated once the participants had identified the maxima (ascending series) or the minima (descending series). To ensure a fair comparison, the participants performed two walks during User Adjustment. In addition to measuring the minima and maxima, we also considered the range between the two (i.e., the range of perceptually natural gains), and the completion time.

Findings of S3: In regards to gain presentation mode, significant main effects were found for both minima, maxima, and the range. Particularly, the results indicated that Random Order led to the largest range of perceptually natural gains, while User Adjustment entailed the smallest range. The latter was also significantly faster, but resulted in larger confidence intervals. A significant main effect of movement type was found in regards to the minima and the range. The post-hoc analysis only indicated that treadmill walking was significantly higher than WIP in relation to Random Order.

Finally, the studies yielded anecdotal evidence raising an interesting question. Days after participating in a study, two participants independently of each other remarked that when consciously paying attention to their everyday walking speeds then they occasionally found the speeds too slow. One interpretation is that the underestimations observed during studies in some capacity may be the product of the study method.

Paper F: The Influence of Step Frequency on the Range of Perceptually Natural Visual Walking Speeds During Walking-in-Place and Treadmill Locomotion

Motivation: It has been proposed that our visual perception of walking speeds may be influenced self-motion information received through other sensory channels than vision (e.g., proprioception) [35]. Thus, it was deemed relevant to explore if the same visual gains are perceived as natural across different step frequencies.

Methods and Materials: In order to investigate if gain perception varies across different step frequencies, we performed a within-subjects study (*n=19*). The study was based on a 2×3 factorial design and crossed two *movement types* (WIP and treadmill locomotion) with three *step frequencies* (1.4, 1.8, and 2.2 steps per second). The study relied on the same method as S1 and S2 of Paper E; i.e., the gain matching task informed by the method of adjustment.

Findings: For both minima and maxima significant main effects were found for movement type and step frequency. With respect to movement type, the post-hoc analyses only revealed significant differences in relation to 2.2 steps per second. As for the influence of step frequency, the results indicated that an increased step frequency might be accompanied by increased underestimations of the visually presented walking speeds.

Paper G: The Perceived Naturalness of Virtual Walking Speeds During WIP locomotion: Summary and Meta-Analyses

Motivation: As apparent from the results of the previous studies, we were not able to conclusively answer the question of whether there is a difference between the gains that are perceived as natural during WIP and treadmill locomotion.

Methods and Materials: Meta-analyses provided us with the means to answer this question. While meta-analyses commonly are performed as part of large-scale literature reviews, the method is also believed to be valuable when applied on a smaller scale [30]. To the best of our knowledge, we have performed the only studies comparing motion perception across WIP and treadmill locomotion. This enabled us to present a detailed summary of all six studies detailed in Papers D, E, and F as well as an additional study that originally was published as a poster [89]. This within-subjects study (*n=19*) crossed the two *movement types* (WIP and treadmill locomotion) and two *HMD weights* (the nVisor SX60 weighing 1050g and a modified version weighing 2050g). A significant main effect of movement type was found, but the effect of HMD weight was not significant. Interestingly the same pattern was present across all seven studies; i.e., when walking on the treadmill the participants tended to find higher speeds natural compared to when they were walking in place. However, the results were equivocal with respect to the statistical significance and magnitude this effect.

A primary aim when performing a meta-analysis is to produce a summary effect size describing the effect across studies. Since we were interesting in the difference between treadmill and WIP locomotion, we relied on the mean difference between the two as a measure of effect size for both minima and maxima. In order to ensure independence, composite effect sizes were calculated for each within-subjects study, and in two cases it was necessary to collapse the effect sizes across studies since the same participants took part in more than one study.

Findings: Based on the meta-analyses, which used the random-effects model, we were able to demonstrate that there indeed was a significant difference across the two movement types for both minima and maxima. Moreover, the meta-analyses provided pooled estimates of the magnitude of this difference which led to the conclusion that participants seemingly found slightly higher speeds to be natural during treadmill waling compared to when they were walking in place.

Conclusions and Future Work

With this thesis, I set out to explore the factors influencing the perceived naturalness of WIP locomotion; i.e., the factors that contribute to making WIP locomotion feel more like the act of physically walking. My choice of focusing on WIP locomotion, rather than some other travel technique, was motivated by the need for inexpensive and convenient methods for facilitating perceptually natural walking within virtual environments. A need that is likely to become prominent if consumers adopt the IVR systems which will become commercially available in the recent future. While current WIP techniques offer a lot of promise, I believed that it might be possible to increase the perceived naturalness of said techniques by exploring how walkers experience the actions and perceptions involved in the user-system information loop. Particularly, I was interested in exploring how users perceive gestural input and walking speeds during WIP locomotion. This led me to perform ten user studies and two meta-analyses documented in the seven papers presented in Part II. In this concluding chapter of the introduction, I discuss the contributions of the presented papers and present reflections on potential future work.

13 Summary and Discussion of Contributions

In what follows I summarize and discuss the contributions relevant to each of the four general research questions presented in Sections 9 and 10. I attempt to address relevant caveats influencing the general validity and applicability of the findings, and suggest directions for potential future research. Each general research question is reprinted here for the sake of clarity.

13.1 Alternative Gestural Input for WIP Locomotion

Q1: *How is it possible to increase the perceived naturalness of the gestural input used for WIP locomotion?*

Q1 served as a primary source of motivation for the work documented in Papers A and B that led to the following findings:

- *Paper A:* Gestural input based on more subtle leg movements (i.e., Tapping-in-Place) better matched real walking in terms of perceived exertion and was perceived as more natural than the traditional WIP gesture. Thus, Tapping-in-Place, or variations of this gesture, might serve as meaningful alternative to the traditional WIP gesture.
- *Paper B:* Gestural input based on arm movements, rather than explicit leg motion, better matched real walking in terms of perceived exertion and was comparable to the traditional WIP gesture in terms of perceived naturalness.
- *Paper B:* Gestural input based on arm movements and the traditional WIP gesture were perceived as more natural than movement generated by pressing a keyboard button.

This necessarily leaves the question of whether Tapping-in-Place or Arm Swinging is preferable as gestural input for WIP locomotion. When comparing the self-reported measures across studies, it becomes apparent that the tapping gesture scores higher than the one based on arm motions. With respect to perceived exertion, it is hard to directly compare the results across the two studies since the phrasing of the question varied slightly. Nevertheless, both were perceived as significantly less strenuous than real walking. The fact that Arm Swinging prevents walkers from using their hands during locomotion combined with the ratings of naturalness leads me to conclude that Tapping-in-Place probably would be preferable for many applications. An inherent limitation of both types of gestural input is that the user does not break contact with the ground which may make turning seem less natural. This led to the conclusion that some form energy efficient marching (essentially a mixture between the traditional gesture and Tapping-in-Place) might be perceived as even more natural.

It is worth noting that some of the results described in Papers A and B do not align perfectly with existing findings. Particularly, Usoh et al. [139] did not find a significant difference between WIP locomotion and push-button-flight with respect to self-reported naturalness. However, it is uncertain if the participants in that study also were instructed to equate the degree of perceived naturalness with the extent to which the virtual walking felt like its real-world counterpart. Additionally, WIP locomotion has previously been found to elicit stronger presence responses than push-button-flight [118, 139]. Neither of the studies documented in Paper A and B found a significant difference in terms of presence. However, as the proverbial saying goes, *"absence of evidence is not evidence of absence"* [2]; i.e., a null result do not justify the conclusion that no effect exists. Thus, considering the relatively low sample sizes of the study in Paper B and the conflicting findings of previous work [118, 139], it seems plausible that WIP locomotion may be superior to push-button-flight with respect to self-reported presence.

It is worth highlighting a limitation of the current studies pertaining to how perceived naturalness was measured. Both studies asked the participants to rate the degree to which they agreed with statements pertaining to *naturalness* (how much it felt like actual walking), *physical strain* (how physically demanding the act of walking was compared to real walking), *self-motion compellingness* (the extent to which they felt like they were actually moving), and acclimatization (how quickly they forgot that they were not really walking). In terms of interaction fidelity, the explicit question about of naturalness and the item pertaining to physical strain loosely reflect the participants' perception of kinematic and kinetic symmetry, respectively. Nevertheless, it would have been meaningful to use a more elaborate questionnaire that did not only include items related to biomechanical symmetry. Moreover, it would be valuable to consider measures assessing the extent to which the participants behaved and performed similar to how they did during real walking [152]. The task used for the current studies were literally a walking in the park, and the results do therefore not reveal if the differences in perceived naturalness persist when the act of walking is not the primary tasks. Instead it would be relevant to perform studies where walking is secondary to some other task imposing cognitive demands in terms of information gathering and spatial knowledge acquisition.

Finally, it is worth noting that the general approach to Q1 only allowed us to explore a small segment of the space of potential gestural input for WIP locomotion. In a vein similar to Figueiredo et al. [43], future work might adopt the Wizard of Oz method and more efficiently compare a wider range of gestures (see Section 4.5).

These caveats notwithstanding, the current work have yielded interesting findings related to Q1. Perhaps, most notably that perceived naturalness of the WIP locomotion can be increased by considering gestures, such as Tapping-in-Place, that better resemble real walking in terms of perceived exertion.

13.2 Unintended Positional Drift

Q2: *How is it possible to minimize the positional drift occurring during WIP locomotion in a minimally disruptive manner?*

The problem UPD was addressed in Papers A, B, and C, which brought about the following findings:

- *Papers A:* The drift occurring during WIP locomotion was formally documented and measures to assess this phenomenon proposed.
- *Paper A and B:* Gestures involving subtle or no leg movement reduces UPD (e.g., Tapping-in-Place and Arm Swinging).
- *Paper C:* Passive haptic feedback in the form of a carpet was the most effective at reducing UPD and was perceived as more helpful and less disruptive than most feedback types involving sudden onset and some involving gradual onset.
- *Paper C:* Feedback with gradual onset was more effective at reducing UPD than feedback with sudden onset.

Based on findings presented in Paper C, we concluded that passive haptic feedback might serve as the most meaningful type of feedback for keeping the user within a fixed walking area. Considering that the results of Papers A and B suggest that gestures involving subtle or no leg motion reduces UPD, it seems possible that a combination of Tapping-in-Place and passive haptic feedback could be used to both delimit an area the user should stay within and minimize UPD, thus making disruptions less frequent. With that being said, there were some patterns in the results that are worth noting, even though they are not all fully corroborated by the statistical analyses. The second, third, and fourth least disruptive feedback types were the ones involving gradual deprivation of the stimuli used to depict the virtual environment. And not surprisingly, the results seem to suggest bimodal warnings were more disruptive than unimodal ones and auditory feedback appeared less disruptive than visual feedback. Moreover, four in six of the feedback types with gradual onset were perceived as more helpful than the ones with sudden onset.

Despite the promising results pertaining to haptic feedback, there appears to be an inherent tension between the goal of guaranteeing that the user will notice the presented warning and preserving the illusion of walking through virtual environment. This points us to one of the biggest limitations of the study presented in Paper C, namely, the task performed by the participants. They performed a simple walking task involving very little attentional load. This presumably skewed the results in favor of the more subtle techniques. Had the study involved a more demanding task, it seems possible that the least disruptive techniques might have been less effective at reducing UPD on account of their subtlety. Thus, future studies should assess the efficacy of different feedback types during virtual scenarios demanding a larger amount of attentional resources, such as, the act of playing an immersive game requiring use of the player's intellect or sensorimotor skills. Here, it is worth referring to the work described in two of the posters not included in the thesis [88, 90]. Inspired by work by Steinicke [122], suggesting that transitional environments can increase the sensation of presence, we proposed that it might be possible to design overt methods for minimizing UPD that are less disruptive than simple warnings; i.e., it might be possible to present an intermediate environment once the user has drifted to far. We performed another study that arguably lends some credence to this claim [90]. Particularly, we found that some participants liked the presentation of certain audiovisual feedback for aesthetic reasons. An example of such an approach could be to represent the parts of the virtual world outside the walking area using wireframe geometry once too much drift occurs. This would alert the user to the drift, but make it easier for the user to return to the walking area without greatly decreasing spatial awareness. Particularly, such an approach could be used as a last resort if the user fails to notice the passive haptic feedback.

Finally, it would be relevant for future studies to include alternatives to eliminating UPD; e.g., physical constraints in the form of a harnesses [112] or restraining cage [150]. A completely different approach worthy of exploration is to try to control UPD rather than minimize it. Elsewhere [88] we have proposed that this could be accomplished by taking advantage of existing subtle redirection techniques.

On a more positive note, anecdotal evidence suggests that the amount of drift may decrease after a relatively short period of time [150]. Thus, if methods such as the ones described here are deployed it may be possible to reduce and control UPD enough to make WIP techniques safe for use outside of a laboratory setting.

13.3 Underestimation of Speeds During WIP Locomotion

Q3: *Is WIP locomotion accompanied by an underestimation of visually presented walking speeds similar to the one occurring during treadmill walking?*

All seven studies presented throughout Papers D, E, F, and G addressed this question. However, this was initially done in the first study of Paper D, which led to the following contributions:

- *Paper D:* It was demonstrated that walkers may underestimate visually presented walking speeds during WIP locomotion.
- *Paper D:* It was demonstrated that there may exist a range of speeds that are perceived as natural during WIP locomotion.

Based on these findings, it would appear that the answer to Q3 is affirmative. However, I am reluctant to provide exact values pertaining to the upper and lower thresholds of natural gain perception accompanying WIP locomotion. The reasons for my reluctance will be outlined in the subsection 13.4.

The results suggesting that there exist a range of perceptually natural gains may be useful in relation to WIP locomotion for a couple of reasons. For one, it has been recommended that self-motion speeds should be kept low in order to reduce visually induced motion sickness [76]. Thus, using gains falling within the lower part of the perceptually natural range may help reduce the visuo-vestibular conflict which may be responsible for motion sickness [103]. Furthermore, it might be easier to produce realistic leg animations during lower walking speeds. Finally, it is conceivable that the virtual speed influences the amount of UPD. If this is the case, then adjustments to the applied gain might help minimize or control the drifting.

13.4 Factors Influencing Speed Underestimation

Q4: *What factors influence underestimations of visually presented walking speeds during WIP locomotion and treadmill walking?*

Q4 was addressed throughout the studies presented in Papers D, E, F, and G, which yielded the following findings:

Display fidelity:

- *Paper D:* DFOV size was found to be inversely proportional to the degree of underestimation of the virtual speeds during treadmill and WIP locomotion.
- *Paper E:* GFOV size was found to be inversely proportional to the degree of underestimation of visual walking speeds during treadmill and WIP locomotion.

Interaction fidelity (biomechanical symmetry):

- *Paper F:* High step frequencies may be accompanied by an increased underestimation of the visually presented walking speeds during treadmill and WIP locomotion.
- *Paper G:* Individuals tend to find slightly higher speeds natural when walking on a treadmill compared to when they are walking in place.

Study method:

- *Paper E:* The choice of gain presentation mode may influence the minimum and maximum gains perceived as natural as well as the range between the two during treadmill and WIP locomotion.
- *Paper E:* Purely anecdotal evidence suggested that some part of the underestimation of visually presented walking speeds might be attributed to the participants explicitly focusing on the perceived naturalness of the speeds.

In addition to the findings listed above, it is interesting to note the null results pertaining to the effect of varying degrees of peripheral occlusion on speed underestimations (Paper E) and the influence of increased HMD weight (Paper G). As before these null results do not permit us to conclude that these factors are inconsequential, but they are nevertheless notable. Arguably, the contributions listed above are of relevance to both research on self-motion perception during walking and for developers attempting to facilitate perceptually natural WIP locomotion.

The results pertaining to the influence of DFOV are consistent with existing research [99], but demonstrates that the effect also is present when optic flow is generated by more ecologically valid stimuli and when the perceiver is receiving self-motion information via other sensory channels (i.e., proprioceptive self-motion information). In part the results may be viewed as evidence in favor of the hypothesis that lamellar flow enables more accurate self-motion perception [4]. That said, they should arguably not be viewed as evidence supporting the peripheral dominance theory suggesting that peripheral stimulation dominates self-motion illusions [50]. Instead, the findings appear to correspond with the suggestion that the strength of self-motion illusions increase as a function of the stimulus size independently of whether the stimuli is presented within the central or peripheral vision [86]. From the perspective of a developer, these results are interesting since they suggest that the visual gains that produce perceptually natural speeds using one HMD are unlikely to be applicable when using a display with a different DFOV. Moreover, the results indirectly open up the possibility that previously identified detection thresholds for translation gains applied during redirected walking might vary depending on the DFOV size. Based on our results, we speculated that the influence of DFOV on speed underestimation might decrease as the DFOV gets larger. However, future studies involving a larger number of DFOV are necessary in order to determine if this indeed is the case.

The identified effect of GFOV is consistent with previous work related to underestimations of visual speeds during driving simulations [34]. However, it is notable that in order for veridical performance to be achieved (i.e., a gain of 1.0 would be perceived as natural) an unnaturally high degree of distortion would be required [124] in case of the HMD used for this study. Here it is worth recalling that Steinicke et al. [124] found that the degree of minification necessary for perceptual natural viewing experiences decreased as the DFOV became large. Thus, future studies might strive to determine how different combinations of DFOV and GFOV influence motion perception.

Turning to the findings pertaining to biomechanical symmetry. With respect to the results indicating that high step frequencies are accompanied by increased speed underestimations, it is worth noting previous work is equivocal with respect to this finding. Specifically, work by Kassler et al. [66]

suggested that the same gain may be applicable across six different treadmill speeds. The varying results might be attributed to variations in the visual display type (HMD and screen-based), the different walking interfaces (a regular treadmill and setup requiring the user to wear a harness), and the high variance in the per participant data in the study by Kassler et al. [66]. Contrarily, the findings of Durgin et al. [37] appear to be consistent with the current findings; i.e., the authors found that gain matches were higher for high-frequency gaits. In order to determine if the speed underestimations only are affected during high step frequencies, future studies might involve a larger number and a bigger range of step frequencies.

The seven studies did, as suggested, provide ambiguous answers to the question of whether underestimations of visually presented speeds vary between treadmill and WIP locomotion. However, meta-analyses enabled us to conclude that individuals do tend to find slightly, but significantly, higher speeds natural when walking on a treadmill compared to when they are walking in place. From a perceptual standpoint, these results are interesting since they suggest that the type of movement being performed influences how we perceive visual motion in IVR. Similarly, they are relevant to developers since they suggest that the gains obtained from studies involving treadmills might not always be directly applicable to WIP locomotion. On a more general note, it seems possible that meta-analyses might prove useful in relation to other domains of IVR research where multiple studies are yielding results about the same phenomena (e.g., the degree of underestimation of virtual distances [65]).

Finally, the third study of Paper F provided evidence suggesting that the manner in which visual gains are presented to the participants may influence the minimum and maximum gains perceived as natural as well as the range between the two. Specifically, randomized presentation of the gains generally caused the participants to find higher and lower gains natural, and user-adjusted gains led to the most conservative estimate with respect to the range, but this method also led to the largest confidence intervals. Notably, the limitations of the method of adjustment are already reflected from its common usage. Gescheider [46] describes that, while this method is used as a clinical device for diagnosing sensory loss, it is rarely used to determine the limits of perception within psychophysical research. Instead, it is primarily used to produce preliminary perceptual thresholds which are further probed using more precise methods, such as, forced-choice methods. This necessarily implies that the use of this method can be considered a limitation of the studies presented in Papers E and F. That does not mean to say that the use of this method invalidates the identified differences caused by GFOV and step frequency altogether, but the precision of the identified minima and maxima is questionable as apparent from the 95% confidence intervals. Moreover, it is conceivable that the null results pertaining to the influence of HMD weight and degree of peripheral occlusion may be attributed to the choice of method. The imprecision of user adjustment, along with the low number of repetitions per condition, presumably made it near impossible to detect very subtle differences.

In continuation hereof, the different ranges of gains used in the studies may be responsible for variations in the results across studies. The two studies documented in Paper D relied on gains ranging from 1.0 to 3.0 (i.e., the slowest possible speed corresponded to the estimated normal walking speed while the highest gain was three times as fast). No gains lower than 1.0 were presented because prior studies related to treadmill walking agree on the direction of the perceptual distortion. Nevertheless, it makes it difficult to rule out that the identified minima and maxima could have been biased in upward direction. Indeed, judging from the results of the study comparing different gain presentation modes (Paper E), this does seem plausible. Two of the compared methods were very similar to the ones used in the studies documented in Paper D, but the range of presented gains differed; i.e., the participants were exposed to gains ranging from 1.0 to 4.0. The higher visual gains seemingly led to both higher minima and maxima. However, we cannot be certain that the increased gains are to blame since this was not the only difference between the studies. Incidentally, all studies with a maximum gain of 4.0 involved an infinite virtual corridor, whereas all studies with a maximum gain of 3.0 used a corridor of 14 m. Moreover, it is interesting to note that for user-adjusted gains, the results do not differ notably between the study involving gains from 1.0 to 4.0 (Paper E) and the remaining studies which included gains ranging from 0.1 to 4.0. If habituation was of influence one might expect these studies to have revealed lower minima and maxima. However, it cannot be ruled out that habituation is of greater influence for lower gains than higher gains, and it is possible that habituation was less influential during user adjusted gains since the participant more rapidly could skip across seemingly unnatural visual gains. If we want to know with more certainty what the thresholds for natural gain perception during WIP locomotion are, future studies should address the study using more precise psychophysical methods [38].

Moreover, I want to call attention to some of the factors that may limit the generalizability of the identified gains. Although virtual corridors with different lengths were used (14 m and infinite), the two were very similar in appearance. Powell et al. [98] found no difference in gain perception across two different virtual environments. However, a study by Durgin et al. [36] suggested that the inclusion of near-space objects positively influences gain-matching performance. Thus, we cannot be certain that the same results would be obtained in a visually different virtual environment.

Furthermore, the current studies were limited to linear walking and may therefore not apply to lateral and backwards movement or walks along a curved path. During both treadmill and WIP locomotion, the participants were asked not to break contact with the handlebars. The participants generally did not support parts of their own weight on the handlebars, but the mere fact that they touched them may have been of influence. As a result we cannot be certain that the gains apply during walks where the participants are free to move their arms.

Finally, it seems possible that the gain matching tasks themselves may have limited the general applicability of the identified gains. During everyday walking, we seldom make judgments about whether the visual speeds we are seeing are too slow relative to how we are walking. After all we have no reason to think that the visual speed is not appropriate. However, after participating in studies documented in Paper E, two participants did so. Independently of each other, they reported that when paying explicit attention to the perceived naturalness of everyday walking speeds, then these speeds sometimes appeared too slow. This opens up for the question of whether some amount of the observed underestimation of virtual walking speeds can be attributed to the participants explicitly focusing on the perceived naturalness of the speeds. One possible implication is that the gains applicable during most types of virtual navigation may be much lower than predicted by the studies presented here. On this note, it is interesting that Jan Goetgeluk, CEO of Virtuix, has stated that they have found no need for accelerating the virtual speeds accompanying virtual locomotion via the Virtuix Omni (a repositioning system based on a friction free platform) [23], and the Oculus Best Practices Guide [95] similarly recommends using real-world walking speeds. One possible explanation is that the perceptual distortion seemingly is eliminated if walkers direct their gaze downward or to the side [4]. Thus, it would be relevant for future studies to assess natural gain perception during conditions that better resemble common travel tasks such as exploration, search, and maneuvering [12].

14 Additional Research Questions

In addition to the ideas for future work brought about by the limitations of the individual studies, the aspiration of facilitating natural actions and perception during WIP locomotion spurred a number of additional research questions. With respect to the facilitation of perceptually natural actions, there appear to be additional challenges worth addressing. While exception do exist [43, 136, 160], most current WIP techniques have focused on facilitating forward locomotion. Thus, it would be relevant for future work to address the following question:

Q5: *What gestural input can be used to facilitate perceptually natural backwards and lateral movement during WIP locomotion?*

In relation to steering during WIP locomotion, Williams et al. [154] found that participants preferred gaze-directed steering over torso-directed steering (see Section 4.4). This is interesting since gaze-directed steering seemingly is the approach that provides the lowest degree of biomechanical symmetry. Notably, Bowman et al. [12] describe that if the orientation of the torso is determined using a tracker, then this tracker should be positioned near the waist. Yet it would seem that it often is located on the chest [41]. Moreover, it is possible to derive the user's virtual orientation based on the orientation of the feet (see Paper A). The difference between the three alternatives to gaze-directed steering may seem minute. However, we have informally observed that steering using a tracker on the chest seems less natural compared to feet-based or hip-based steering. A likely explanation is that walkers, when looking around the environment, may slightly turn the torso and thereby introduce unwanted adjustments to the heading. As a consequence it would be relevant for future work to address the question:

Q6: *What body parts should be mapped to virtual orientation in order to allow for the most natural walking experience?*

Besides from studies of how users internally perceive their own movements, this thesis focused exclusively on of how walkers perceived exocentric motion. This leaves the question of how to represent the user's virtual body during WIP locomotion. Slater [114] has described the virtual body as the focal point where the illusions of place (the illusion of "being there", i.e., presence) and the illusions of plausibility (the illusion that the virtual events are really happening) are fused. Therefore, it would seem that the illusion of virtual body-ownership is crucial to compelling IVR experiences. However, this illusion may prove particularly difficult to sustain during WIP locomotion. The reason being that visuomotor asynchrony may break the illusion [70]. If the user's virtual representation exhibit normal gait behavior (i.e., actual walking), the virtual limb movement will be asynchronous with the real leg movements (i.e., stepping in place). For that reason, it will be interesting to address the following question:

Q7: *To what extent can virtual body-ownership be sustained during WIP locomotion despite the asynchrony between the movement of real and virtual legs?*

In addition to the potential future work proposed in the current and preceding section, it would be relevant for future studies to address the perceived naturalness, usability and performance of WIP locomotion during repeated and prolonged usage. After all the participants have had a lifetime of experience with walking, but most studies draw their conclusions from performance, behavioral and self-reported measures following relatively short exposure to WIP locomotion.

15 Concluding Remarks

Even if we are able to develop WIP techniques facilitating a reasonably high degree of perceived naturalness, there appear to be at least two factors that will determine if said techniques become widely adopted by consumers and other individuals in need of low-cost locomotion interfaces: the general attitudes of the potential user group and competing low-cost interfaces.

What I am alluding to when talking about the attitudes of the potential user group is the question of whether users (particularly gamers) will be interested in the degree of physical activity required by WIP techniques. Particularly, the physical demands may limit the amount of time a player is able to engage with a game in one "sitting." Moreover, the physical demands imposed on players are likely to force game designers to rethink the way games are designed. Nevertheless, the way in which devices such as the Virtuix Omni have been received by the community seems to suggest that there is a reasonably large segment of users who will be happy to break a sweat while traveling through virtual worlds. This brings me to the second point. In Section 3, I generally dismissed repositioning systems, such as mechanical omnidirectional treadmills, as being impractical and too expensive for deployment outside of laboratories of universities and private companies. Nevertheless, friction free platforms, like the Virtuix Omni, do appear to be a promising way of facilitating relatively natural locomotion. However, few formal evaluations of the perceived naturalness accompanying this type of locomotion have been performed [135]. Moreover, such interfaces do require a considerable amount of space, and may be relatively noisy. Furthermore, WIP techniques are likely to be even more inexpensive; user does not need to be tethered (if we can eliminate or control UPD); and WIP locomotion is compatible with a wider range of movements (e.g., lying down or crawling in place). Combined these limitations and advantages suggest that WIP locomotion does make up a meaningful alternative to friction free platforms.

While WIP techniques might never afford the degree of perceived naturalness strived for by the evil scientists mentioned in the opening quote of the introduction, such techniques may prove natural enough to facilitate compelling walking experiences for users in need of a low-cost approach to virtual locomotion. My hope is that the contributions documented in this thesis will help bring WIP locomotion one step closer to this goal.

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Part II

Papers

Paper A

Tapping-in-Place: Increasing the Naturalness of Immersive Walking-in-Place Locomotion Through Novel Gestural Input

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Abstract

Walking-in-Place (WIP) techniques provide one possible solution to the problem emerging when an immersive virtual environment (IVE) offers a larger freedom of movement than the physical environment where the interaction is taking place. Such techniques are particularly useful when the spatial constraints are very prominent. However, many previous WIP techniques rely on the same gesture for input – a stepping gesture resembling the one performed when walking up a flight of stairs. It seems possible that this gesture may be perceived as more physically straining than real walking which may lead to a less natural walking experience. In this paper, we present two novel forms of gestural input for WIP locomotion and describe a within-subjects study comparing these to the traditional stepping gesture. The two gestures proposed are: a wiping gesture where the user alternately bends each knee, moving one lower leg backwards, and a tapping gesture where the user in turn lifts each heel without breaking contact with the ground. Visual feedback was delivered through a head-mounted display, and auditory feedback was provided by means of a 24-channel surround sound system. The gestures were evaluated in terms of perceived naturalness, presence, and real world positional drift. The tapping gesture was significantly more natural than the wiping gesture and was experienced as significantly less strenuous than the other two techniques. Finally, the tapping gesture resulted in significantly less positional drift.

1 Introduction

A particularly problematic obstacle facing developers of immersive virtual environments (IVEs) is what might be referred to as the problem of incompatible spaces. A virtual space may be virtually infinite in size. Thus, the user should be able to move freely to the extent that the virtual topography and architecture allow it. However, in the real world the user's movement is confined to a limited physical space. As long as the virtual space is smaller than, or the same size as, the physical space we may regard the two spaces as compatible. However, if the virtual environment offers a larger freedom of movement than the physical environment, the incompatibility emerges. At best the incompatibility may be detrimental to the user experience. The user may inadvertently probe the boundaries of the system which in turn may hamper the illusion of presence – often defined as the sensation of "being there" in the virtual environment [31]. At worst the incompatibility can be dangerous since immersed users may be unaware of real world obstacles.

Within the academic community numerous different solutions to the problem of incompatible spaces have been proposed in relation to interactive walking simulation. These can be grouped into at least three categories:

1. *Mechanical repositioning:* Elaborate mechanical setups facilitating relatively natural walking without changing the user's position relative to the physical environment [7, 11, 12, 13, 18].
2. *Redirected walking:* A collection of techniques which makes it possible to discretely or continuously reorient or reposition the user through overt or subtle manipulation of the stimuli used to represent the virtual world [6, 8, 10, 19, 30, 32].
3. *Walking-in-Place (WIP) techniques:* Alternative interaction strategies enabling users to move within the virtual environment by performing body movements resembling real world walking while remaining stationary [9, 24, 29, 37, 38].

All three may serve as potential solutions to the problem of incompatible spaces in their own right. With that being said, they are not equally viable if applied outside a laboratory setting where the spatial and technological constraints are even more prominent, i.e., in the household of an average consumer. Such consumer IVEs are far from commonplace, but recent technological developments such as the Microsoft Kinect[1] and the Oculus Rift[2] usher in a future where IVEs no longer have to be confined to the laboratories of public and private institutions. However, the limited space available to many consumers effectively renders redirection techniques ineffective since these are contingent upon some degree of movement on behalf of the user. Similarly, current mechanical setups, such as omnidirectional treadmills, cannot be considered a feasible alternative within a foreseeable future [2]. For the moment, this leaves WIP techniques as the most promising of the three.

While WIP techniques in their current forms cannot compete with real walking in terms of simplicity, straightforwardness, naturalness [37], studies do suggest that they may elicit a stronger sensation of presence than techniques where users push a button to propel themselves forward [29]. Particularly, the convenience and cost-effectiveness have been highlighted as factors making the lower level of control and naturalness worthwhile tradeoffs [9]. Slater, Usoh and Steed [28] describe that a primary advantages of their original Walking-in-Place technique [26] is that the gestural input generates proprioceptive feedback similar, albeit not identical to, the one resulting from real walking. In turn, this entails a higher degree of correspondence between the proprioception and stimuli in other modalities suggesting exocentric motion perception. Moreover, Williams and colleagues [39] found that walking in place on the Wii was as effective as physically walking in a simple spatial

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[1] www.xbox.com/kinect

[2] www.oculusvr.com

orienting task. These potential advantages suggest the need for finding the best possible WIP technique.

Even though exceptions do exist [14, 34, 35], many WIP techniques seemingly rely on the same gesture for instigating forward viewpoint displacement, namely, leg movements resembling those performed when ascending a flight of stairs. It would seem that this gesture may be more physically straining than real walking. In this paper we describe a study performed with the intention of determining how this gesture measures up against two novel forms of gestural input in terms of naturalness, presence and real-world positional drift. The evaluation was essentially motivated by the hypotheses that a better match between the perceived physical effort of walking in place and real walking would lead to an experience of more natural WIP locomotion. The paper is structured as follows: In section 2 we present previous attempts at facilitating virtual travel using WIP techniques. In section 3 we discuss the discrepancies between the biomechanics of real walking and the gesture most commonly used for WIP locomotion and then we introduce two alternatives to this gesture. Section 4 details the study performed with the intention of evaluating how the two alternative gestures measure up against the prevalent one and each other. Section 5 summarizes the results which are discussed further in Section 6. Finally, Section 7 summarizes and concludes upon the presented study before outlining potential future work.

2 Related Work

To our knowledge, no previous attempts at comparing gestural input for WIP locomotion have been performed. However, several different WIP techniques have been implemented. On the most general level it is possible to distinguish between techniques relying on manipulation of a physical interface for step detection and techniques dependent on various forms of motion tracking to determine whether the user is walking or not. Physical interfaces do in principle also perform primitive gesture tracking in the sense that the manipulation of the physical interface is equated with a given gesture being performed. However, proper tracking systems rely on continuous detection of positions or velocities of given body parts.

Secondly, it is possible to classify WIP techniques according to whether the mapping between the performed gesture and the virtual locomotion is direct or indirect [9]. In case of the former there is a direct correspondence between the motion of the tracked body part and the viewpoint displacement, and in the latter case no such relationship exists. Notably that does not mean that indirect approaches necessarily entail discontinuous viewpoint displacement since a continuous velocity may be determined from discrete phenomena, such as the step frequency.

2.1 Physical Interfaces

Almost without exception, the WIP techniques relying on physical interfaces employ an indirect mapping between the stepping gesture and the viewpoint's displacement. Many of these use the forces exerted when a foot comes into contact with the ground to detect that a step has been taken. Since this impact is a discrete event, it is impossible to map directly the continuous movement of the legs to the translation of the viewpoint.

One such interface is the Walking Pad [3, 4] which detects the user's steps through 60 iron switch sensors embedded on a 45cm x 45cm plexiglass surface. Moreover, processing of the binary values provided by the switches makes it possible to determine the orientation of the user's feet when these touch the ground and based on this information the walking direction is determined.

Similarly Bouguila and colleagues [5] describe a platform which facilitates foot based locomotion through four embedded load sensors. Notably this interface differs in that it can reorient users towards a visual display since the platform also serves as a mechanical turntable. Additionally, this device is capable of simulating surface inclines and declines via three air cylinders mounted underneath the turntable.

It is interesting to note that a commercially available physical interface already have been used to facilitate WIP locomotion, namely, Nintendo's Wii Balance Board.[3] Williams, Bailey, Narasimham, Li, and Bodenheimer [39] combine the balance board, which is embedded with four pressure sensors, with an orientation sensor. Their WIP—Wii algorithm detects how rapidly the user applies weight to each corner of the board and translates the viewpoint accordingly. The orientation sensor is used to determine the direction of heading.

The Wizdish [34] presents an example where there is a direct mapping between virtual locomotion and interaction with a physical interface. Strictly speaking the Wizdish is not a physical interface since it relies on a motion capture system for detecting the user's movement. However, the interaction is contingent upon the gesture being performed via the Wizdish itself. The surface of the Wizdish is concave and almost spherical. Users wearing a pair of low friction shoes are able to take steps by simultaneously sliding one foot forward and the other backward without breaking contact with the surface of the dish. The magnitude of the walking motion is then based on the forward motion of the feet. Notably this is one of the examples of a WIP technique which does not rely on "stair ascending" gesture.

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[3] www.nintendo.com/wii/enhance/#/accessories

2.2 Motion Tracking

Slater and colleagues [26] describe one of the earliest implementations of a WIP techniques, originally dubbed the Virtual Treadmill [29]. This technique does not explicitly rely on tracking of leg movements. Instead, it detects whether users are walking in place via a neural network recognizing patterns in the tracked head movement. Feasel, Whitton, and Wendt [9] describe that the viewpoint displacement used for the original virtual treadmill was discrete rather than continuous. When the neural network registered a step, the viewpoint abruptly jumped a full step length forwards. Moreover, this algorithm may have been perceived as somewhat unnatural since movement was not instigated until four steps in place were detected and it would similarly not terminate the movement unless no steps had been detected for two full cycles.

Another implementation which also relies on head movement is the so-called Shake-Your-Head technique proposed by Terziman et al. [35]. However, rather than detecting the head movements resulting from walking in place, this technique relies on more explicit head gestures such as lateral head oscillation for walking and lateral head movement for jumping. An interesting implication of this is that the technique also can be used by seated users.

Zielinski, McMahan, and Brady [41] present a WIP technique that uses a camera to track the shadows cast by the users' feet onto the floor of an under-floor projection system within a six-sided CAVE. In addition to enabling forwards movement, it also includes to the possibility of sidestepping. While the gesture used for forward locomotion seemingly correspond to the one commonly used for WIP techniques, sidestepping is achieved through a pinch gesture similar to the one used touch screen devices.

The motion tracking based solutions described so far employ discrete mapping between the WIP gesture and the forward movement of the viewpoint. However, systems using direct mappings have been proposed. Feasel, Whitton, and Wendt [9] describe a technique referred to as Low-Latency, Continuous-Motion Walking-in-Place (LLCM-WIP). This technique controls the viewpoint displacement based on the speed of the user's vertical heel movement and promises low starting and stopping latency, smooth motion between steps, within-step control of the speed, and turning on the spot without erroneous forward movement.

Wendt, Whitton, and Brooks' Gait-Understanding-Driven Walking-in-Place (GUD WIP) [38] similarly takes the vertical speed of the heel as an input. However, it sets itself apart from its predecessors in that it is informed by gait principles and thereby produces walking speeds that correspond better with those of real walking. Moreover, it is worth noting that WIP locomotion also has been achieved using commercially available motion tracking systems such as the Microsoft Kinect which can be used for WIP locomotion in combination with the Flexible Action and Articulated Skeleton Toolkit (FAAST) [33]. Interestingly, Kim, Gracanin, and Quek [14] have proposed the technique Sensor-Fusion Walking-in-Place (SF-WIP), which relies on the acceleration and magnetic sensors embedded within two smartphones in combination with a magnet to produce WIP locomotion from any walking like movement performed by stationary users.

3 Gestural Input for WIP Locomotion

As suggested, it would appear that many of the WIP techniques reviewed in section 2 rely on the same gesture for input. The user alternately lifts each leg as if climbing a flight of stairs or marching on the spot. Henceforth we refer to this gesture as *Marching*. While this gesture does bear semblance with normal walking, the two differ in more than one regard.

3.1 Biomechanics at a Glance

We are generally able to describe the act of walking through repeated gait cycles – the period from initial contact of one foot until the same foot makes contact again. The gait cycle is normally divided into the two phases: the stance phase (loading response, midstance, terminal stance, and preswing) and the swing phase (initial swing, midswing, and terminal swing) [22]. The act of walking is sometimes described as controlled falling [15]. Dynamic stability is achieved through a combination of support forces, momentum and inertial forces, and energy is conserved by taking advantage of the forward kinetic energy and the gravitational potential energy of the center of body mass. According to [1] it seems that the most important factor in the gait cycle is hip moment. During the initial phase this moment is primarily provided by the quadriceps muscle group (located on the anterior of the thigh), whereas the terminal phase is dominated by the hamstring group (located on the posterior of the thigh) [1].

As previously suggested, a main advantage of the Marching gesture is that it provides proprioceptive feedback similar, but not identical to, to one produced during real walking [28]. However, like any gesture serving as a proxy for its real word counterpart the feedback is not identical. Most notably, the marcher does not swing the legs, but rather lifts them as if ascending a flight of stairs. A related area in which the two differ appears to be energy consumption. Unlike the case of real walking, gravity and forward momentum cannot be used to reduce the work performed by the muscles during walking in place. This presumably results in an even larger activation of the quadriceps muscle group during the initial "swing" phase.

3.2 Alternative Gestures

Laboring under the assumption that the Marching gesture indeed is more physically straining than real walking, it seems plausible that WIP locomotion might be perceived as more natural if it relied on gestures activating different muscle groups or demanding less muscle activity. Currently we have conceived of two such alternative forms of gestural input for WIP locomotion:

Wiping Gesture

The first of the two gestures resembles the movement performed when wiping one's feet on a doormat. The user alternately bends each leg backwards in order to produce movement. Thus, the initial swing is replaced by the user bending one knee and moving the leg backwards while the terminal swing is replaced by the user lowering the leg again. This is believed to activate the hamstring muscle group which is normally activated during the last part of the gait cycle. While this gesture does involve some of the muscle activation of real walking, it seems possible that it may be perceived as equally as physically straining as the Marching gesture. Throughout the following we refer to this gesture as *Wiping*.

Tapping Gesture

The second alternative is a gesture where movement is generated by tapping each heel against the ground. The initial swing is now replaced by the user lifting one heel off the ground without breaking contact with the toes and the terminal swing corresponds to lowering the heel again. We refer to this gesture as *Tapping*. As with the Marching gesture, the intention is for Tapping to provide proprioceptive feedback similar, but not identical to, the one experienced during real walking. Moreover, Tapping is also believed to activate the quadriceps muscle group during the initial swing phase, as is the case with real walking [1]. However, Tapping and Marching differ since the former requires less muscles activity. Thus, the correspondence between the energy consumption of Tapping and real walking is believed to be higher than that of Marching and real walking. Figure 1 illustrates the three gestures at the point which would correspond to midswing of a gait cycle.

4 Study Design

The evaluation was performed with the intention of determining how the two novel forms of gestural input for WIP locomotion would compare to the

Fig. 1: The three gestures used for the study at the point corresponding to midswing of a normal gait cycle. Marching (left): The user alternately lifts each foot off the ground by raising the thighs in front of the body. Wiping (middle): The user in turn bends each the knee while keeping the upper leg relatively steady which results in backwards movement of the feet. Tapping (right): The user alternately lifts each heel off the ground while keeping the toes in contact with the ground.

prevailing gesture and each other in terms of perceived naturalness. We performed a comparative study using a within-subjects design including three conditions – one corresponding to each of the three gestures, Marching, Wiping, and Tapping. The order of the conditions was randomized so as to control potential order effects.

4.1 Participants and Procedure

A total of 27 participants (19 males, 8 females) took part in the experiment. They were between the ages of 19-43 years (M=29.8 years, SD=7.1) and were recruited via a mailing list comprising volunteers from Aalborg University Copenhagen and subscribers to the Danish periodical Ingeniøren (The Engineer). No compensation was offered for participation. All participants reported having normal or corrected-to-normal vision and hearing. None of them had previously tried virtual travel by means of a WIP technique. Initially, the three gestures were demonstrated, and the participants were informed of the general purpose of the experiment. Moreover, it was made clear that within the context of the current experiment a natural walking experience would be one that felt like real walking. Before each trial, the system was calibrated by asking the participants to perform the particular gesture until they felt comfortable doing so. In addition to calibrating the system for the individual gestures, this process also ensured that the participants understood the gestures and felt comfortable performing them. During the walk, the experimenter observed the participants to make sure that they performed the gestures correctly. Once the walk was over, the participants were asked to fill out an electronic questionnaire. The three walks took on average 52.9 seconds to complete (SD = 12.4).

Fig. 2: Left: A top-down view of the environment. The path the participants walked along has been highlighted with red. Right: A screen shot of the environment as it looks from the user's point of view.

4.2 Task and Environment

In all three conditions, the participants were asked to perform a simple locomotion task, namely, walking from one point to another by following a clearly visible path. This relatively straightforward task was favored over more complex ones, such as precision or wayfinding tasks, since we wanted the walking experience to take a natural scenario as its point of departure. For the same reasons, we chose a scenic, albeit not particularly grand, countryside environment as a setting for the walk. The path was 400 meters long.

The participants were instructed to walk at a steady pace they found comfortable; to stay on the path, if possible; and to refrain from stopping or walking in the opposite direction. We purposely avoided using a straight path since we wanted to ensure that the participants were forced to turn to both sides during the walk. The path and environment were identical for all three conditions. A top-down view of the path and a screenshot of the environment as it looks from the user's point of view are shown in Figure 2.

4.3 Setup

The IVE was simulated using an adapted version of the multimodal architecture described by Nordahl et al. [21], which originally was developed for the purpose of simulating walking-based interactions through visual, auditory and haptic stimuli [36].

Hardware

The movement of the user – the walking gestures and the head motion – was acquired by tracking the position and orientation of three markers – one placed on the head-mounted display (HMD) and one placed on each of the user's ankles. The markers were tracked by means of a 16 cameras

Optitrack motion capture system[4]. The 16 cameras were placed along the circumference of a circle with a diameter of 7 meters. 12 of the cameras were placed at a height of approximately 2.9 meters, and the remaining 4 were placed about 1.8 meters from the ground. Placement of the markers on the ankles was chosen since the Tapping gesture only involved subtle movement of the heels. It was therefore regarded as beneficial to place the marker as close to the heel as possible. Moreover, it is worth noting that the placement of the markers on the front side of the lower leg would have led to some degree of occlusion during the Wiping gesture. Visual stimuli were delivered through a nVisor SX head-mounted display, with a resolution of 1280x1024 in each eye and a diagonal field of view of 60 degrees. A 24-channel surround sound system was used to deliver auditory stimuli. The system consisted of two RME Fireface 800 interfaces and one RME ADI-8 DS converter. 16 Dynaudio Bm5A mk II active monitors were evenly distributed at ear height along the circumference of the circle defined by the motion capture system, and an additional 8 Dynaudio Bm5A mk I speakers were distributed around the circle on the floor.

Software

The virtual environment stimuli and the motion tracking algorithm were produced in the multiplatform game development environment Unity3D[5] which facilitates stereoscopic viewing by the placement of two cameras within one environment. The soundscape accompanying the visuals was composed of ambient sounds, such as the sound of wind blowing and water flowing and was delivered using the real-time synthesis engine Max/MSP.[6] A schematic drawing of the system used for the current study can be seen in Figure 3.

The same algorithm was used to produce forward viewpoint displacement from all three gestures. Each of the two markers placed on the user's ankles yield a three-dimensional position and orientation which were used to control the forwards movement of the viewpoint within Unity3D. In connection with WIP locomotion, the velocity of forward movement is often defined by estimating the stepping frequency of the user. However, a different solution was employed since the three gestures may involve markedly different stepping frequencies. The velocity of the viewpoint transformation can generally be described in terms of the following equation:

$$viewpoint\ velocity = normal\ velocity \times scale\ factor \qquad (1)$$

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[4] www.naturalpoint.com/optitrack

[5] www.unity3d.com

[6] www.cycling74.com

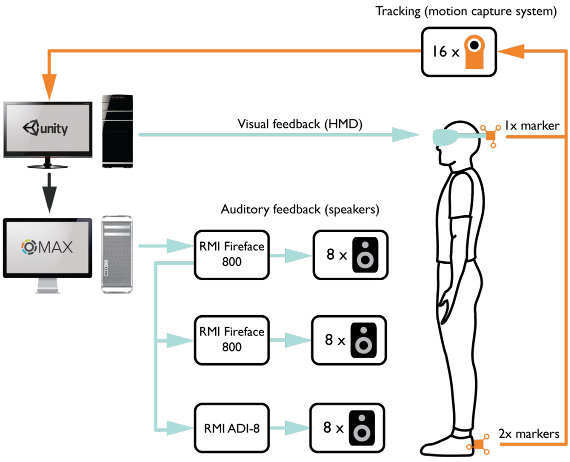

Fig. 3: Schematic drawing of the setup used for the study.

Since height is positively correlated with step length [38], the normal velocity was defined in terms of the user's height – acquired during the calibration of the system – as follows:

$$normal\ velocity = \frac{user\ height}{C} \tag{2}$$

The constant C was established through informal evaluations of the perceived walking speed achieved by varying the divisor. A suitable value was found to be $C = 0.45$. It is worth noting that this caused the algorithm to produce walking speeds closer to those of a fast runner. That these were perceived as more natural can presumably be ascribed to the fact that motion perception is influenced by peripheral vision when speed judgements rely on optic flow [23]. In this case, the field of view was restricted by the HMD. The user influenced the virtual velocity through vertical movement of the feet in the case of all three gestures. The vertical components (y) of the position data were used to define the scale factor and thereby influence the viewpoint velocity. However, since the vertical positions vary considerably from gesture to gesture the scale factor is defined as follows:

$$scale\ factor = \frac{highest\ recent\ foot\ position}{expected\ step\ height} \tag{3}$$

The highest recent foot position was defined as the highest value of y within the last 0.5 seconds, and the expected step height was the mean step height obtained during pretest calibration. Thus, regardless of what gesture was being performed, if the marker was at the same height as it was during the calibration, the normal velocity would not be scaled. If the user stood still, the normal velocity would be multiplied by zero. The scale factor value was clamped between 0 and 1.75 entailing that highest possible velocity was a 75% increase in the normal walking speed. Since the task performed by the participants involved continuous motion from start to end starting and stopping latencies were not formally measured. However, it would take about half a step cycle before the user reaches the normal velocity and stopping latencies of at least 0.5 seconds were to be expected given the definition of the highest recent foot position.

Finally, it is worth noting that the viewpoint was not transformed forward along the gaze direction of the user. Instead, the orientation of the two markers mounted on the ankles are used to approximate the direction of the feet. Thus, it is possible to produce an estimate of the body orientation, which in turn defines the direction of heading, by averaging the two vectors corresponding to the forward orientation of the markers.

4.4 Measures

While the primary purpose of the study was to determine how the three gestures would compare in terms of naturalness, we decided to include two additional measures, namely the sense of presence and the amount of real-world positional drift occurring during the walk. Naturalness and presence were assessed by means of a questionnaire, and positional drift was evaluated based on behavioral data.

4.5 Subjective Measures of Naturalness and Presence

The experienced degree of naturalness was assessed by four questionnaire items requiring the participants to rate their level of agreement with particular statements on a scale from '1' to '7' ('1' signified strong disagreement and '7' signified strong agreement). The four items related to the following topics:

1. *Naturalness:* As in other questionnaires related to the experience of IVEs [16, 17, 29, 40] we included one questionnaire item explicitly asking the participants to rate how natural they found the experience of walking in the IVE.

2. *Physical strain:* It seems highly likely that a WIP gesture will be experienced as more natural, if it requires a similar degree of muscle activity as real walking. Thus, we included an item asking the participants in-

dicate whether the given gesture was more physically strenuous than the action it was serving as a proxy for.

3. *Self-motion compellingness:* Since natural walking involves exocentric motion perception, we added an item asking the participants to rate whether they indeed felt as if they were moving during the virtual walk.
4. *Acclimatization:* In order to determine how quickly interaction via the gestures became second nature, the questionnaire contained an item asking the participants to rate how quickly they forgot that they were not really walking.

Moreover, the questionnaire included three items pertaining to the participants sensation of presence within the IVE, namely, the three items featured in the original version of the Slater-Usoh-Steed (SUS) questionnaire [26, 27]. These items assess the subjective sense of presence based on three factors: 1) The extent to which the participants had a sensation of "being there" in the IVE. 2) The extent to which the IVE becomes the dominant reality and is perceived as such. 3) The extent to which exposure to the IVE gave rise to a sense of viewing images as opposed to having visited a place. Like the remaining questions, these items were answered on rating scales ranging from ′1′ to ′7′ where a high rating would be indicative of presence.

Finally, an item in the questionnaire encouraged the participants to comment freely on their experience of the three conditions.

4.6 Behavioral Measures of Unintended Positional Drift

During previous user studies, we have informally observed that many individuals wearing a HMD while walking in place, physically move in the same direction as they are headed within the virtual environment. We refer to this phenomenon as unintended positional drift (UPD). If a WIP interaction technique is to be considered a meaningful solution to the problem of incompatible spaces, it is crucial that the user remains stationary. Thus, UPD should be considered crucial to the evaluation of any WIP technique intended for use in combination with a HMD. We employed three measures of UPD: *maximum drift* (the largest physical distance the user has been from the point where the locomotion started), *total drift* (the total physical distance covered by the user), and the *drift/travel ratio* (the ratio describing how far the user has drifted in the real world per traveled distance in the virtual world). In order to produce these measures we logged the participants′ real and virtual position twice a second. The logging was commenced and terminated once the participants crossed two previously defined points along the gravel path.

Finally, in order to get a measure of the velocity of the viewpoint transformation performance data related to completion time and traveled distance.

5 Results

An error related to the electronic questionnaire forced us to eliminate the questionnaire data from two participants. Moreover, an error during the logging of the real and virtual positions made it impossible to retrieve the data from three trials. Thus, the self-reported measures and the measures of UPD are based on 25 and 26 participants, respectively. Repeated-measures analyzes of variance (ANOVAs) were used to compare the means obtained from all measures. All ANOVAs were performed using a significance level of .05. Significant measures were subsequently analyzed by means of paired sample, two tailed t-tests using Bonferroni-corrected alpha values of 0.017 per test. The p-values obtained from these post-hoc analyzes are presented in Table 1.

5.1 Perceived Naturalness

The results obtained from the three questionnaire items related to perceived naturalness are shown in Figure 4. Significant differences were found in relation to the item asking explicitly about how natural the walking experience was $(F(2,24) = 5.44, p < .01)$ and in relation to the item required the participants to rate whether the gesture had been more physically straining than real walking $(F(2,24) = 22.34, p < .01)$. In the former case the post-hoc analysis revealed a significant difference between the Wiping and Tapping gestures. In regards to physical strain, Tapping was significantly different from both Marching and Wiping. No significant differences were found between the means obtained from the items related to perceived self-motion compellingness and the item asking how quickly the participants forgot that they were not really walking.

Table 1: P-values obtained from paired sample, two-tailed t-tests. Values indicating a significant difference are highlighted with bold (α = 0.017). Marching = M, Wiping = W, and Tapping = T.

	M-W	M-T	W-T
Naturalness	0.051	0.179	**0.007**
Fatigue relative to real walking	0.247	<**0.001**	<**0.001**
Total drift	0.114	<**0.001**	<**0.001**
Maximum drift	0.048	<**0.001**	<**0.001**
Drift/travel ratio	0.103	<**0.001**	<**0.001**
Virtual velocity	0.083	<**0.008**	<0.409

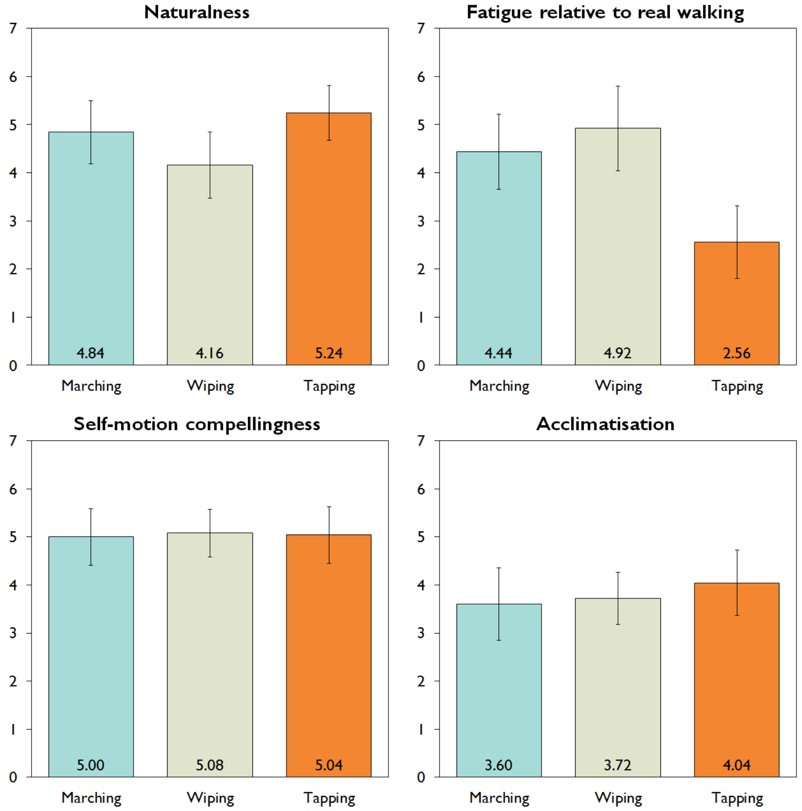

Fig. 4: Results pertaining to the self-reported measures of perceived naturalness. Error bars indicate 95% confidence intervals.

5.2 Presence

The means pertaining to the three items featured in the SUS questionnaire are shown in Figure 5 along with the grand mean of the three items – the SUS mean. The comparison by means of the repeated-measures ANOVA revealed no significant differences.

5.3 Unintended Positional Drift

Figure 6 shows the results related to UPD. The comparison by means of repeated-measures ANOVAs yielded significant differences for all three measures of UPD: total drift ($F(2,25) = 19.79, p < .01$), maximum drift ($F(2,25) = 39.04, p < .01$), and drift/travel ratio ($F(2,25) = 20.42, p < .01$). The post-hoc analyzes indicated that Tapping was significantly different from both March-

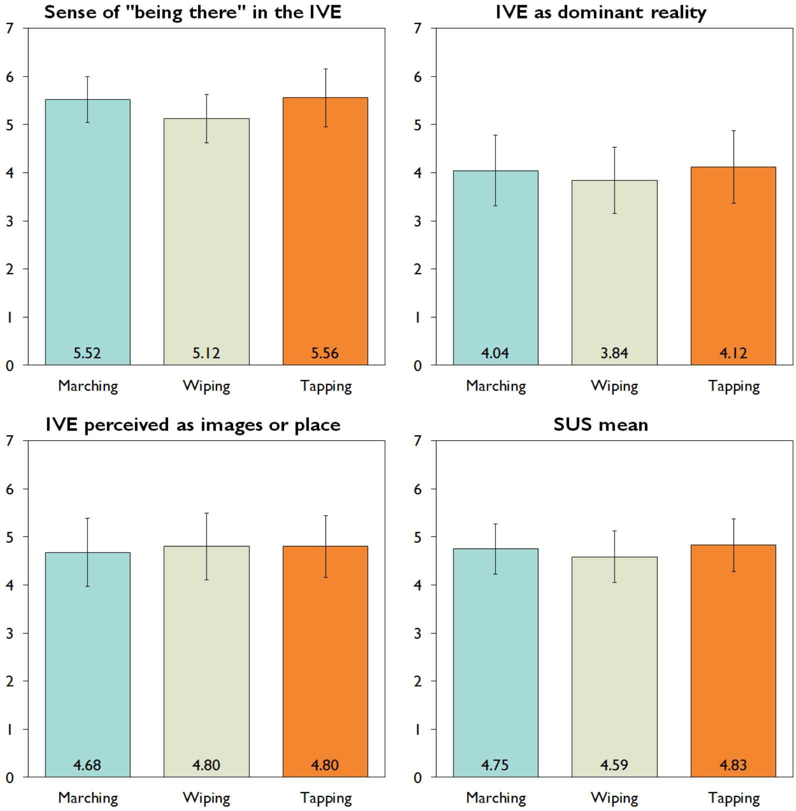

Fig. 5: Results pertaining to the self-reported measure of presence. Error bars indicate 95% confidence intervals.

ing and Wiping in regards to all measures, while the two in no cases differed significantly from each other. Finally it is worth noting that analysis of the performance data revealed that there was a significant difference in terms of the mean velocity of the viewpoint displacement across the three conditions $(F(2,25) = 3.55, p < .04)$.

6 Discussion

The results obtained from the questionnaire item asking the participants to rate explicitly how natural they found the experience of walking, yielded some interesting information. The participants did on average find the Tapping gesture to be the most natural and the mean pertaining to this gesture was significantly higher than the one corresponding to the Wiping gesture.

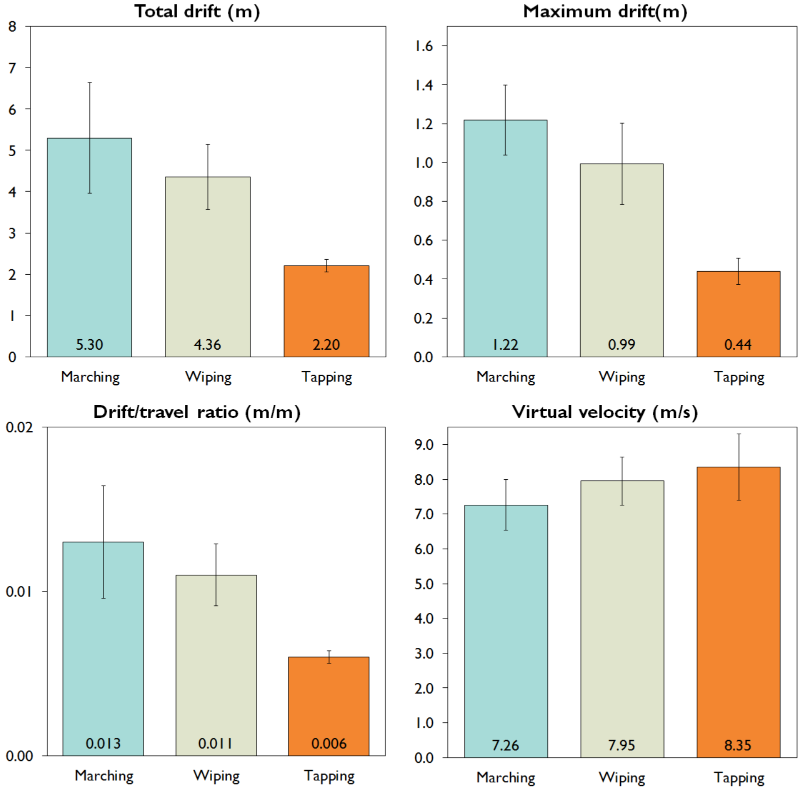

Fig. 6: Results pertaining to the measures of unintended positional drift and the results related to virtual velocity. Error bars indicate 95% confidence intervals.

The Tapping gesture was also perceived as significantly less strenuous compared to Marching and Wiping while the two did not differ significantly from one another. Judging from the mean ratings themselves, it would seem that Tapping was the only of the three gestures that generally was not regarded as more physically demanding than real walking. With that being said, we cannot claim that we have confirmed the assumption that the Marching gesture is more physically straining than real walking since no physiological data related to muscle activity were collected. While the current study did not reveal such an effect, it seems plausible that the activation of the soleus muscles (the large muscles inside the calves) during Tapping might lead to fatigue during prolonged interaction. However, it would seem that the Tapping gesture is successful at partially imitating both the proprioceptive feedback and the perceived degree of muscle activity associated with real walking. Here it is worth noting that a significant difference was found in regards to the virtual speed resulting from the three gestures. Marching resulted in a significantly lower speeds compared to Tapping. This may be viewed as a sign of fatigue during Marching since the inability to maintain high steps would result in reduced virtual speeds. With that being said, it cannot be ruled out that the differences in velocity might have influenced the participants' ratings of naturalness and presence. The measure of self-motion compellingness did not reveal any significant differences between the three gestures suggesting that that all three in part elicited a compelling sensation of movement. Similarly, no differences were found between the means related to the question of how quickly the participants forgot that they were not really walking. Even though the setup used for the current study does not permit tracking of real walking over long distances, a comparison with such a condition could have provided insights regarded how natural the three gestures were compared to their real world counterpart. Moreover, it would have been useful to include a more traditional form of virtual travel (e.g., joystick interaction) since this would have provided a known ground for comparison. The inclusion of these two conditions would similarly have been useful for the assessment of presence.

While the results from the SUS questionnaire did indicate that the participants may have experienced some degree of presence, no significant differences were found between the three gestures. It is possible that the gestures do not elicit different degrees of presence. After all, the three are very similar compared to the WIP technique and push button flight which did differ in terms of presence [29]. With that being said, it is also entirely possible that the employed measure of presence was not sensitive to the difference in presence, or reliably measured it for that matter. Indeed, it has been questioned whether it is sufficient to rely on questionnaires as the sole measure of presence [25].

Finally the results pertaining to UPD were clear and consistent across the three measures. The Tapping gesture differed significantly from the two other gestures in terms of how far the participants on average moved, how far away the participants on average went from the starting point, and how far they on average moved per traveled meter in the IVE. While no significant differences were found between the two other groups, it is worth noting that Marching on average performed the worst in regards to all three measures. The reason why Tapping led to significantly less drift compared to the other two is most likely that the participants while walking straight did not break contact with the ground. Even though this may have prevented them from drifting, four participants explicitly mentioned that it made turning seem unnatural since they during this action were forced to break contact. This necessarily leaves the question: should Tapping be considered the best alternative of the three. When it comes to reducing UPD, the answer is yes, but in regards to naturalness it seems possible that a gesture mixing Marching and Tapping might be ideal. To be more exact, if the user performs the Tapping gesture without constantly keeping contact with the ground – in essence energy efficient Marching – then the user would receive the desired proprioceptive feedback and be able to turn in a more natural fashion. However, it has yet to be determined whether such energy efficient Marching is accompanied by large amounts of UPD. If it is, it seems possible that existing redirection techniques such as subtle reorientation of the user or overt delimitation of the physical space might be used to minimize the issue [20]. An interesting attribute of the Tapping gesture as well as energy efficient Marching, is that they in principle can be used as input for most of the WIP techniques described in section 2, if these were calibrated accordingly. The implementation used for the current study demonstrated that the Tapping gesture generates sufficient vertical foot movement to generate viewpoint displacement. Similarly, vertical foot movement is needed for LLCM-WIP [9] and GUD WIP [38]. Moreover the SF-WIP [14] seems like a viable candidate for controlling virtual movement by means of Tapping or Wiping for that matter. The fact that the user does break contact with the heal when Tapping should the gesture detectable by physical interfaces such as the Walking Pad [3, 4] or the Wii Balance Board. Finally, it seems possible that Tapping will produce enough head movements in order to be used in combination with algorithms requiring such input [26, 35].

7 Conclusions and Future Work

In this paper we have described a study investigating how two novel forms of gestural input for WIP locomotion (Tapping and Wiping) compared to the most commonly used gesture (Marching) in terms of naturalness, presence and positional drift. The participants walked along a path in a virtual environment delivered via a HMD and a 24-channel surround sound system. The results indicate that the gesture Tapping is the most natural and best matches the perceived physical effort of real walking. This has led us to believe that Tapping, or variations of this gesture, might serve as ideal input for WIP techniques since the proprioceptive feedback and perceived physical strain appear similar to the ones experienced during real walking. Finally, no differences were found in terms of presence, but the Tapping gesture produced significantly less positional drift than both of the other gestures. While the current study yielded interesting information, future evaluations are necessary in order to optimize the gestural input for WIP locomotion. Particularly, it seems relevant to perform evaluations involving tasks that are sufficiently general in order to assess differences in usability and performance. Such tasks could include object avoidance and precision tasks, e.g., as starting and stopping efficacy. Moreover, it will be crucial to design tasks allowing for comparison with real walking and more conventional locomotion interfaces.

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Paper B

The Perceived Naturalness of Virtual Locomotion Methods Devoid of Explicit Leg Movements

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Abstract

Walking-in-Place (WIP) techniques have potential in terms of solving the problem arising when an immersive virtual environment offers a larger freedom of movement than the physical environment. Such techniques are particularly useful when the spatial constraints are very prominent, as they are likely to be in relation to immersive gaming systems located in the homes of consumers. However, most existing WIP techniques rely on movement of the legs which may cause users, wearing a head-mounted display, to unintentionally move. This paper details a within-subjects study performed with the intention of investigating how two alternative types of gestural input relying on arm and hip movements compare to the traditional WIP gesture and keyboard input. Visual feedback was delivered through a head-mounted display, and auditory feedback was provided by means of a 16-channel surround sound system. The gestures were evaluated in terms of perceived naturalness, presence, and real-world positional drift. The results suggest that both WIP and arm swinging are perceived as significantly more natural than hip movement and the keyboard configuration. However, arm swinging better matched real walking in terms of energy expenditure and led to significantly less positional drift.

1 Introduction

The advent of low-cost motion tracking and display technology, such as the Microsoft Kinect and Oculus Rift, may bring immersive virtual reality (IVR) into the homes of consumers and into the hands of players within a foreseeable future. We reserve the term IVR to describe systems relying on high-fidelity tracking and multisensory displays to facilitate natural perception and interaction within computer-generated environments. A particularly problematic obstacle facing developers of IVR systems is that users should be able to move freely within the virtual space insofar as the virtual topography and architecture allow it. However, users' real movement is confined to a limited physical space. At best this spatial discrepancy may be detrimental to the user experience. The user may inadvertently probe the boundaries of the system which may hamper the illusion of presence – often defined as the sensation of "being there" in the virtual environment [35]. At worst the discrepancy can be dangerous since immersed users may be unaware of real world obstacles. The problem may become particularly prominent in relation to consumer IVR systems since the limited size of many households makes the spatial discrepancy even greater.

It should be stressed that this problem primarily applies to body-centric locomotion where movement is accomplished through direct interaction with the environment. In regards to vehicular travel, the user indirectly produces movement by manipulating the controls while remaining stationary relative to the vehicle. Since it is possible to generate compelling self-motion illusion even in the absence of vestibular stimulation (e.g., [10], [19], [25], [41]), simulated vehicular travel may elicit a convincing sensation of movement on behalf of stationary users, thus eliminating the problem imposed by possible spatial constraints.

Several potential solutions to the problem of body-centric locomotion within a limited space have been proposed. These include, but are not limited to, elaborate mechanical setups facilitating relatively natural walking without changing the user's position relative to the physical environment (e.g., [8], [12], [13], [14], [20]), and redirection techniques can be used to subtly or overtly reorient or reposition the user within the physical space by manipulating of the stimuli used to represent the virtual world (e.g., [5], [34], [36]). While these solutions have their merits they might not be suitable for application when the spatial, technological and financial constraints are prominent, as they may be in relation to immersive gaming taking place in an average household.

A third group of solutions that better meet the requirements of consumers exists. Walking-in-Place (WIP) techniques enable users to move freely within the virtual environment by performing body movements resembling real world walking while remaining stationary with respect to the physical environment (e.g., [9], [24], [33], [40], [42]).

Existing research on WIP locomotion has involved investigations of how to optimize the performance of the forwards movement in terms of factors such as starting and stopping latency, smoothness of between step motion, within-step speed control, and the efficacy of the step detection (e.g. [9],[42]). However, studies related to the perceived naturalness of WIP interaction are scarce. Moreover, the majority of current WIP techniques rely on gestural input involving movement of the legs. More specifically, it would seem that most techniques take the same gesture as input. The user alternately lifts each leg as if climbing a flight of stairs or marching on the spot. Nilsson, Serafin and Nordahl [22] found that this form of gestural input may be problematic since it leads to unintended positional drift (UPD). That is, users relying on this gesture for locomotion while wearing a head-mounted display (HMD) physically move forwards when walking through the virtual environment. If a WIP interaction technique is to be considered a viable method of input, it is crucial that the user remains stationary.

In the current paper, we present a within-subjects study performed with the intention of investigating how two alternative forms of gestural input, relying on arm and hip movements, compare to the traditional WIP gesture and keyboard input. The paper is structured as follows: Section 2 presents related work pertaining to the facilitation of virtual movement using WIP techniques. Section 3 details a conceptualization of perceived naturalness based on the continuous exchange of information occurring between user and

IVR system. Section 4 details the methods and materials forming the basis for the performed user study. Section 5 summarizes the results which are discussed further in Section 6. Finally, Section 7 summarizes and concludes upon the presented study.

2 Related Work

In their current form WIP techniques cannot compete with real walking in terms of simplicity, straightforwardness, naturalness [40]. However, studies do suggest that they may elicit a stronger sensation of presence than techniques where users press a button to produce forward movement [33]. Particularly, the convenience and cost-effectiveness have been highlighted as factors making the lower level of control and naturalness worthwhile trade-offs [9]. Slater, Usoh and Steed [32] describe that a primary advantage of their original Walking-in-Place technique [30] is that the gestural input generates proprioceptive feedback similar, albeit not identical, to the one resulting from real walking. Moreover, Williams and colleagues [43] found that walking in place on the Wii was as effective as physically walking in a simple spatial orienting task. These potential advantages, combined with consumers' need for low-cost locomotion techniques functioning despite large spatial constraints, suggest the need for finding the best possible WIP technique.

Several different WIP techniques have been implemented. Some rely on step detection via motion tracking technology, such as optical motion capture systems [42], magnetic tracking [9], camera-based tracking of cast shadows [47], or commercially available hardware (i.e. the Microsoft Kinect) [37]. Other techniques rely on interaction with a physical interface such as custom made platforms [2], [3], [4] or readily available hardware (i.e. the Nintendo Balance Board) [43]. These WIP techniques register the walking gesture via explicit tracking of the feet. Notably Slater and colleagues have devised a WIP technique which registers steps via a neural network recognizing patterns in the tracked head movement [30], [33]. An alternative approach is to have the users perform walking-like gestures while standing on a platform preventing them from moving, such as the Wizdish [38] and the Virtuix Omni (www.virtuix.com). When using the Wizdish the user stands on a concave and almost spherical surface. By wearing a pair of low friction shoes users are able to take steps by simultaneously sliding one foot forward and the other backward without breaking contact with the surface. The Virtuix Omni functions in a similar manner but allows the user to perform movements which better resemble real steps.

Most techniques do as suggested rely on variations of the stepping-in-place gesture [21]. Nevertheless, a few exceptions do exist. The so-called Shake-Your-Head technique, proposed by Terziman et al. [39], relies on lateral head oscillation for walking. Sega's game Rise of Nightmares uses the Microsoft Kinect to enable walking by placing one foot in front of the other. The game Kinect Rush: A Disney Pixar Adventure allows users to make virtual characters run and jump by swinging their arms. However, to the authors' knowledge no attempts have been made at comparing these alternative forms of gestural input with the more established WIP gesture.

3 Perceptually Natural Virtual Locomotion

Skalski et al. [28] use the term natural to describe the degree to which users perceive the interaction as predictable, logical or in line with expectations. Thus, they conceptualize naturalness as a psychological state influenced by individual differences as well as the technology itself. Real world actions should be inherently natural considering that we through a lifetime of practice become experts at manipulating the world directly through our body or indirectly by using objects. Skalski et al. [28] argue that, while perceived naturalness should be dependent on the degree of similarity between the real and virtual actions, it seems plausible that repeated use of peripherals, such as a mouse and keyboard, might cause players to find these natural.

3.1 Natural Mapping of Real and Virtual Actions

In his original description of natural mapping Norman [23] did not refer exclusively to the mapping between human actions and their digital counterparts, but rather to the general relationship between controls, their movement and the resulting outcome in the world. Following his account, mapping can range from being completely arbitrary (there is no correspondence between user actions and the outcome of these) to fully natural (it relies on physical analogies or cultural standards to produce a clear connection between the action and its outcome).

In relation to interaction with virtual environments mapping refers to how a system connects human actions with corresponding changes in a mediated environment [35]. The mapping is both a function of the input device as well as the way in which physical actions are translated into their virtual correlates when the input device is manipulated. In relation to video games, natural mapping is commonly viewed as the degree of resemblance between in-game actions and the real actions used to produce them [28]. Skalski et al. [28] describe that it is possible to distinguish between four types of natural mapping which should elicit an increasing degree of naturalness:

1. *Directional natural mapping:* There is a correspondence between the directionality of the controller manipulation and the virtual events (e.g., pressing the right arrow key will produce rightward movement).

2. *Kinesic natural mapping:* The user performs actions mimicking real world behavior, albeit without a physical controller (e.g., the game Air Guitar relies on computer vision to track gestures reminiscent of plucking a guitar).
3. *Incomplete tangible natural mapping:* The user performs real-life actions by means of a tangible controller. Thus, the sensation of touching the virtual object is partially replicated (e.g., the Nintendo Wii allows users to hit a tennis ball by swinging the controller as one would swing a tennis racket)
4. *Realistic tangible natural mapping:* Finally, the highest degree of natural mapping can be achieved through the addition of a realistic, tangible controller (e.g., a physical steering wheel or a gun controller).

This typology provides a good explanation of how different controllers might influence the perceived naturalness of interaction with virtual objects. However, it is less applicable to direct interaction with the environment which does not involve object manipulation (e.g., walking) and it is not sensitive to variations in naturalness caused by different mappings between the physical gestures and the corresponding virtual actions (e.g., when walking in place is used as a proxy for real walking).

3.2 A Natural Sensorimotor Loop

Game designer and writer Chris Crawford has defined interaction as "a cyclic process in which two active agents alternately (and metaphorically) listen, think and speak" [7]. By describing natural interaction in terms of this cyclic exchange of information between the user and system (Figure 1), it seems possible to provide an account of the factors influencing perceived naturalness which is generally applicable to IVR systems, including immersive gaming. To use the example of walking in place as a means of navigating through a virtual environment: the IVR system registers the actions of the user (steps in place), processes this information, and provides an output in one or more sensory modalities (forward translation of the viewpoint in the direction of heading). The user perceives this output (an obstacle is obscuring the path), entailing cognitive and affective processes on his or her behalf, which in turn elicit a behavioral response (the user changes direction). This behavioral response may include actions registered by the system, thus completing the cycle (the user has successfully avoided the obstacle).

In order for the interaction to be perceived as natural the output produced by the user's actions has to be predictable, logical, or in line with expectations. For an IVR simulating physical reality, these expectations are generated from the users past experiences of the real world. In regards to systems relying on natural gestures, perceived naturalness may be viewed as the degree to which performing the gesture produces an experience similar to the real thing. In case of locomotion via walking in place the expectations are based on the user's real world experiences of what speeds might normally be generated from gait parameters such as step frequency and step length. However, it would seem that the perceived naturalness is not just contingent upon the perception of external stimuli, like optic flow contributing to the sensation of self-motion [16]. Internal percepts, such as proprioception, may also be influential.

Indeed, an advantage of WIP techniques may be that they generate proprioceptive feedback similar, albeit not identical, to the one resulting from real walking [32]. Moreover, it would seem that it is not just the sensation of the change in position of one's legs that influences perceived naturalness. A study performed by Nilsson et. al. [21] suggests that the physical effort required to take a step might also be of influence. The perceived naturalness of three different types of gestural input for WIP locomotion was compared: 1) The traditional WIP gesture where users alternately lifts each foot off the ground by raising the thighs in front of the body. 2) A gesture where the users in turn bend each the knee producing backward movement of the lower leg. 3) The user alternately lifts each heel off the ground while keeping the toes in contact with the ground. The self-reported measures revealed that the third gesture, which was the only one of the three that was not perceived as more physically straining than real walking, was perceived as the most natural.

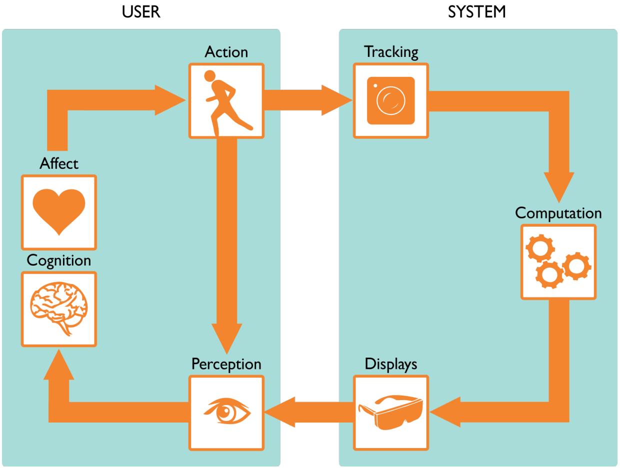

Fig. 1: Illustration of the cyclic exchange of information occurring between user and system during exposure to an IVR system.

4 User Study

It would seem that the perceived naturalness of gestural input for virtual locomotion may be influenced by the sensation that one's limbs are moving as well as the effort it takes to accomplish this movement. Bipedal walking is surprisingly energy efficient since energy is conserved by taking advantage of the forward kinetic energy and the gravitational potential energy of the body's center of mass [15]. Thus, it would seem that gestural input requiring a low energy expenditure might be favorable. In addition to considering energy expenditure, it may also be worth considering gestural input where the user does not break contact with the ground as this may reduce UPD [21]. Since research into gestural input devoid of explicit leg movement seems scarce, it was regarded meaningful to investigate users' walking experiences accompanying virtual locomotion relying on the following gestures:

Hip Movement (HM): Since hip movement is an important factor in the gait cycle [1] a gesture involving such movement was considered. In order produce virtual movement, the user would alternately swing the hips right and left while keeping both feet grounded. Thus, it was the hope that HM would generate proprioceptive feedback which to some extent resembles the one produced during real walking. The biggest potential advantage of this type of gestural input is probably that the user should remain in contact with the ground, thus reducing UPD.

Arm Swinging (AS): Walking is frequently accompanied by rhythmic swinging of the arms [46]. Thus, it was regarded as meaningful to consider gestural input where the user produced virtual movement solely by swinging both arms back and forward. While the proprioceptive feedback generated by AS in some capacity mimics the one experienced during real walking, it comes at a cost. That is, this input method may limit the user's ability to use the arms and hands during locomotion (e.g. manipulating virtual objects or gesturing as part of social interactions). Lastly, in addition to reducing UPD, it was the belief that this gesture would be perceived as less strenuous compared to the traditional WIP gesture.

Walking-in-Place (WIP): Because stepping in places appears to be the most frequently used form of gestural input for WIP locomotion, this gesture was included as a baseline for comparison. A primary advantage of this input method is that it generates proprioceptive feedback similar, albeit not identical, to real walking. As suggested, a drawback is that WIP locomotion may be accompanied by considerable UPD.

Keyboard (KB): Finally it was decided to include an input method, reminiscent of the controls of first person games, where the user simply pressed a button to produce forwards movement. While the absence of appropriate proprioceptive feedback may be regarded as a limitation of this input method, it should result in a minimal amount of UPD.

A within-subjects study was performed in order to determine how the four types of input would compare in terms perceived naturalness, sensation of presence and UPD.

4.1 Participants and Procedure

Twenty participants (17 males, 3 females) aged between 19 and 43 years (M=29.8 years, SD=7.1) took part in the study. They were recruited via a mailing list comprising volunteers from Aalborg University Copenhagen and subscribers to the Danish periodical Ingeniøren (The Engineer). Tickets for the movie theater were offered as compensation for participation. All participants reported having normal or corrected-to-normal vision and hearing. Initially, the four input methods were explained, and the participants were informed of the general purpose of the experiment. It was made explicit that within the context of the current experiment a natural walking experience would be one that felt like real walking. Before the three walks involving gestural input, the system was calibrated by asking the participants to perform the individual gestures until they felt comfortable doing so. This also ensured that the participants understood the gestures. During the walks, the experimenter observed the participants to ensure that they performed the gestures correctly. Once each walk was over, the participants were asked to fill out an electronic questionnaire. The three walks took on average 127.7 seconds to complete (SD = 39.5). The participants tried the four input methods in randomized order.

4.2 Task and Environment

The participants performed the same simple locomotion task during all four walks. They were instructed to walk from one point to another by following a clearly visible path with a length of 400 meters. This relatively straightforward task was favored over more complex ones (e.g. precision or wayfinding tasks) since the intention was for the walking experience to take a natural scenario as its point of departure. For the same reasons, we chose a scenic countryside environment as a setting for the walk. The participants were told to walk at a steady pace they found comfortable; to stay on the path to the extent that it was possible, and to refrain from stopping or walking in the opposite direction. A curved path was purposely chosen since this ensured that the participants were forced to turn to both sides during the walk. The path and environment were identical for all three conditions. A top-down view of the path and a screenshot of the environment as it looks from the user's point of view are shown in Figure 2.

Fig. 2: Left: A top-down view of the environment. The path the participants walked along has been highlighted with red. Right: A screen shot of the environment as it looks from the user's point of view.

4.3 Setup

The movement of the user – the walking gestures and the head motion – was acquired by tracking the position and orientation of markers placed on the body of the user. In all conditions, one marker was placed on the HMD, and one was placed on the chest of the user. No additional markers were used during the KB condition. For HS one marker was placed on the lower back. Two additional markers were placed on the wrists of the user in the AS condition and for the WIP condition two markers were placed on the user's ankles. A 16 camera Optitrack motion capture system was used to track the markers. The 16 cameras were placed along the circumference of a circle with a diameter of 7 meters. Twelve of the cameras were placed at a height of approximately 2.9 meters, and the remaining 4 were placed about 1.8 meters from the ground. The visual feedback was created in the multi-platform game development environment Unity3D and was delivered through a nVisor SX60 head-mounted display with a resolution of 1280x1024 and a diagonal field of view of 60 degrees in each eye. The soundscape accompanying the visuals was composed of ambient sounds, such as the sound of wind blowing and water flowing. An 18-channel surround sound system was used to deliver auditory feedback. The sound system consisted of two RME Fireface 800 interfaces and 16 Dynaudio Bm5A mk II active monitors evenly distributed at ear height along the circumference of the circle defined by the motion capture system. A schematic drawing of the system used for the current study can be seen on Figure 3.

4.4 Synthesis of Virtual Locomotion

The four input methods relied on similar sequences of operations for translating the user's actions into virtual movement. The algorithms used to generate movement from the WIP, HM and AS gestures followed the following four

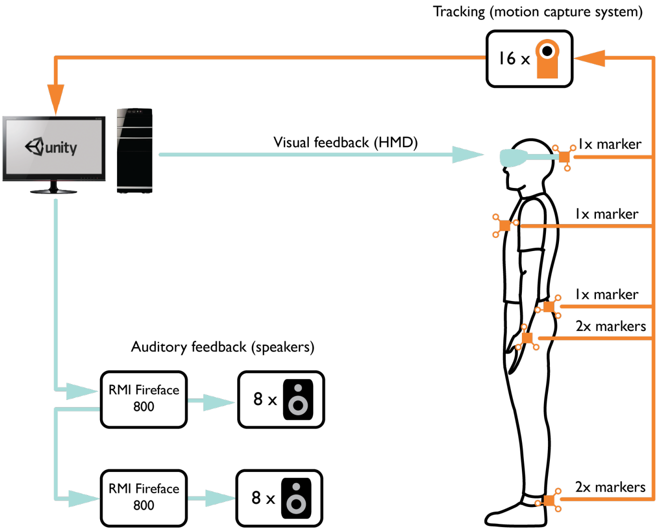

Fig. 3: Schematic drawing of the setup used for the study.

general steps: 1) Preprocessing of motion capture data. 2) Proxy step detection. 3) Gait parameter estimation. 4) Application of estimated velocity and orientation. Only steps 3 and 4 were applied in case of the KB condition.

Data preprocessing: The data obtained from all markers used to generate movement were subjected to preprocessing. The purpose of the marker placed on the chest was twofold; to provide information about the orientation of the body and to serve as a reference when establishing how the markers on the hip, ankles and arms moved relative to the body' orientation. In order to minimize noise the motion capture data was sampled 20 times per second. This data was smoothened using a low-pass filter defined as, $x_n = ax_n + (1-a)x_{n-1}$, where x_n is the current sample, x_{n-1} is the previous sample, and a is the filter's coefficient ($0 < a < 1$). For the current algorithm $a = 0.1$.

Proxy step detection: The primary purpose of this step was to determine whether the movement of the markers indicated that a proxy step was being taken. All three gestures involved oscillating movement of the body part being tracked. Initially, the movement of each marker relative to the body's orientation was determined. That is, the global coordinates of each marker were transformed into the local space of the reference marker mounted of the chest of the participant.

- *WIP:* A step was registered when the vertical oscillation of either of the two ankle markers reached the lower extreme - a minimum.
- *HM:* A step was detected from the left and rightward oscillations when the marker reached either of the two extremes - minima and maxima.
- *AS:* When either arm, oscillating back and forwards, reached the front most extreme - a maximum - a step was registered

The registration of these proxy steps was performed using a peak detection algorithm relying on simple numerical differentiation. If two consecutive derivatives suggested a positive slope followed by a negative slope or a critical point, then a maximum was detected. The same logic applied to the detection of the minima, albeit with a positive slope followed by a negative one.

Gait parameter estimation: Walking velocity ($|v|$) can generally be expressed as the product of step frequency (f) and step length(l): $|v| = f \cdot l$ [45]. Research emanating from the field of biomechanics has shown that step frequency and step length are positively correlated [11]. Moreover, it has been reported that the walk ratio ($\frac{l}{f}$) does not vary considerably over a range of different speeds [27], [48]. Thus, step frequency should be a sufficient predictor of walking speeds in relation to over-ground walking. Indeed, measures of step frequency have previously been used to estimate virtual walking speed in relation to WIP locomotion [42]. However, the relationship between real gait parameters and walking speeds might not be ideal for the generation of virtual movement in relation to WIP locomotion [6]. To be exact, Bruno et al. [6] highlight that the physical movements of stepping in place differ from those of actual walking. Unlike real walking, the feet motion is predominately vertical and the time it takes to perform a step in place may also be lower than taking an actual step. For that reason Bruno et al. [6] suggest that, instead of primarily relying on temporal characteristics of the WIP gait cycle, one might use the footstep amplitude (the step height). Seeing as the gestures used for the current study differed considerably from actual walking the algorithms used to generate the virtual speed relied on estimations of both f and l. Because the virtual velocity was given as the product of the f and l it was ensured that a combination of very short step lengths and unnaturally high step frequencies would not produce exaggerated velocities.

In case of all three types of gestural input, f was derived from the time between the last two proxy steps. In order to determine the step length the maxima and minima, obtained through peak detection, was used as follows:

- *WIP:* The mean distance between the latest vertical minimum and maximum for each foot (the mean height of the last two steps).

- *HM:* The distance between the latest sideward maximum and minimum was used (the magnitude of the last hip oscillation).
- *AS:* The mean distance between the minimum and maximum in the forward direction was established (the mean magnitude of the last two arm swings).

Because these distances did not represent actual step lengths, a scale factor was applied. This scale factor was established during the calibration performed before each walk. Based on their heights h, the normal step length of the individual participants was defined as $l_{norm} = h \cdot 0.41$ [26]. The scale factor was then defined as $S = l_{norm}/d_{cal}$, where d_{cal} corresponds to the mean distance between minima and maxima obtained during the calibration. In the KB condition the step frequency was fixed as 2.5 steps per second and the step length equal to l_{norm} at all times.

Application of velocity and orientation: Finally, if it was established that the user was not currently standing still, the walking velocity was applied in the direction defined by the marker on the user's chest. The following criteria was used to determine whether the user was stationary:

- *WIP:* If neither of the two ankle markers had moved less than 1 cm. within the last 200 ms then it was assumed that both feet were grounded and the user thus stationary.
- *HM:* If the hip marker had moved less than 0.5 cm within the last 200 ms or if the distance between the last maximum and minimum was less than 10% of the average distance established during calibration.
- *AS:* If the largest movement performed by one of the two wrist markers was less than 0.5 cm within the last 200 ms or if the distance between the last maximum and minimum for one of the two arms was less than 10% of the average distance established during calibration.

In the KB condition the orientation of the chest marker was also used to determine the direction of heading and the user was considered stationary if the key was released.

4.5 Measures

The primary purpose of the study was to determine how the four input methods compared in terms of perceived naturalness. However, two additional factors were considered, namely, the participants' sense of presence and the amount of UPD occurring during the walks. Perceived naturalness and presence were assessed by means of self-reports and UPD was evaluated based on behavioral data.

Self-reported Measures of Naturalness and Presence

The perceived naturalness was assessed by means of four questionnaire items requiring the participants to rate their level of agreement with particular statements on 7-point Likert-type scales. The four items related to the following topics:

- *Naturalness:* As in other questionnaires related to the experience of IVRs [17], [18], [33], [44], one questionnaire item explicitly asked the participants to rate how natural they found the experience of walking in the IVR.

- *Physical strain:* It seems likely that gestural input will be experienced as more natural if it requires a degree of muscle activity similar to real walking. Thus, an item was included which asked the participants to indicate how physically strenuous the input methods were compared to the action they were serving as a proxy for.

- *Self-motion compellingness:* Since natural walking involves exocentric motion perception, an item was added asking the participants to rate whether they indeed felt as if they were moving during the virtual walk.

- *Acclimatization:* In order to determine how quickly interaction via the input methods became second nature, the questionnaire contained an item asking the participants to rate how quickly they forgot that they were not really walking.

Moreover, the questionnaire included three items pertaining to the participants' sensation of presence within the virtual environment. The included items were the three items featured in the original version of the Slater-Usoh-Steed (SUS) questionnaire [30],[31]. These items assess the subjective sense of presence based on three factors: 1) The extent to which the participants had a sensation of "being there" in the IVR. 2) The extent to which the IVR was perceived as the dominant reality. 3) The extent to which exposure to the IVR gave rise to a sense of viewing images as opposed to having visited a place. Like the remaining questions, these items were answered on 7-point scales where a high rating would be indicative of presence.

Behavioral Measures of Unintended Positional Drift

In order to quantify the amount of positional drift accompanying the four input methods we employed the three measure of UPD proposed by Nilsson et al. [21]: 1) *Maximum drift* (the largest physical distance the user had been from the point where the locomotion started). 2) *Total drift* (the total physical distance covered by the user during the walk). and 3) *Drift/travel ratio:* (the ratio describing how far the user has drifted in the real world per traveled distance in the virtual world).

In order to produce these measures, the participants' real and virtual positions were logged twice a second. The logging was commenced and terminated once the participants crossed two previously defined points along the gravel path. Finally, performance data related to completion time and traveled distance was recorded, so as to get a measure of the velocity of the viewpoint transformation.

5 Results

Repeated-measures analyzes of variance (ANOVAs) were used to compare the means obtained from all measures ($\alpha = .05$). Significant measures were subsequently analyzed by means of paired sample, two-tailed t-tests using Bonferroni-corrected alpha values ($\alpha = .008$). The p-values obtained from these post-hoc analyzes are presented in Tables 1 and 2.

5.1 Perceived Naturalness:

The results obtained from the questionnaire items related to perceived naturalness are shown in Figure 4. Significant differences were found in relation to the item asking explicitly about how natural the walking experience was ($F(3, 19) = 10.07, p < .01$) and in relation to the item requiring the participants to rate whether the gesture had been less or more physically straining than real walking ($F(3, 19) = 38.61, p < .01$). In the former case, the post-hoc analysis revealed a significant difference between the KB and AS, KB and WIP, HM and AS, and HM and WIP (Table 1). In regards to physical strain, significant differences were found between KB and HM, KB and AS, KB and WIP, and AS and WIP (Table 1). No significant differences were found between the means obtained from the items related to perceived self-motion compellingness or the item asking how quickly the participants forgot that they were not really walking.

5.2 Sensation of Presence:

The means pertaining to the three items featured in the SUS questionnaire are shown in Figure 5 along with the grand mean of the three items – the SUS mean. The comparison by means of the repeated-measures ANOVAs revealed a significant difference in regards to the question related to the sensation of "being there" in the virtual environment ($F(3, 19) = 3.51, p = .02$) and the SUS score ($F(3, 19) = 3.11, p = .03$). In regards to the sensation of the sensation of "being there", the post-hoc analysis only indicated that there

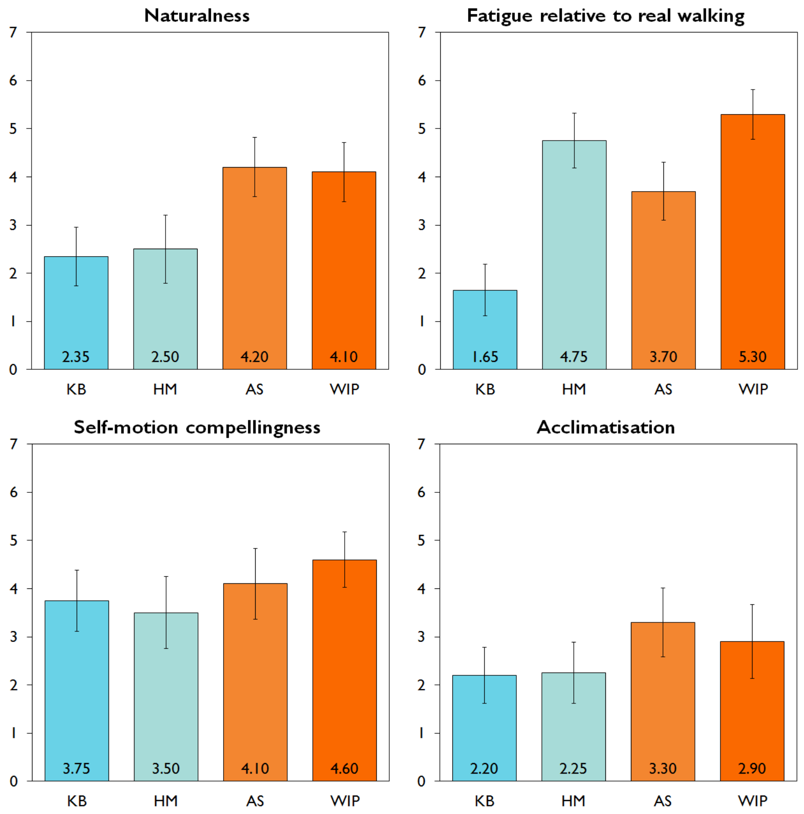

Fig. 4: Results pertaining to the self-reported measures of perceived naturalness. Error bars indicate 95% confidence intervals.

was a significant difference between HM and AS. The post-hoc analysis revealed no significant differences between the individual means of the SUS mean (Table 1).

5.3 Unintended Positional Drift:

Figure 6 shows the results related to UPD. The comparison by means of repeated-measures ANOVAs yielded significant differences for all three measures of UPD: total drift ($F(3, 19) = 29.14, p < .01$), drift/travel ratio ($F(3, 19) = 29.95, p < .01$), and maximum drift ($F(3, 19) = 43.66, p < .01$). In regards to total drift and the drift/travel ratio, the post-hoc analyzes indicated significant differences between all conditions except HM and AS. For maximum drift, significant differences were found between KB and WIP, HM and WIP, and AS and WIP (Table 2). Finally, it is worth noting that analysis of the

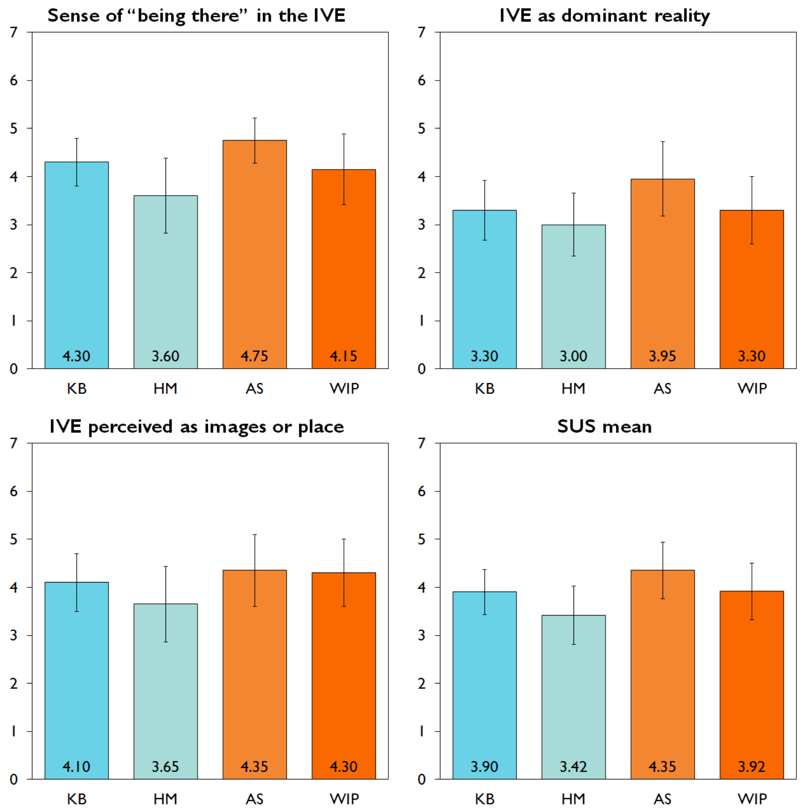

Fig. 5: Results from the self-reported measure of presence. Error bars indicate 95% confidence intervals.

performance data revealed that there was a significant difference in terms of the mean velocity of the viewpoint displacement across the three conditions ($F(3, 19) = 9.88, p < .01$).

6 Discussion

The questionnaire item asking the participants to rate how natural they found the walking experiences yielded some interesting indications. The participants did in average find AS and WIP to be significantly more natural than KB and HM. Neither AS and WIP, nor KB and HM, differed significantly from one another. Considering that the poles of the scale indicated that the participants were either disagreeing or agreeing with the statement that the walking experience was natural, it would seem that both AS (4.20) and WIP

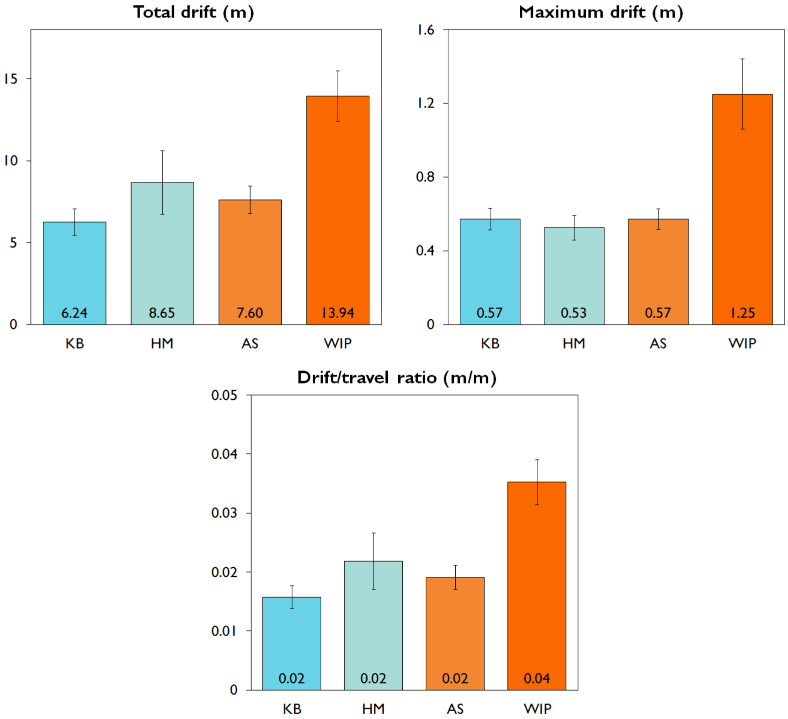

Fig. 6: Results pertaining to the measures of UPD. Error bars indicate 95% confidence intervals.

(4.10) in average were perceived as somewhat natural while KB (2.35) and HM (2.50) were not.

When looking at the ratings pertaining to fatigue relative to real walking, it is worth recalling that the lowest rating on the 7 point scale indicated that the interaction had required much less physical effort than real walking, while the highest rating signified that the interaction had required much more effort. Thus, ratings of '4' would suggest that the required physical effort was similar or identical to the one of real walking. KB was found significantly less strenuous than the three interaction techniques relying on gestural input. The average rating of 1.65 for KB suggests that this input method was perceived as less physically straining than real walking. This was to be expected given that the only movement required by this method was the one performed when the user turned to alter the direction of heading. Moreover the mean ratings for HM (4.75), WIP (5.30) and AS (3.70) suggest that HM and WIP were regarded as the techniques requiring the most physical effort, but only WIP differed significantly from AS. A possible explanation for this difference is that AS involves a pendulum swinging motion and grav-

	Naturalness	Relative fatigue	"Being there"	SUS mean
KB-HM	.769	<**.001**	.064	.158
KB-AS	<**.001**	<**.001**	.013	.156
KB-WIP	<**.001**	<**.001**	.659	.949
HM-AS	**.001**	.023	**.008**	.012
HM-WIP	**.005**	.186	.172	.117
AS-WIP	.781	<**.001**	.137	.165

Table 1: P-values obtained from paired sample, one-tailed t-tests related to the self-reported measures of perceived naturalness and presence. Values indicating a significant difference are highlighted with bold (α = .008).

	Total drift	Max drift	Drift/travel ratio
KB-HM	**.007**	.240	**.007**
KB-AS	<**.001**	.969	<**.001**
KB-WIP	<**.001**	<**.001**	<**.001**
HM-AS	.179	.133	.159
HM-WIP	**.001**	<**.001**	**.001**
AS-WIP	<**.001**	<**.001**	<**.001**

Table 2: P-values obtained from paired sample, one tailed t-tests related to the behavioral measures of unintended positional drift. Values indicating a significant difference are highlighted with bold (α = .008).

ity, therefore, exerts a restoring force on the arms. Moreover, the two other gestures involved movement of a large part of the lower body. Notably, AS would appear to be the technique that best resembled real walking in terms of physical effort.

Based on these results it seems plausible that the proprioceptive feedback accompanying WIP may have contributed to this technique being perceived as natural, whereas the similarity between the physical strain of AS and real walking may have contributed AS being perceived as natural. Moreover, it is worth recalling that real walking often is accompanied by rhythmic swinging of the arms [46]. AS may therefore also have involved some of the proprioceptive feedback generated during real walking, albeit originating from the arm movements rather than legs. Notably, it was observed that some participants, despite being instructed not to move their legs, found it hard keeping their legs static while using AS for locomotion.

The results from the SUS questionnaire suggest that some participants may have experienced presence in some capacity. However, the marginally significant differences revealed by the analysis of variance and the insignificance of the post-hoc test leaves us unable to conclude whether some gestures elicited a stronger sensation of presence than others. It is possible that the four techniques did not lead to varying degrees of presence on behalf of the participants. It also conceivable that the employed measure of presence was not sensitive to the difference in presence, or reliably measured presence for that matter. Indeed, it has been questioned whether it is sufficient to rely on questionnaires as the sole measure of presence [29].

Finally, the results pertaining to UPD were relatively clear and consistent across the three measures. However, one cautionary note should be added. The physical positions of the participants were tracked using the marker mounted on the back of the HMD. An implication of this is that the participants' head movements may have become registered as drift. While the measure of maximum drift is unaffected, both total drift and the drift/travel ratio have become exaggerated. With that being said, the two measures still provide information about the relative difference between the four techniques. WIP differed significantly from the remaining three input methods in terms of total drift, maximum drift and travel/drift ratio. That is, when the participants used the WIP technique, they in average drifted more in total, moved further away from the starting position, and drifted more per traveled distance in the virtual environment. The relatively large difference in UPD can most likely be ascribed to the fact that WIP was the only input method involving explicit leg movement. KB differed significantly from the other techniques in terms of total drift and drift/travel ration, suggesting that the users moved shorter in total and drifted less per traveled virtual distance. Generally this suggests that WIP leads to the largest amount of UPD while KB lead to the least. Notably, KB did not differ significantly from HM and AS in terms of maximum drift. Moreover, it is interesting to note that HM and AS seemingly led to a bit more UPD than KB. It was observed that some participants had a tendency to occasionally break contact with the ground while moving their hips from side to side. This could have entailed a limited amount of UPD. Also, some participants found it hard not to move their legs while swinging their arms, which might explain why this gesture led to slightly more UPD than KB.

7 Conclusions and Future Work

The current paper detailed a study investigating how two alternative interaction techniques for virtual locomotion (HM and AS) compared to the most commonly used gesture (WIP) and locomotion via button pressing (KB). The four input methods were compared in terms of perceived naturalness, the sensation of presence and unintended positional drift. The participants walked along a path in a virtual environment delivered via a HMD and a 16-channel surround sound system. The results indicate that AS and WIP were perceived as the most natural. WIP was experienced as the most physically straining and KB the least. AS was the gesture that best matched real walking in terms of perceived energy expenditure. No significant differences were found between the four conditions in terms of presence. Finally, WIP led to significantly more drift than the remaining three gestures and KB led to the least. Conclusively, it would seem that WIP and AS are preferable over KB in terms of perceived naturalness while AS appear to exceed WIP in terms of perceived physical strain and UPD. Thus, it would seem that AS may be considered a meaningful alternative to the WIP gesture – assuming that the interaction does require use of one's arms during the locomotion. With that being said, it might be worth considering alternative arm gestures. Particularly, it would be interesting to adopt the flexed arm posture accompanying jogging and rely on the elbow flexion-extension pattern for input. In addition to serving as an alternative to AS, this gesture might also be used to differentiate between walking and running. That is, WIP alone would result in walking while a combination of WIP and arm movements would result in running. Even though the current study yielded interesting information regarding the perceived naturalness of the different input methods, future evaluations are necessary in order to optimize the input methods. Particularly, it will be relevant to perform evaluations relying on tasks that are sufficiently general in order to assess differences in usability and performance. Such tasks could include object avoidance and precision tasks, e.g., starting and stopping efficacy. Moreover, it might be relevant to assess the usability, performance, and perceived naturalness during more complex interaction with the environment, such as item localization tasks or pursuit and flight scenarios.

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Paper C

A Comparison of Different Methods for Reducing the Unintended Positional Drift Accompanying Walking-in-Place Locomotion

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Abstract

If Walking-in-Place (WIP) techniques are to be considered a useful way of facilitating virtual locomotion, it is crucial that the user remains stationary with respect to the physical environment. However, it has recently been documented that WIP locomotion may lead to unintended positional drift (UPD). Users walking in place while wearing a head-mounted display tend to drift physically in the direction which they are headed within the virtual environment. This paper details a within-subjects study evaluating different methods for minimizing UPD. The study included 14 conditions: 13 different types of feedback informing the user that a certain amount of drift had occurred and a control condition devoid of feedback. The feedback differed in terms of sensory modality (auditory, visual or audiovisual), onset mode (gradual or sudden) and presentation mode (either the feedback constituted a warning or a deprivation of the stimuli used to represent the virtual world). Finally, a condition providing passive haptic feedback (a circular carpet) was included. The types of feedback were assessed in terms of how effectively they reduced UPD as well as how helpful and intrusive they were perceived. The results suggest that both passive haptic feedback and feedback types with gradual onset are the most efficient at controlling the user's physical movement. However, the passive haptic feedback was regarded as more helpful and perceived as less disruptive than some of the feedback types with a gradual onset.

1 Introduction

Recent advances in display and tracking technologies, such as Microsoft's Kinect (www.xbox.com/kinect) and the Oculus Rift (www.oculusvr.com), may bring immersive virtual reality (IVR) into homes of consumers within a foreseeable future. Since compelling self-motion illusions may be elicited on behalf of stationary individuals [8, 14, 22, 32], vehicular travel may be achieved with relative ease using consumer IVR systems. However, the same does not appear to be the case in relation to body-centric locomotion (i.e., walking or running). Within the virtual environment, the user should be able to move freely, insofar as the virtual topography and architecture allow it. However, the user's real world movement is typically confined to a limited interaction space. Potential solutions to this problem include elaborate mechanical repositioning systems, such as omnidirectional treadmills [5, 11, 12, 15], subtle and overt redirection and repositioning of the user [10, 27, 28] and Walking-in-Place (WIP) techniques [7, 13, 25, 30, 31, 33]. While the problem brought about by the discrepancy between the size of the virtual and real environments may be solved using either mechanical repositioning systems or redirection and reorientation of the user, these are not currently viable when spatial, technological and economic constraints are prominent (i.e. in the household of an average consumer). The advantages of WIP techniques include, but are not limited to, convenience and cost-effectiveness [7], good performance on simple spatial orienting tasks [20, 34], generation of proprioceptive feedback similar, albeit not identical to, the one resulting from real walking [24], and the capacity for eliciting a stronger sensation of presence than more traditional peripherals when used for virtual locomotion [25, 31]. Thus, WIP techniques constitute a promising approach to facilitating relatively natural virtual locomotion on behalf of users interacting with virtual worlds within the privacy of their homes. However, it has recently been documented that users relying on WIP techniques for virtual locomotion need not always remain stationary. Nilsson, Serafin and Nordahl [18] describe that users wearing a head-mounted display (HMD) while walking in place often physically move in the direction which they are headed within the virtual environment. The authors refer to this phenomenon as unintended positional drift (UPD). Notably, the problem of UPD has also been addressed by Williams et al. [36] and positional drift has previously been observed on behalf of blindfolded individuals walking or running in place after they have been walking or running on a treadmill [1, 21]. If WIP interaction techniques are to be considered meaningful solutions to the problem of incompatible real and virtual spaces, it is crucial that the users remain stationary.

This paper details a study performed with the intention of investigating how different types of feedback compare in terms of their ability to minimize the positional drift occurring when users wear a HMD while relying on WIP techniques for facilitating virtual locomotion.

2 Related Work

Research explicitly addressing the problem of UPD is scarce. Generally it would seem that existing approaches to minimizing UPD can be divided into two categories, namely, alternative forms of gestural input and physical constraints. Moreover, existing virtual redirection techniques might also be applicable to WIP locomotion.

2.1 Alternative forms of gestural input

Nilsson et al. [16] performed a study investigating how three different forms of gestural input for controlling WIP locomotion compared to one another in terms of naturalness, presence and positional drift [16]. The compared gestures were: 1) The gesture most commonly used in relation to WIP, namely, a gesture where the user alternately lifts each foot off the ground by raising the thighs in front of the body. 2) A gesture where the user in turn bends each knee producing backward movement of the lower leg. 3) The user alternately lifts each heel of the ground while keeping the toes in contact with the ground. While UPD originally was intended as a secondary measure, the evaluation yielded interesting results. The third gesture led to significantly less UPD compared to the other forms of gestural input. The authors argue that the reason why this gesture led to significantly less drift most likely is that the participants while walking straight did not break contact with the ground. Nilsson, Serafin and Nordahl [17] recently performed a similar study comparing four different input methods for WIP locomotion: 1) The common WIP gesture. 2) A gesture where the user alternatively swings the hip to the right and left while keeping both feet grounded. 3) A gesture involving swinging both arms back and forward. 4) The user presses a button to produce forwards movement. The results revealed that the common WIP gesture led to significantly more drift compared to the other three types of input. Again, the difference in UPD was believed to be caused by the leg movements accompanying the common WIP gesture.

2.2 Physical constraints

Williams et al. [36] present a study comparing gaze directed and torso direct WIP locomotion. While the study did not explicitly assess UPD, the authors do present the measure they took in order to minimize positional drift. Since the motion detection was implemented using two Microsoft Kinects it was essential that the user remained relatively stationary. In order to ensure this, the participants were asked to walk in place on a 1×1 meter cardboard pad which was taped to the floor. It was the belief that the participants would be able to stay within the 1×1 meter area by relying on the passive haptic feedback provided by the pad.

2.3 Redirection techniques

Redirection techniques cover a collection of approaches to support natural walking within immersive virtual environments by subtly or overtly influencing the orientation or position of the user by continuously or discretely manipulating the stimuli used to represent the virtual world [28].

Subtle redirection techniques are as the name implies intended to redirect or reorient the user without the manipulation being noticed [28]. Subtle repositioning may be achieved by manipulating the virtual walking speed, that is, application of translation gains falling below a perceivable threshold [27, 37]. While the use of translation gains does not seem particularly relevant in regards to the issue of UPD, it is possible that the amount of UPD might be influenced by the perceived virtual velocity.

Subtle reorientation may similarly be achieved by applying rotation gains and thereby exaggerating or decreasing the rotation of the user [27]. Subtle reorientation may also be accomplished by manipulating the virtual architecture in ways that are not physically possible [29]. It does seem possible that subtle techniques such as illusory manipulation of architecture [29] may be applicable. However, it has been argued that the application of rotational gains to the user's point of view may be particularly promising in relation to WIP locomotion [18]. Steinicke et al. [27] performed a study demonstrating that it is possible to turn stationary users 49% more or 20% less than the perceived virtual rotation and that it is possible to reorient walkers by 13% while covering a distance of 5m. Considering that a drifting user moves at considerably slower speed than a walker, it should be possible to apply subtle rotational gains and achieve an even greater reorientation per traveled physical distance. Thus, gradual rotation of the user's point of view might make it possible to achieve controlled UPD. Moreover, it seems possible that subtle manipulation of the user's orientation may be performed in a markedly different way in order to reduce UPD. That is, it may be possible to slightly increase the inclination of the environment causing the user to lean backwards Potentially this could reduce UPD and perhaps even cause the user to drift backward.

Unlike subtle redirection, overt techniques are not designed to be imperceptible. Overt repositioning may be achieved by continuously translating the user's position relative to the virtual environment, thus producing experiences similar to being on a moving walkway, or by facilitating physically impossible movements such as teleportation [2, 3]. Overt reorientation has been made possible through freeze-and-turn resetting [35] where the virtual view is frozen, and the users are instructed to reorient themselves towards a certain point. Once the user is facing in the desired direction, the virtual view is unfrozen. Different types of visual feedback have also been used to make the user aware that the edge of the physical space has been reached. Cirio et al. [4] introduce three novel metaphors for safe navigation within virtual environments mediated via a CAVE-like system: 1) *Constrained Wand and Sign* which extends the traditional wand-metaphor by adding warning signs informing the user that the CAVE wall is close. 2) *Magic-barrier tape* where barrier tape is displayed when the user reaches a physical boundary and reorientation, can be performed by manipulating the tape. 3) *The Virtual Companion* where a small bird warns the user that he or she has gotten close to the physical boundary. Nilsson, Serafin and Nordahl [18] hypothesize that similar results could be achieved in relation to WIP locomotion through use of a simple Heads-Up Display warning the user when he or she has drifted too far. Moreover, the authors propose that it may be possible to design overt redirection techniques that are less detrimental to the sensation of presence. To elaborate, it has been shown that gradual transition into a given virtual environment through a portal displayed within an intermediate transitional environment can increase the sensation of presence [26]. Similarly, it may be possible to use a metaphor of the theater stage to delimit the possible walking area [18]. If the user drifts or deliberately steps away from walking are, the spotlight is exited and environment gradually becomes darker. If user wish to stay 'on stage', a step backward will ensure that this happens. Moreover, if the user has stepped 'off stage', it is possible to look back at the spotlight and see the virtual environment "inside" the cone of light. This is believed to make the steps on and off the virtual stage intuitive and possibly less intrusive [18].

3 User Study

The usefulness of WIP locomotion is largely contingent upon the user remaining within an area of relatively limited size. However, no formal studies evaluating the efficacy of different methods for reducing UPD have been performed. Consequently, the objective of this study was to determine how different types of feedback compare in terms of their ability to minimize UPD. Common to the different types of feedback was that they were intended to keep the user within a walking area with a fixed size. The introduction of such feedback may potentially have a negative influence on the experience of the virtual environment. Therefore, the study was also intended to determine the degree to which the feedback disrupted the sensation of being there in the virtual environment.

3.1 Study Design

In order to meet this aim, a within-subjects study was performed including 14 conditions. Thirteen of the conditions corresponded to a unique type of feedback and one condition devoid of any feedback was included as a control. The feedback differed in terms of the sensory modality used to provide the stimuli (*visual*, *auditory*, *audiovisual* or *haptic*). In case of the visual, auditory and audiovisual feedback different conditions were also included depending on the feedback onset mode and the presentation mode. The onset mode was either *sudden* (the feedback was presented suddenly when the participant reached a fixed distance from the physical position where the locomotion started) or *gradual* (the feedback gradually became more prominent as the user moved further away from the position where the locomotion started). The presentation mode varied in terms of whether the feedback acted as a *warning* (feedback extraneous to virtual environment was presented so as to alert the user) or as a *deprivation* (the user was alerted through deprivation of the stimuli used to represent the virtual environment). The conditions were presented in randomized order. Figure 1 provides an overview of the 14 conditions used for the study.

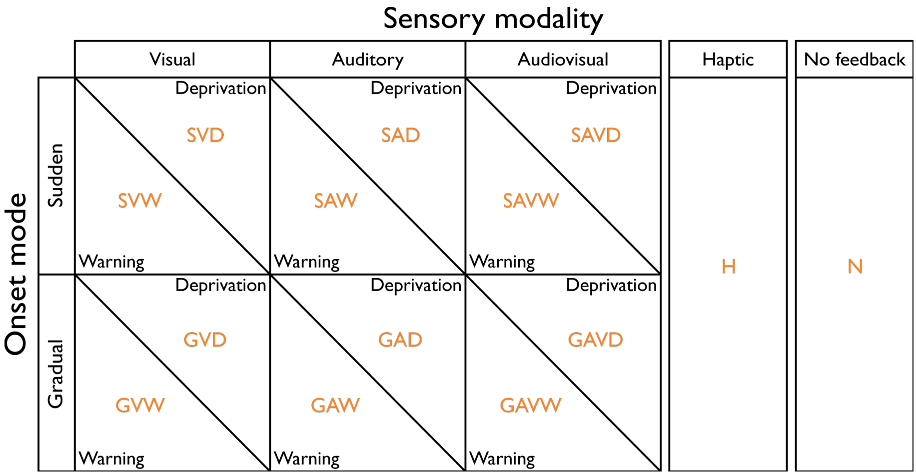

Fig. 1: Overview of the 14 conditions used for the study. The labels used when referring to the individual conditions are presented in red font.

3.2 Participants

Twenty participants (18 males, 2 females) aged between 19-41 years (M=25.6 years, SD=6.4) took part in the study. They were recruited via a mailing list comprising volunteers from Aalborg University Copenhagen and readers of the Danish periodical Ingeniøren (The Engineer). Tickets for a movie theater were offered as compensation for participation. All participants reported having normal or corrected-to-normal vision and hearing.

3.3 Task and Environment

The participants performed a simple locomotion task, namely, walking from one point to another along a clearly visible path through a virtual forest (Figure 2). In all conditions the users relied on the traditional stepping in place gesture for generating virtual movement. This gesture was chosen since it seemingly is the type of gestural input that leads to the largest amounts of UPD [16, 17]. The participants were instructed to walk at a steady and comfortable pace; to stay on the path to the extent that it was possible, and to refrain from stopping or walking in the opposite direction. Moreover, they were told to use the feedback to stay within the center of the walking area to the best of their abilities. The task and environment were identical across all conditions.

Fig. 2: A screenshot of the environment as it appeared to the participants.

3.4 Setup

A 16 camera Optitrack motion capture system was used to track the movement of the participants. The 16 cameras were placed along the circumference of a circle with a diameter of 7 m. Twelve of the cameras were placed at a height of approximately 2.9 m, and the remaining 4 were placed about 1.8 m from the ground. Markers were placed on the HMD and on the participants' hip and ankles. The visual feedback was produced using Unity3D and was delivered through an nVisor SX60 head-mounted display with a resolution of 1280×1024 and a diagonal FOV of 60° in each eye. The soundscape accompanying the visuals was composed of ambient sounds, such as the sound of wind blowing. The amplitude of the soundtrack was identical across all conditions except the ones involving auditory deprivation (SAD, SAVD, GAD and GAVD). A 16-channel surround sound system was used to deliver auditory feedback. The sound system consisted of two RME Fireface 800 interfaces and 16 Dynaudio Bm5A mk II active monitors evenly distributed at ear height along the circumference of the circle defined by the motion capture system. A schematic drawing of the system can be seen in Figure 3.

3.5 Study Stimulus

The walking area was defined as a circle with a center corresponding to the initial, physical xz-position of the participant and a radius of 40 cm. The different types of feedback did as suggested delineate a walking area within which virtual locomotion was possible. In the conditions involving a sudden onset of the feedback, no feedback was presented until the distance from the center exceeded 40 cm. In case of the conditions involving gradual onset the walking area was divided into two zones (see Figure 4): the *safe zone* (the central region of the walking area with a radius of 20 cm) and *warning zone* (the portion of the walking area not occupied by the safe zone). As long as the participant remained within the safe zone no feedback was presented. Once

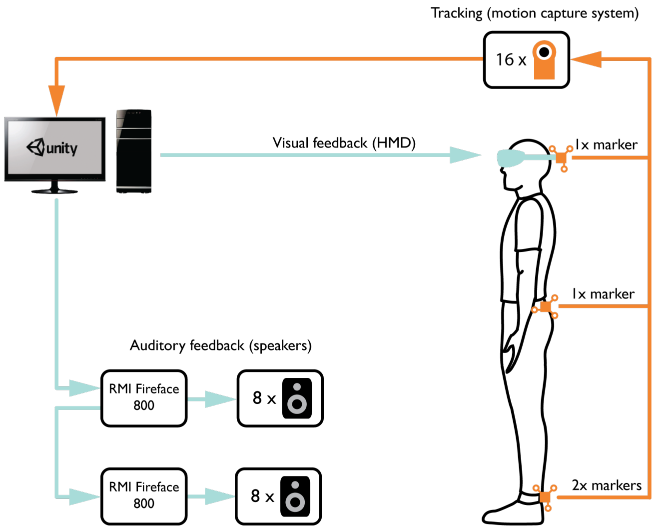

Fig. 3: A schematic drawing of the setup used for the study.

the participant entered the warning zone, the feedback gradually became more intense. The intensity of the feedback was mapped to the distance between the participant and the inner edge of the warning zone. That is, when the distance to the center of the walking area was 20 cm or less no feedback was presented. As this distance increased, the intensity of the feedback increased proportionally and reached its maximum when the distance to the center was 40 cm or higher. The visual, auditory and audiovisual feedback used for the study can be summarized as follows:

1. *Visual warning:* The visual warning comprised of a red stop sign placed at the center of the participants' field of view. For gradual feedback onset, the intensity of the feedback corresponded to the opacity of the sign (see Figure 5).

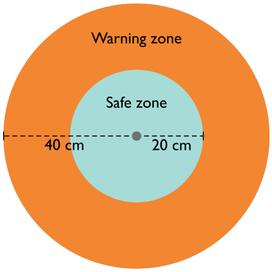

Fig. 4: Illustration of the walking area defining the area where virtual locomotion is possible.

2. *Auditory warning:* The auditory warning comprised a synthesized alarm sound akin to that of a car alarm. For gradual feedback, onset the intensity of the auditory feedback corresponded to the amplitude, which got gradually higher as the participant got closer to the edge of the walking area.
3. *Audiovisual warning:* The audiovisual warning comprised a combination of 1. and 2.
4. *Visual deprivation:* When the participants were deprived of visual feedback the image became black. For the gradual onset, the image became gradually darker as the participant got closer to the edge of the walking area (see Figure 5).
5. *Auditory deprivation:* Auditory deprivation involved the sound of the virtual environment becoming silenced. For the gradual onset of the feedback, the amplitude became gradually lower as the participant got closer to the edge of the walking area.
6. *Audiovisual deprivation:* The audiovisual deprivation comprised a combination of 4. and 5.

In addition to the conditions listed above, a condition involving passive haptic feedback was included. To be exact, the users would stand on a circular carpet with a diameter corresponding to the one of the walking area (80 cm). In all conditions, except the one involving no feedback, virtual locomotion was only possible while the participant remained within the walking area.

3.6 Synthesis of Virtual Locomotion

The algorithm facilitating WIP locomotion relied on a simple sequence of operations for translating the user's steps in place into virtual movement. That is, the following four general steps: 1) Preprocessing of motion capture data. 2) Proxy step detection. 3) Gait parameter estimation. 4) Application of estimated velocity and orientation.

Data preprocessing: The vertical component of the data obtained from the two makers placed on the ankles were subjected to preprocessing. The motion capture data was sampled 20 times per second and subsequently this data was smoothened using a first order low-pass filter defined as, $x_n = ax_n + (1 - a)x_{n-1}$, where x_n is the current sample, x_{n-1} is the previous sample and a is the filter's coefficient ($0 < a < 1$). For the current algorithm $a = 0.1$.

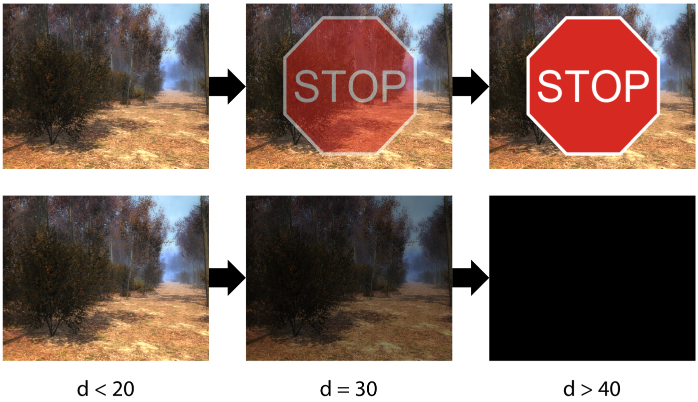

Fig. 5: The visual feedback as it appeared during conditions involving gradual onset (top: visual warning, bottom: visual deprivation). The intensity of the feedback was depended on variations in the distance (d) between the participant and the center of the walking area. During conditions involving sudden feedback onset the appearance of the visual feedback occurred instantaneously once $d > 80$.

Proxy step detection: The purpose of this step was to determine whether the movement of the ankle markers indicated that a proxy step had been taken. A step was registered when the vertical oscillation of either of the two ankle markers reached the lower extreme – a minimum. The registration of these proxy steps was performed using a peak detection algorithm relying on simple numerical differentiation. If two consecutive derivatives suggested a negative slope followed by a positive slope or a critical point, then a minimum was detected.

Gait parameter estimation: Walking velocity ($|v|$) can generally be expressed as the product of step frequency (f) and step length (l): $|v| = f \cdot l$ [38]. Research emanating from the field of biomechanics has shown that step frequency and step length are positively correlated [9]. Moreover, it has been reported that the walk ratio ($\frac{l}{f}$) does not vary considerably over a range of different speeds [23, 39]. Thus, step frequency should be a sufficient predictor of walking speeds. Indeed, measures of step frequency have previously been used to estimate virtual walking speeds in relation to WIP locomotion [33]. Wendt et al. [33] describe that because step length is correlated with height it is possible to estimate the normal walking speed at a given step frequency from an individual's height. With an outset in empirical investigations of these gait parameters, Dean [6] has formalized the relationship between walking speed ($|v|$), step frequency (f) and height (h) in terms of an equation, which Wendt et al. [33] has rewritten as,

$$|v| = (\frac{f}{0.157} \times \frac{h}{1.72})^2 \tag{1}$$

where the constant 1.72 represents a common height and 0.157 is the constant featured in the equation of Dean's original regression line [6]. The step frequency was derived from the time between the last two proxy steps, and the height of the user was established during a calibration prior to the first walk. It has recently been documented that users relying on WIP techniques for virtual locomotion tend to regard realistic walking speeds as being too slow [19]. Consequently, the walking speed was scaled by a factor of 2, thus producing speeds twice as fast as the ones established using equation 1.

Application of velocity and orientation: Finally, if it was determined that the user was not currently stationary, the scaled walking velocity was applied in the direction defined by the marker on the user's hip. The user was regarded as stationary if neither of the two ankle markers had moved less than 1 cm within the last 200 ms which would be the cases if both feet were grounded. Since the task performed by the participants involved continuous motion from start to end, starting and stopping latencies were not formally measured.

3.7 Measures

The introduced feedback was evaluated in terms of the actual and perceived helpfulness and the degree to which the participants found it intrusive.

Behavioral measure of UPD: Nilsson et al. [16] relied on the three measures of UPD, namely, *maximum drift* (the largest physical distance the user had been from the point where the locomotion started), *total drift* (the total physical distance covered by the user during the walk), and *drift/travel ratio* (the ratio describing how far the user had drifted in the real world per travelled distance in the virtual world). However, neither total drift nor the drift/travel ratio are in their current form applicable within the context of the present study. That is, the physical movement of a user attempting to step back towards the center of the walking area would erroneously be registered as positional drift. Consequently, only maximum drift was taken into account. Moreover, the following behavioral measures were employed: the percentage of time spent in the safe zone and outside the walking area, and the number of time the participants stepped outside the walking area. The user's position in the floor plane was identified based on the mean position of the two ankle markers.

Subjective measures of helpfulness and intrusiveness: The perceived helpfulness and intrusiveness of the feedback were assessed by means of self-reports. After each walk, the participants were asked to rate their level of agreement with two statements on 9-point Likert-type scales where '1' signified strong disagreement and '9' signified strong agreement. The scales only included anchors at the end points. The statement related to helpfulness explicitly asked the participants to rate the degree to which the feedback had made it easy for them to stay within the walking area. The item pertaining to intrusiveness asked the participants to indicate to what extent they had found the feedback disruptive for the sensation of being there in the virtual environment.

3.8 Results

The data pertaining to maximum drift, mean distance from the center and percentage of time spent in the safe zone were normally distributed, as assessed by Shapiro-Wilk's tests ($p > .05$). Repeated-measures analyzes of variance (ANOVAs) were used to compare the results of these behavioral measures. Mauchly's test indicated that the assumption of sphericity had been violated for maximum drift ($\chi^2(90) = 199.46, p < .05$) and mean distance from the center ($\chi^2(90) = 214.18, p < .05$). Thus, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity for maximum drift ($\epsilon = .24$) and mean distance to the center ($\epsilon = .19$). Moreover, Levene's tests were used to test the assumptions of homogeneity of variance. In case of violations, degrees of freedom were adjusted using the Welch-Satterthwaite method. Subsequently, significant measures were subjected to post-hoc analyzes by means of paired sample, two-tailed t-tests using Bonferroni-corrected alpha values. Normality could not be assumed in relation to the percentage of time spent outside the walking area and the number of times the participants exited the walking area. Consequently, Friedman tests were used to compare the results, and median and median absolute distance (MAD) were used as measures of central tendency and variability, respectively. The data resulting from the subjective measures of helpfulness and intrusiveness were treated as ordinal and Friedman tests were used to test for statistical significance. All results compared using Friedman tests were subsequently subjected to pairwise comparisons using Dunn's tests with Bonferroni corrected alpha values.

3.9 Unintended Positional Drift

The behavioral measures assessing how efficient the different methods were at minimizing UPD are summarized in Figures 6 to 10. The repeated measures ANOVAs revealed significant differences in relation to maximum drift

($F(3.12, 59.28) = 16.58, p < .01$), mean distance from the center of the walking area ($F(2.47, 46.93) = 14.55, p < .01$), and percentage of time in the safe zone ($F(13, 247) = 18.94, p < .01$). The performed Friedman tests indicated significant differences for both the percentage of time spent outside the walking area ($\chi^2(13) = 132.35, p < .01$) and number of times the participants exited the walking area ($\chi^2(12) = 132.81, p < .01$). Since the no-feedback condition did not encourage the user to step back into the walking area, this condition was not taken into consideration in relation to the number of times the participants exited the walking area.

The most notable finding of the post-hoc analyses related to maximum drift (Figure 6) was that the mean of the no feedback condition (N) was significantly higher than all the other conditions except sudden auditory deprivation (SAD) and sudden visual deprivation (SVD). In relation to mean distance from the center of the walking area (Figure 7), the post-hoc analysis showed that, with exception of gradual auditory deprivation (GAD), all of the means related to gradual feedback onset were significantly lower than the no feedback condition (N). Moreover, most of the means related to conditions involving gradual feedback were significantly lower than the ones related to sudden feedback onset. The most notable exception is gradual auditory deprivation (GAD) which only differed significantly from sudden visual deprivation (SVD). Looking at the means related to sudden and gradual onset in isolation, none of the conditions involving stimuli deprivation differed significantly from the conditions involving warnings. Finally, the condition involving passive haptic feedback (H) only differed significantly from sudden audiovisual warning (SAVW).

In regards to the percentage of time spent in the safe zone (Figure 8), none of the conditions involving sudden feedback onset differed significantly from the no-feedback condition. Also, the condition involving passive haptic feedback (H) did not differ significantly from the no feedback condition (N). Contrarily, the means related to the conditions involving gradual feedback onset were significantly higher than the no feedback condition with exception of gradual auditory deprivation (GAD). Similarly, all of the means related to gradual feedback onset were significantly higher than the means pertaining to sudden onset, with exception of gradual auditory deprivation (GAD), which only differed from sudden visual deprivation (SVD) and sudden audiovisual warning (SAVW).

Turning to the topic of the results pertaining to the percentage of time spent outside the walking area (Figure 9). The median of the no-feedback condition (N) was as expected the highest, and it differed significantly from the passive haptic condition (H) and all of the conditions involving gradual feedback onset. The passive haptic condition differed significantly from all conditions involving sudden feedback onset. The feedback type during which the participants spent the most time outside of the walking area was

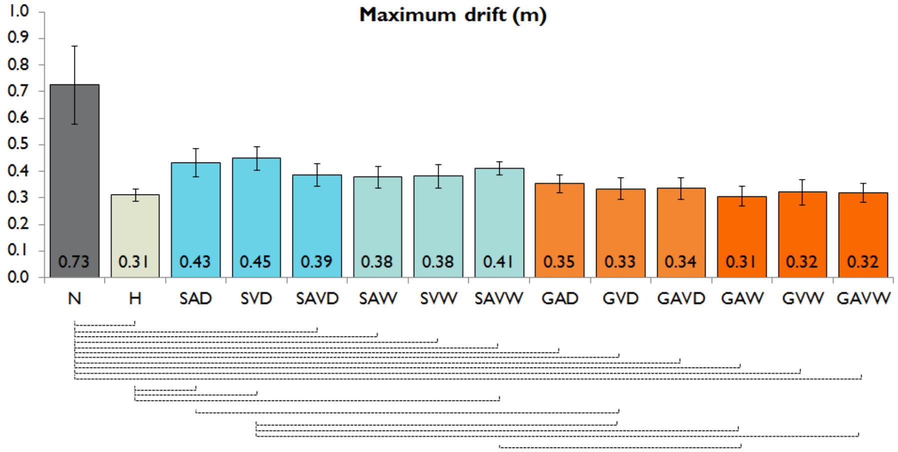

Fig. 6: Means pertaining to maximum drift (m). Error bars indicate 95% confidence intervals. Dotted lines indicate significant differences at $\alpha = .0005$.

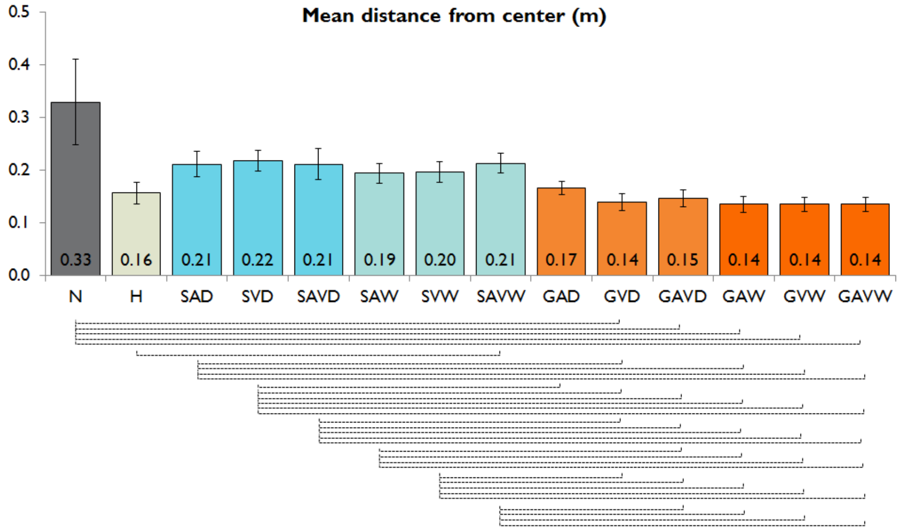

Fig. 7: Means pertaining to the mean distance (m) from the center of the walking area. Error bars indicate 95% confidence intervals. Dotted lines indicate significant differences at $\alpha = .0005$.

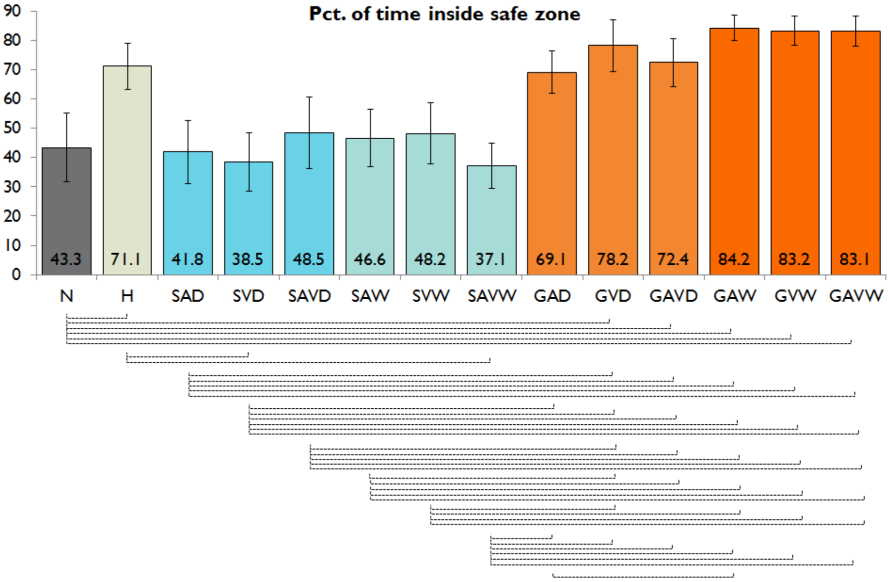

Fig. 8: Means pertaining to the percentage of time spent in the safe zone. Error bars indicate 95% confidence intervals. Dotted lines indicate significant differences at $\alpha = .0005$.

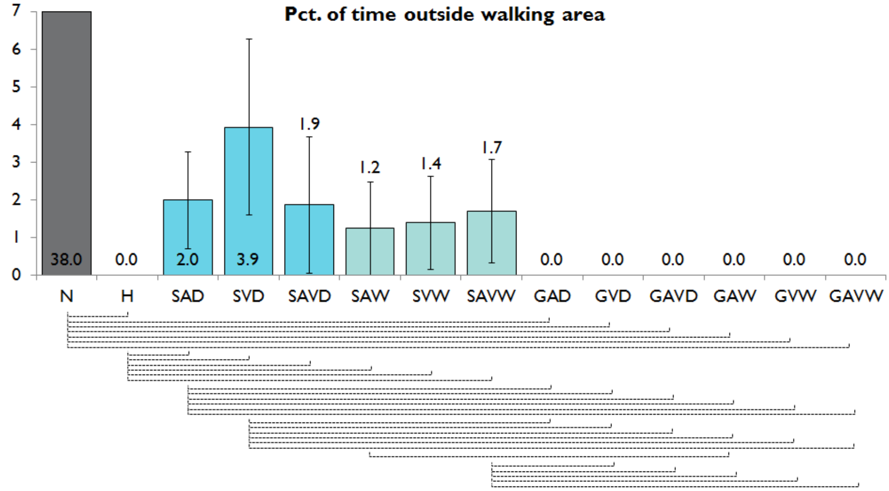

Fig. 9: Medians pertaining to the percentage of time spent outside the walking area. Error bars indicate ± median absolute difference. Dotted lines indicate significant differences revealed during pairwise comparisons ($\alpha = .0005$).

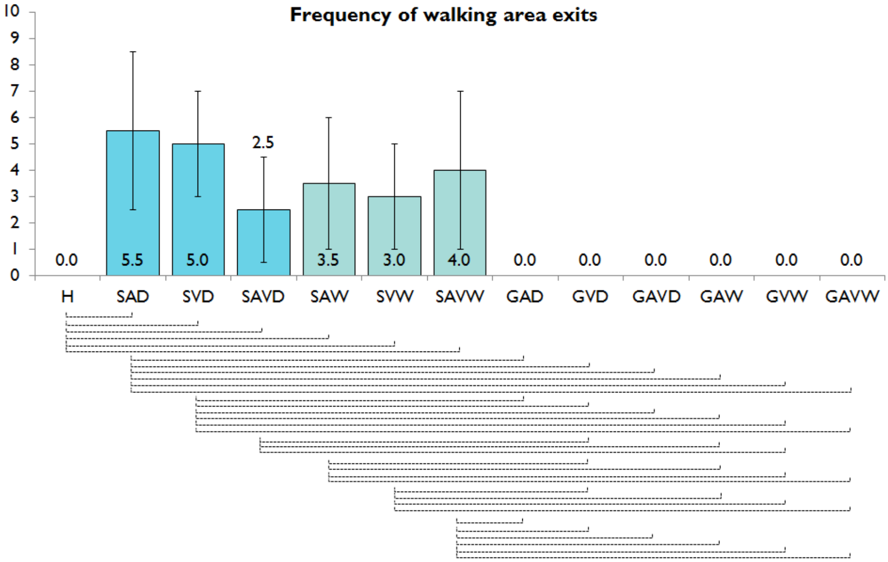

Fig. 10: Medians pertaining to the number of times the participants exited the walking area. Error bars indicate ± median absolute difference. Dotted lines indicate significant differences revealed during pairwise comparisons ($\alpha = .0006$).

sudden visual deprivation (SVD). This condition differed significantly from all conditions involving gradual feedback onset. Generally, the medians related to sudden feedback onset were higher than the ones related to gradual feedback onset.

The pairwise comparison of the medians pertaining to the number of times the participants exited the walking area painted a similar picture (Figure 10). The passive haptic condition (H) and the conditions involving gradual feedback onset generally caused the participants to exit the walking area fewer times than the sudden onset conditions. The passive haptic condition (H) differed significantly from all conditions involving sudden feedback onset. Moreover, sudden auditory deprivation (SAD), sudden visual deprivation (SVD) and sudden audiovisual warning (SAVW) were significantly higher than all of the conditions involving gradual feedback onset.

3.10 Helpfulness and Intrusiveness

Figures 11 and 12 detail the medians pertaining to perceived helpfulness and intrusiveness, respectively. The performed Friedman tests indicated significant differences for both perceived helpfulness ($\chi^2(12) = 54.02, p < .01$) and intrusiveness ($\chi^2(12) = 77.03, p < .01$). The condition devoid of feedback was not included in these comparisons since there had been no feedback which

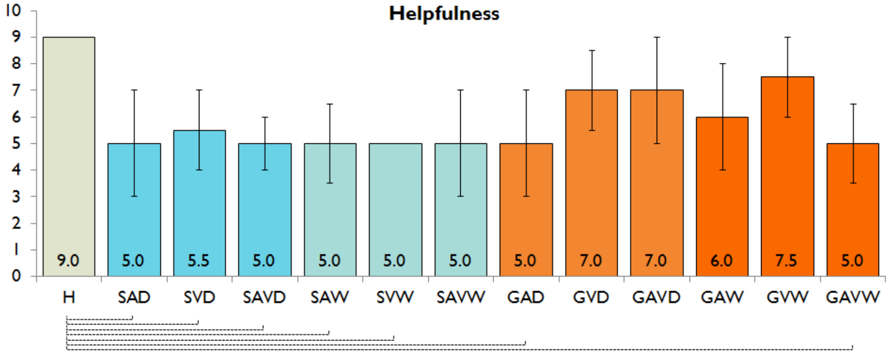

Fig. 11: Medians pertaining to the self-reported measure of helpfulness. Error bars indicate ± median absolute difference. Dotted lines indicate significant differences revealed during pairwise comparisons ($\alpha = .0006$).

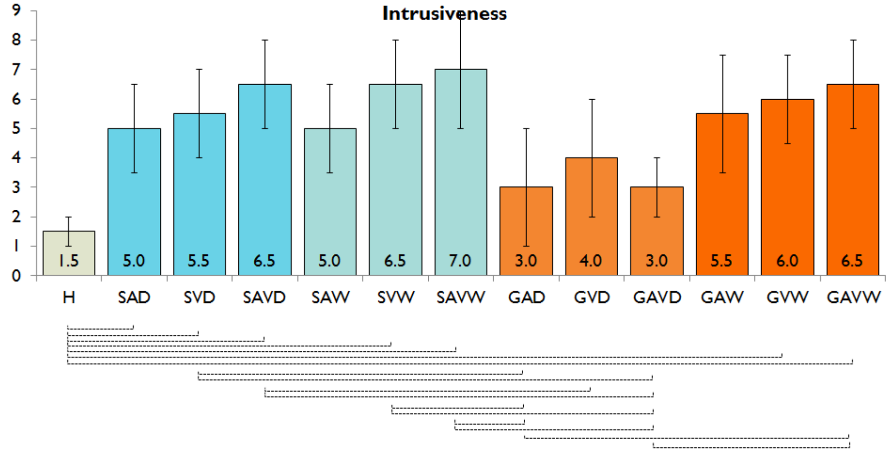

Fig. 12: Medians pertaining to the self-reported measure of intrusiveness. Error bars indicate ± median absolute difference. Dotted lines indicate significant differences revealed during pairwise comparisons ($\alpha = .0006$).

the participants could base their judgments on.

The medians pertaining to the question of how easy the feedback made it to stay within the walking area (Figure 11) suggest that the passive haptic condition (H) was perceived as more helpful than the conditions involving sudden feedback onset. With exception of sudden audiovisual warning (SAVW), the passive haptic condition differed significantly from all sudden feedback onset conditions. The passive haptic condition differed from gradual auditory deprivation (GAD), but none of the other gradual onset conditions. No other significant differences were identified. The passive haptic condition (H) was similarly perceived as being the least disturbing for the sensation of being there in the virtual environment (Figure 12). Significant differences were found between the passive haptic condition and all of the conditions where feedback was presented suddenly, except sudden auditory warning (SAW). Moreover, the passive haptic condition differed significantly from both conditions involving gradual visual warnings (GVW and GAVW). Notably the three conditions with the second, third and fourth lowest medians involved gradual deprivation (GAD, GVD, and GAVD).

4 Discussion

The measure of maximum drift clearly showed that the introduction of feedback reduced the amount of UPD. All of the feedback types significantly reduced how far the participants moved away from the center of the walking area compared to the condition devoid of feedback. The results pertaining to the participants' mean distance from the walking area indicated that feedback onset mode may influence performance. When relying on gradually presented feedback the participants generally remained closer to the center of the walking area throughout the walk compared to feedback presented suddenly. This hardly comes as a surprise considering that the participants had no way of knowing how close they were to the edge of the walking area when relying on feedback with a sudden onset. Interestingly, gradual auditory deprivation was less successful at keeping the participants away from the edge of the walking area. It seems likely that the gradual decrease in the amplitude of the environmental sounds simply was too inconspicuous. Since these environmental sounds were dominated by the sound of wind blowing, it seems possible that the decreases in amplitude may have been mistaken for diminishing wind speeds. Moreover the results did not suggest that the presentation mode (warning or deprivation) influenced the mean distance from the center of the walking area. Finally, the passive haptic condition did not seem to differ radically from the conditions involving sudden onset of auditory, visual and audiovisual feedback. Indeed, the onset of the passive haptic feedback does in a sense qualify as sudden, since the participants were unable to feel it until they were at the edge of the walking area. This was also apparent from the measure of the percentage of time the participants spent within the safe zone. This measure suggested that gradual feedback onset was more efficient at ensuring that the participants stayed within the safe zone. Nevertheless, the passive haptic feedback proved efficient in regards to the percentage of time spent outside the walking area. It seems possible to offer at least two explanations for why this may have been the case. First, since the participants may have reacted faster to the passive haptic feedback, they may have returned to the walking area swifter or perhaps avoided exiting it in the first place. Second, since the passive haptic feedback did not require the estimated user position reach the edge of the walking area, it cannot be ruled out that the participants in some cases may have noticed the passive haptic feedback sooner than the audiovisual feedback. Notably, the gradual feedback onset also appeared to reduce the amount of time spent outside the walking area. Presumably because the participants were alerted to the proximity of the edge prior to reaching it and, therefore, were less likely to step across it. The results pertaining to the number of times the participants stepped outside of the walking area yielded similar indications. Both the passive haptic feedback and the gradual feedback onset resulted in the participants stepping outside fewer times.

In relation to the subjective measures, the passive haptic condition generally appears to surpass the remaining feedback types. Whereas the feedback types involving gradual onset did not differ significantly from the ones involving sudden onset, the passive haptic feedback was perceived as the most helpful and differed significantly from almost all of the conditions involving sudden feedback onset. Since the participants were walking more or less straight for the majority of the walk, a step backward would almost always bring them back towards the center of the walking area. Despite being informed of this, 12 participants explicitly mentioned that a feature of the carpet which they particularly liked was that they could feel where they were facing with respect to the center of the walking area. Moreover, the passive haptic feedback was the type of feedback that was perceived as the least disruptive for the subjective sensation of being there in the virtual environment and the participants found it significantly less disruptive than the conditions involving visual warnings. Interestingly, the second, third and fourth least disruptive feedback types were the ones involving gradual deprivation of the stimuli used to depict the virtual environment. A possible explanation is that these feedback types did not depend on stimuli which did not naturally belong in the environment. Contrarily, the superimposition of such extraneous element may have interfered during conditions involving warnings.

5 Conclusion

This paper has detailed a within-subjects study investigating how different types of feedback compared in terms of minimizing positional drift during WIP locomotion. The study compared 13 different types of feedback informing the user that a certain amount of drift had occurred and a control condition devoid of feedback. The feedback types differed in terms of the sensory modality used to supply the feedback (auditory, visual or audiovisual), onset mode (gradual or sudden) and presentation mode (warning or deprivation). Finally, one condition provided passive haptic feedback (a circular carpet). The types of feedback were evaluated in terms of their ability to reduce UPD, and the perceived helpfulness and intrusiveness. Generally the results suggest that feedback with a gradual onset and passive haptic feedback were better at limiting positional drift to a confined area. However, the passive haptic feedback was perceived as more helpful and less disruptive than some of the conditions involving gradual feedback onset. Considering that carpets of the type used for the study are very inexpensive, it would seem that this form of passive haptic feedback potentially could serve as a meaningful way of minimizing unintended positional drift. With that being said, future studies should assess the efficacy of this and other feedback types during virtual scenarios demanding a larger amount of attentional resources, such as, the act of playing an immersive game requiring use of the player's intellect or sensorimotor skills. Finally, future studies may address how different shapes and sizes of the walking area might influence the efficacy and experience of the different methods.

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Paper D

Establishing the Range of Perceptually Natural Visual Walking Speeds for Virtual Walking-in-Place Locomotion

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Abstract

Walking-in-Place (WIP) techniques make it possible to facilitate relatively natural locomotion within immersive virtual environments that are larger than the physical interaction space. However, in order to facilitate natural walking experiences one needs to know how to map steps in place to virtual motion. This paper describes two within-subjects studies performed with the intention of establishing the range of perceptually natural walking speeds for WIP locomotion. In both studies, subjects performed a series of virtual walks while exposed to visual gains (optic flow multipliers) ranging from 1.0 to 3.0. Thus, the slowest speed was equal to an estimate of the subjects' normal walking speed while the highest speed was three times greater. The perceived naturalness of the visual speed was assessed using self-reports. The first study compared four different types of movement, namely, no leg movement, walking on a treadmill, and two forms of gestural input for WIP locomotion. The results suggest that WIP locomotion is accompanied by a perceptual distortion of the speed of optic flow. The second study was performed using a 4×2 factorial design and compared four different display field-of-views (FOVs) and two types of movement, walking on a treadmill and WIP locomotion. The results revealed significant main effects of both movement type and field of view, but no significant interaction between the two variables. Particularly, they suggest that the size of the display FOV is inversely proportional to the degree of underestimation of the virtual speeds for both treadmill-mediated virtual walking and WIP locomotion. Combined, the results constitute a first attempt at establishing a set of guidelines specifying what virtual walking speeds WIP gestures should produce in order to facilitate a natural walking experience.

1 Introduction

The technology used for immersive virtual reality (IVR) systems has come a long way since Sutherland proposed the first virtual reality display [60], [61]. Here, the designation IVR is used to describe systems relying on high-fidelity tracking and multisensory displays in order to facilitate natural perception and interaction within computer-generated environments. In other words, IVR supports a sensorimotor loop similar to that of the real world, thus enabling users to interact and perceive as they would during unmediated experiences. Recent technological advances, such as the Microsoft Kinect (www.xbox.com/kinect) and the Oculus Rift (www.oculusvr.com), usher in a future where IVR no longer is confined to the laboratories of public and private institutions. Indeed, the technology has reached a level of maturity that soon may allow consumers to enjoy immersive experiences in their own homes.

Natural user interaction is at the crux of compelling IVR experiences [57].

Particularly, natural walking experiences are crucial since locomotion is one of the most common activities connected to user interaction within 3D environments [6]. However, facilitation of natural locomotion is problematic when a limited interaction space constrains the physical movement of the user. While several potential solutions to this problem have been proposed (e.g. [11], [38], [55], [57], [59]), Walking-in-Place (WIP) techniques seem particularly suitable for consumer IVR where spatial, technological, and financial constraints may be prominent. WIP techniques enable users to move freely within the virtual environment by performing body movements resembling real world walking while remaining stationary with respect to the physical environment. Advantages of WIP techniques include, but are not limited to, convenience and cost-effectiveness [21], good performance on simple spatial orienting tasks [75], and generation of proprioceptive feedback similar, albeit not identical, to the one resulting from real walking [53]. Moreover, locomotion relying on such stepping motions have been shown to elicit more natural walking experiences and a stronger sensation of presence compared to interaction via more traditional peripherals [54], [68].

Existing research on WIP locomotion has primarily sought to optimize performance in terms of factors such as starting and stopping latency, smoothness of between step motion, within-step speed control, and the efficacy of the step detection [21]. While exceptions do exist [41], [54], [68], research pertaining to the perceived naturalness of WIP locomotion is scarce. Whitton and Peck [73] describe that one of the main technical challenges for developers of WIP locomotion is controlling the user's velocity in a manner that is both responsive and smooth. In addition to ensuring the smoothness and responsiveness of the virtual velocity, it would seem that it is crucial to determine what constitutes perceptually natural speeds for WIP locomotion.

This paper describes two studies performed to establish the range of perceptually natural, visual walking speeds for WIP locomotion. A visual walking speed will qualify as natural if the user finds that there is a correspondence between the speed of the visual flow and the movements performed in order to generate it. Establishing the range of perceptually natural walking speeds is a prerequisite for facilitating natural walking experiences on behalf of users navigating virtual worlds using WIP techniques. The results provide guidelines specifying what virtual walking speeds WIP gestures should produce in order to facilitate a perceptually natural walking experience. The first study investigates whether WIP locomotion indeed is accompanied by a perceptual distortion of the speed of optic flow similar to the one experienced during treadmill-mediated IVR [46]. That is, the perceived speed during treadmill-mediated locomotion is perceived as slower than the actual walking speed. The second study investigates how the range of perceptually natural walking speeds varies across different display fields of view (FOV).

2 Background and Related Work

This section details existing research on WIP locomotion, introduces the perceptual distortions of visual velocities accompanying real and treadmill-mediated virtual walking and outlines examples of research related to the influence of FOV on exocentric motion perception.

2.1 Walking-in-Place Locomotion

Existing WIP techniques may be broadly divided into two categories based on the technology used to register user input. Some rely on manipulation of a physical interface for step detection, while others depend on various forms of motion tracking. Strictly speaking, the physical interfaces also perform primitive gesture tracking since the manipulation of the physical interface is equated with a given gesture being performed. However, such interfaces commonly detect contact between the feet and the ground – discrete events – as opposed to proper motion tracking systems that enable continuous detection of the position or velocity of body parts.

The Walking Pad [4] detects the user's steps through 60 iron switch sensors embedded on a 45cm×45cm plexiglass surface. Similarly, Bouguila et al. [5] describe a platform that facilitates foot-based locomotion through four embedded load sensors. Interestingly, Nintendo's Wii Balance Board (www.nintendo.com) has also been used to facilitate WIP locomotion [75]. The Wizdish [62] and the Virtuix Omni (www.virtuix.com) present examples of a direct mapping between virtual locomotion and interaction with physical interfaces. For both interfaces, the interaction is contingent upon the gesture being performed via physical platforms. In the case of the Wizdish, virtual movement is possible by simultaneously sliding one foot forward and the other backward without breaking contact with the concave and almost spherical surface of the platform. The Virtuix Omni functions in a similar manner but enables the user to interact via a gesture more similar to real walking since it is possible to break contact with the platform's surface. This is made possible by having the user wear a belt attached to the device.

Slater and colleagues [54] describe what may be the first implementation of a WIP technique, namely, the Virtual Treadmill. While this technique relies on motion tracking, it does not explicitly track leg movements. Instead, it detects whether users are walking in place via a neural network recognizing patterns in the head movement. The users may have perceived the resulting movement as somewhat unnatural since it was not instigated until four steps in place were detected, and it would similarly not terminate movement unless no steps had been detected for two full cycles [21]. Another implementation relying on head movement is the so-called Shake-Your-Head technique described by Terziman et al. [63]. Rather than detecting the head movements resulting from walking in place, this technique relies on explicit head gestures (i.e. lateral head oscillation for walking). Notably, this makes it possible to use the technique while remaining seated.

Zielinski, McMahan, and Brady [79] present a WIP technique that uses a camera to track the shadows cast by users' feet onto the floor of an underfloor projection system within a six-sided CAVE. Feasel, Whitton, and Wendt [21] have proposed the technique Low-Latency, Continuous-Motion Walking-in-Place (LLCM-WIP). This technique controls the virtual velocity based on the speed of the user's vertical heel movement and promises low starting and stopping latency, smooth motion between steps, within-step control of the speed, and turning on the spot without erroneous forward movement. Notably, WIP locomotion has been achieved using commercially available motion tracking systems as well. The Microsoft Kinect can be used for WIP locomotion in combination with the Flexible Action and Articulated Skeleton Toolkit (FAAST) [58] and, Kim, Gracanin, and Quek [33] have proposed a technique that relies on the acceleration and magnetic sensors embedded within two smartphones in combination with a magnet to produce WIP locomotion.

Most of the above WIP techniques rely on the same gesture for input, namely, a stepping gesture resembling the one performed when walking up a flight of stairs. Nilsson et al. [41] performed a study comparing this gesture to two alternative gestural inputs: a gesture where the user alternately bends each knee, thus moving the lower leg backwards, and a gesture where the user in turn taps each heel against the ground without breaking contact with the toes. The results indicate that the latter, dubbed Tapping-in-Place, is perceived as the most natural. A possible explanation is that the proprioceptive feedback produced by this gesture better matches the one generated during real walking in terms of the physical effort required to take each step.

A particularly promising WIP technique has been proposed by Wendt, Whitton, and Brooks [72], namely, the Gait-Understanding-Driven Walking-in-Place (GUD WIP). In addition to outperforming the LLCM-WIP, it sets itself apart from its predecessors in that it is informed by gait principles and thereby produces walking speeds that correspond better with those of real walking. To be exact, the virtual velocity is controlled by a biomechanics-inspired state machine which can estimate the step frequency multiple times during each step. Moreover, the technique relies on a biomechanics-inspired method for estimating the walking velocity. GUD-WIP's ability to reproduce natural walking speeds is notable, but it is worth questioning whether faithful reproduction of real walking speeds is desirable. Indeed, in connection with treadmill-mediated IVR, individuals tend to underestimate optic flow speeds. An implication of this perceptual distortion of optic flow speeds is that exaggerated speeds are perceived as the most natural. Thus, it seems necessary to identify the range of visual gains, or optic flow multipliers [32], that produces perceptually natural walking speeds on behalf of users relying on WIP techniques for virtual locomotion.

2.2 Perceptual Distortions of Exocentric Motion

Several studies suggest that individuals experience a reduction in the perceived optic flow speed of expanding flow fields when walking on a treadmill [14], [44], [65]. That is, the visually perceived speed appears too slow compared to the walking speed. Notably, the perceived speed of real walking is also susceptible to distortions as demonstrated by the ability to manipulate virtual speeds without walking users noticing the discrepancy between the real and virtual velocity [55]. Similarly, individuals tend to underestimate traveled distances in immersive virtual environments (see citations in [31]). Moreover, it is interesting to note that, optic flow may also influence behavior. Pailhous et al. [43] found that free walking speeds were reduced when walkers were exposed to floor projections of a pattern of dots moving backward. Similarly, Konczak [36] demonstrated that forward or backward displacement of the walls of a physical corridor increased or decreased free walking speeds, respectively. Warren et al. [70] and Prokop et al. [48] performed studies where the participants walked on a treadmill while viewing visual flow patterns displayed on wide-FOV projection screens. The results revealed that decreased rates of expansion or contracting optic flow fields led to increased walking speeds. On the contrary, increased rates of expansion were accompanied by decreases in walking speed. Studies by Mohler et al. [39] have demonstrated that gait transition speeds and preferred walking speeds may be influenced by visual motion cues. Participants were walking on a treadmill and visual speeds, displayed on a projection screen with a 180° horizontal FOV, were either slower than, identical to, or faster than the actual walking velocity. Higher visual speeds led to lower gait transition speeds and lower preferred walking speeds.

Banton et al. [2] describe a series of studies investigating the perceptual distortion of optic flow speeds during treadmill-mediated IVR. The first study sought to confirm the observation that geometrically correct optic flow is perceived as too slow. The participants walked at a speed of 3.0mph and were asked to report whether the speed of the optic flow, displayed using a head-mounted display (HMD), should be increased or decreased to match the walking speed. The results suggested that a speed of 4.7mph (a gain of 1.57) was perceived as the best match.

A study performed by Kassler et al. [32] suggests that slightly higher gains than the 1.57 reported by Banton et al. [2] might be appropriate. The participants were asked to match the optic flow speed of projected visuals to the speed of the treadmill by turning a knob. The results indicate that a matched gain of 2.0 was constant across six treadmill speeds. The variations in the reported visual gains may be ascribed to the use of different display types. However, it also seems plausible that there exists a range of tolerance in relation to normal gain perception.

Indeed, while most studies have aspired to identify a single perceptually normal visual gain, Powell et al. [46] sought to investigate whether normal gain perception is variant. In addition to establishing the range of perceptually normal visual gains, the study compared two visually different virtual hallways and compared two modes for presenting the gain changes. In one mode, the gain was changed once the participants had reported whether they experienced the virtual speed as normal. In the other mode, the gain was gradually changed, and the participants were asked to report verbally whenever they noticed a change in gain. In both cases, the participants were asked to report whether they found the virtual speed to be ‘too slow’, ‘normal’ or ‘too fast’. For each of the four conditions, the participants were presented with 30 gain changes, ranging from 0.2 to 3.0 times the treadmill speed, which varied dynamically according to the pace of the participants. The results revealed no significant differences in the range of perceptually normal gains across the two environments or the two presentation conditions. However, they did suggest that there exists a tolerance in the range of perceptually normal gains. While the identified visual gains vary across studies, the direction of the perceptual distortion is identical. That is, the visual flow is generally perceived as slower than it really is.

According to Durgin [17] such perceptual distortions have previously been attributed to suppression of optic flow so as to advance the perception of a stationary world [69]. However, recent studies suggest that the reduced visual speeds may play a role in the assessment of self-motion as well [17]. Notably, Durgin and colleagues [19], [17] describe that the relationship between perceived and actual speeds comply with an equation originally used to describe interaction within one modality [3]. If applied to walking, Barlow’s [3] equation stipulates that the perceived speed of optic flow is equal to the actual speed of the optic flow minus some amount of the self-motion experienced via other sensory channels:

$$\begin{aligned} &perceived\,visual\,velocity = \\ &\qquad actual\,visual\,velocity\; - K\; \times\; felt\,velocity \end{aligned} \tag{1}$$

where K is a constant, and felt velocity corresponds to velocity perceived nonvisually. As apparent from the equation, walking is an intrinsically multisensory activity in that several sources of sensory information become intertwined by experience [17]. These sources of perceptual information include optic flow [23], acoustic flow [51], proprioceptive feedback [24], and vestibular stimulation [25]. Indeed, Durgin et al. [19] have extended Barlow’s model and created a multicue subtractive model that more explicitly accounts for motor and vestibular estimates of self-motion. Since the movements performed when walking influence self-motion perception, it seems reasonable to assume that existing findings pertaining to treadmill-mediated IVR need not be directly applicable to WIP locomotion.

2.3 Field of View and Exocentric Motion Perception

Considering the aforementioned role of optic flow in motion perception, another factor likely to influence motion perception during WIP locomotion is the display FOV, that is, the vertical and horizontal angles subtended by the visual display [56]. Indeed, variations in the FOV are believed to influence a variety of aspects of human performance and perception, including, but not limited to, navigation performance in real [29], [67], [66] and virtual environments [26], postural stability [15] , reaching distance estimation [71], as well as simulator sickness [37] and the sensation of presence [49]. Moreover, Jones et al. [31] have highlighted that conflicting evidence exists in regards to whether FOV variations contribute to underestimations of distances within immersive environments [77], [35], [10], [31].

Within the field of vection (illusory self-motion) research, a substantial amount of studies have been performed with the intent of uncovering what region of the retina is most important for self-motion perception [76]. Drawing on prior research on illusory self-motion, Riecke [50] describes that one of the primary factors contributing to compelling self-motion illusions is the solid angle subtended by the visual motion stimuli, i.e., the FOV. To be exact, even though it has been possible to elicit self-motion illusions with FOVs as small as 7.5° [1], larger FOVs generally lead to enhanced illusions and full-field stimulation may elicit illusions that are so compelling that they become indistinguishable from the real thing [8], [7], [13], [27]. However, Riecke [50] describes that even though earlier studies [7], [13], [30] indicate that visual motion stimuli presented peripherally more effectively elicit vection than central stimulation, this need not be the case. Studies have given rise to the notion that central and peripheral motion presented on similar-sized display areas have similar effects on motion perception [1], [28], [40], [45], [76]. It should be noted that several of the studies in question pertain to circular vection rather than self-motion illusions occurring along the direction of heading. Regardless of the relative importance of peripheral and central motion stimulation, variations in FOV remain a factor of importance when simulating motion within IVR.

Pretto et al. [47] performed an experiment suggesting that circular FOVs larger than 60° may be preferable when the perception of motion relies on visual flow information. The participants were seated within a panoramic screen (230° × 125° FOV), and optic flow was produced using white dots displayed on a dark background. The experiment followed a two-interval forced-choice paradigm where the participants compared a standard stimulus (full FOV and a fixed speed of the optic flow) to a stimulus with varying visual speeds at nine different FOVs with occlusion of either the central or peripheral area of the FOV. In addition to revealing that the visual flow could be used to estimate the speed of the forward virtual movement, the results showed that the participants underestimated the speed for FOVs smaller than 60° and the underestimation was inversely proportional to the size of FOV. Moreover, the participants overestimated the speed when as little as 10° of the central area of the FOV was occluded.

Interestingly, two of the previously mentioned studies by Banton et al. [2] reveal that the perceptual distortion of the speed of optic flow is eliminated when the gaze is directed either downwards or to the side. Both studies relied on the methods of limits, and the participants were required to match optic flow speeds to three treadmill walking speeds. The participants did so while looking straight ahead, thus producing radial flow in central vision, or while looking either downwards or to the side, which entailed maximal exposure to lamellar flow. The change in motion perception accompanying the different gaze directions led Banton et al. to hypothesize that lamellar flow is a prerequisite for accurate speed perception and that such cues are eliminated by limited FOVs when participants direct their gaze straight ahead while walking. However, it would seem that direction of gaze was confounded with environmental structure [20].

Given the impact FOVs have on self-motion perception, it seems more than likely that variations in the FOV will also influence the perceived naturalness of virtual walking speeds during WIP locomotion. Thus, it is necessary to investigate the influence of different FOVs when attempting to produce a set of meaningful guidelines specifying what virtual walking speeds WIP gestures should produce.

3 Study I: The influence of gestural input

The objective of the first study was to investigate whether WIP locomotion is accompanied by a perceptual distortion of the speed of optic flow similar to the one experienced during treadmill-mediated IVR. In a vein similar to Powell and colleagues [46], the aspiration was to ascertain whether there exists a tolerance in the range of normal, or natural, visual gains. Establishing the range of perceptually natural virtual speeds in relation to WIP techniques is a prerequisite for facilitating natural walking experiences on behalf of users navigating virtual worlds using such techniques.

3.1 Study Design

To meet this aim, a within-subjects study comparing four different types of user motion was performed. The four types were: Stationary (the user remained still with both feet on the ground), Tapping-in-Place (TIP) (the user alternately tapped each heel against the ground without breaking contact with the toes), Walking-in-Place (WIP) (the user alternately lifted each foot of the ground), and Walking (the user walked on a treadmill). TIP and WIP were included in order to determine whether different types of gestural input for WIP locomotion yield different ranges of perceptually natural virtual speeds, and Stationary and Walking were included with the intention of determining whether the subtle movements of the WIP techniques had an effect compared to no motion and actual walking.

3.2 Participants

Twenty-two participants (18 males, 4 females) aged between 20-58 years (M= 28.9 years, SD=8.9) took part in the study. They were recruited via a mailing list comprising volunteers from Aalborg University Copenhagen and readers of the Danish periodical Ingeniøren (The Engineer). Tickets for a movie theater were offered as compensation for participation. All participants had prior experience with using WIP techniques for virtual locomotion due to participation in previous studies performed in the same laboratory. This was considered advantageous as it might reduce the likelihood of the participants being distracted by the novelty of navigating a virtual environment using a gesture serving as a proxy for walking. All participants reported having normal or corrected-to-normal vision and hearing.

3.3 Procedure

The participants experienced 22 gain changes for each of the four walking methods (11 different visual gains, repeated twice). The participants were exposed to the four walking methods in randomized order. Previous studies have relied on known treadmill speeds in order to establish the actual walking speed. However, seeing as only one condition in four involved activation of the motorized treadmill this was not an option. Instead, all participants were asked to perform the gestures involving motion in synch with a metronome, thus ensuring a fixed step frequency across the four conditions. The metronome was also audible during the condition where the participants remained stationary. This provided the participants with a reference to the step frequency despite the absence of actual steps. Prior to the condition involving walking the users were asked to walk on the treadmill while wearing the HMD without visuals being displayed. The speed of the treadmill was then adjusted until the participants were able to walk in sync with the metronome at a pace they found comfortable.

Since the study was performed with the intention of establishing the range of perceptually natural gains in relation to WIP locomotion, the normal walking speed of the individual participant was derived in manner similar to the one used relation to GUD-WIP [72]. Walking velocity can generally be expressed as the product of step frequency and step length. [78]. Because step length is correlated with height it is possible to estimate the normal walking speed at a given step frequency from an individual's height. With an outset in empirical investigations of these gait parameters, Dean [12] has formalized the relationship between walking speed ($|v|$), step frequency (f) and height (h) in terms of an equation, which Wendt et al. [72] express by

$$|v| = (\frac{f}{0.157} \times \frac{h}{1.72})^2 \tag{2}$$

where 1.72 represents a common height, and 0.157 is the constant featured in the equation of Dean's original regression line [12]. The height of the user was established during calibration, and all walks were performed at a step frequency of 1.8 steps per second. In order to ensure the safety and comfort of the participants while walking on the treadmill, we purposely chose a step frequency just below the one accompanying normal gait speed for both men and women [42].

The 11 visual gains ranged from 1.0 to 3.0, in increments of 0.2, implying that the slowest speed was equal to the estimated normal speed, whereas the highest speed was three times greater than the estimated normal speed. No gains lower than 1.0 were included since previous studies related to treadmill-mediated IVR have shown that individuals generally perceive the virtual speed as slower than the actual walking speed [46]. Generally, the employed method resembles the one used by Powell et al. [46]. However, in the current study the order of the gains was randomized. In the study by Powell et al. [46] each session (30 gain changes) always started with the lowest gain (0.2). The gains incrementally increased after each walk until the highest possible gain (3.0) was reached, and then incrementally decreased until the gain returned to the lowest one. This presentation method was not used since a pilot study revealed that participants might base their self-reports on strategic thinking rather than their perception of the visual movement (e.g. by taking into account the number of walks it took before the first occurrence of the perceptually natural stimuli during previous sessions). Similar to the study by Powell et al. [46], the participants were asked to report whether they had found the virtual speed of each walk 'too slow', 'natural', or 'too fast'. The participants gave verbal judgments when they felt confident enough to do so or when the walk was over. We favored this approach over the two-alternative forced-choice task which has been used to establish the detection

Fig. 1: Illustration of the virtual environment (left). The environment as it appeared from the perspective of the participants (right).

threshold of translation and rotation gains applied during redirected walking [55]. The reason being that this should make it possible to establish the true range of perceptually natural gains, rather than the threshold separating gains perceived as either too slow or too fast [46].

3.4 Study Stimulus

The visual stimulus was comprised of a 14m long hallway (Figure 1) and was delivered by means of a nVisor SX60 HMD, with a resolution of 1280×1024 and a diagonal FOV of 60° in each eye. A 16 camera Optitrack motion capture system was used to track the position and orientation of a marker placed on the HMD, thus providing information about the user's head movement. The cameras were placed along the circumference of a circle with a diameter of 7m. Twelve of the cameras were placed at a height of approximately 2.9m and the remaining 4 were placed about 1.8m from the ground. The virtual height of the users was based on the estimate of their real height obtained during calibration. The participants stood on the treadmill (ProForm 520 XLT) and held onto the handlebars during all four conditions. A schematic drawing of the system used for the current study can be seen in Figure 2.

3.5 Results

For the 22 walks performed using each of the four gestures, a weighted mean was calculated for the visual gains reported as 'natural'. Moreover, the minimum and maximum of the visual gains rated 'natural' were identified for each condition. The corresponding results are summarized in Table 1 and are visualized in Figure 3. Repeated-measures analyzes of variance (ANOVAs) were used to compare the results of all measures. Mauchly's test indicated that the assumption of sphericity had not been violated in any cases. There-

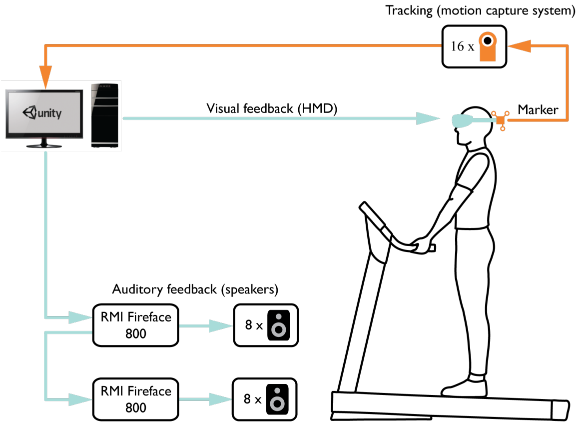

Fig. 2: Schematic drawing of setup used for the study.

fore, no corrections of the degrees of freedom were performed. Significant measures were subsequently analyzed by means of paired-sample, two-tailed t-tests using Bonferroni-corrected alpha values ($\alpha = .008$). Paired sample t-tests were used to compare the minimum and maximum gains, and one sample t-tests were used to compare the mean and minimum gains with the normal gain of 1.0.

While the ANOVAs revealed a significant difference between the minimum gains ($F(3,21) = 3.75, p = .02$), no significant differences were found between the mean and maximum gains corresponding to the four types of input. The post-hoc analysis suggested that there was a significant difference between TIP and Walking. Significant differences were found between the minimum and maximum gains of the individual types of movement. Also both the mean and minimum visual gains of all four movement types differed significantly from the normal gain.

3.6 Discussion

The mean visual gains pertaining to both TIP and WIP suggest that the perceptual distortion of optic flow speeds, known to occur during treadmill-mediated IVR, also may be present on behalf of users navigating virtual worlds using WIP locomotion. Indeed, both the mean and minimum visual gains for TIP and WIP were significantly different from the normal visual gain of 1.0. Moreover, the fact that all the minima and maxima differed significantly from one another suggests that there exists a range of perceptually natural visual gains which might be applied to WIP locomotion, i.e., a range from 1.58 to 2.40 for TIP and 1.65 to 2.44 for WIP. It should be noted that since the minima and maxima pertaining to the two gestures did not differ significantly across the two types of movement, it seems plausible that the range of visual gains might be identical for the two. Considering that the two types of movement do not differ drastically from one another, it does seem plausible that similar gains might apply to both.

In regards to the difference between the four movement types, the results are less conclusive. Following both Barlow's [3] subtractive model and the multicue subtractive model proposed by Durgin et al. [19], one should expect to see lower visual gains for stationary users and higher gains for walking users. Particularly, one would expect the two to differ from one another since the act of walking, unlike being stationary, would generate kinesthetic feedback indicative of self-motion, which would be subtracted from the actual optic flow speed. Indeed, Durgin and Gigone [16] have found that, for optic flow speeds appropriate to walking, individuals who are walking are more precise at assessing visuals speeds than stationary individuals.

However, it is possible to offer an explanation for the discrepancy between the theory and the current results. In the stationary condition, the users were asked to take into account the sound of the metronome signifying their step frequency. It is plausible that the auditory stimuli may have served as nonvisual information about their self-motion and thus been subtracted from the actual optic flow speed. In regards to walking, it seems likely that the self-motion perception may have been influenced by the employed methodology. Prior to commencing the trials involving walking, the speed of the treadmill was adjusted until the participants were able to walk in sync with the metronome at a comfortable pace. While the walk ratio ($steplength/stepfrequency$) generally is invariant over a large range of walking speeds during overground walking, Durgin et al. [20] describe that the walk ratio of participants walking on a treadmill tend to be lower, i.e., shorter and more frequent steps. Since the step frequency was fixed in the current study, it is possible that the step length may have differed from that of normal walking. In turn, this may have entailed that there was a larger mismatch between the treadmill speed and the normal walking speed estimated using equation 2. Notably, the study performed by Powell et al. [46], which was performed using a similar methodology, suggests slightly lower gains for treadmill walking (mean = 1.96 ± 0.26, min = 1.55 ± 0.31, max = 2.41 ± 0.33) than the current study (mean = 2.09 ± 0.16, min = 1.75 ± 0.16, max = 2.45 ± 0.19). This difference is to be expected if the treadmill speeds used for the current study were slower than the estimated normal speed.

One way of circumventing this problem would be to establish the normal walking speed used for the different types of movement based on walks on the treadmill prior to the study. This would necessarily make the results less specific to WIP locomotion relying on GUD-WIP. Alternatively, the treadmill speed could be based on the speed estimated using equation 2 rather than the requests of the participants.

Table 1: Mean values ± one standard deviation pertaining to the maximum, mean and minimum visual gains rated 'natural'.

	Stationary	TIP	WIP	Walking
Maximum	2.45 ± 0.17	2.40 ± 0.20	2.44 ± 0.19	2.45 ± 0.19
Mean	2.10 ± 0.15	1.99 ± 0.15	2.02 ± 0.16	2.09 ± 0.16
Minimum	1.74 ± 0.15	1.58 ± 0.15	1.65 ± 0.17	1.75 ± 0.16

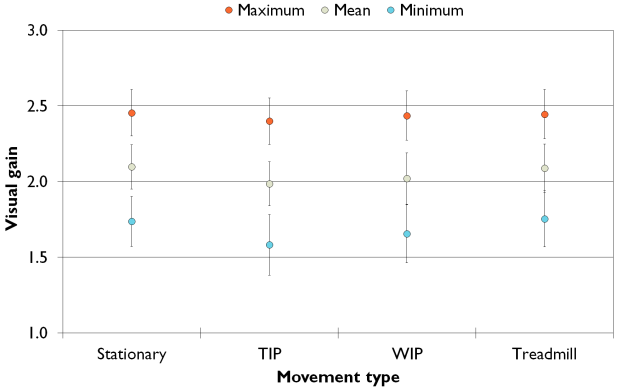

Fig. 3: Results pertaining to the minimum, mean and maximum visual gains rated 'natural'. Error bars indicate 95% confidence levels.

Even though these limitations make it difficult to conclude whether the same range of perceptually natural gains is applicable to both WIP locomotion and treadmill-mediated IVR, the results provide a useful guideline for what virtual speeds to apply during virtual WIP locomotion. Considering that Powell et al. [46] found no significant differences across environments it seems plausible that the identified gains may be applicable to different types of visual environments. With that being said, different gains might apply to more open environments since lamellar flow is known to negatively influence the accuracy of gain perception [2]. Finally, since visual motion perception is influenced by peripheral vision [47], the current results first and foremost serve as a guide for IVR presented using HMDs with a FOV similar to the one experienced by the participants in the current study.

4 Study II: The influence of display FOV

The FOV of visual displays may, as suggested in section 2.3, influence self-motion perception. Thus, it seems likely that variations in FOV might affect what speeds are perceived as natural during WIP locomotion. In other words, the range of perceptually natural visual gains might vary across different

FOVs. While Study I revealed that there indeed exists a tolerance in the range of perceptually natural, the second study was intended to uncover how the upper and lower bounds of this range might vary across different FOVs.

4.1 Study Design

In order to investigate how varying display FOVs influence the perceived naturalness of locomotion speeds during WIP locomotion, a within-subjects study was performed. The study design crossed four viewing conditions (different display FOVs), with two movement types (the WIP gesture and real walking on a treadmill), resulting in a 4×2 factorial design.

4.2 Participants

Twenty-one participants (18 males, 3 females) aged between 18-44 years (M= 28.6 years, SD=6.0) took part in the study. They were recruited via a mailing list comprising volunteers from Aalborg University Copenhagen and readers of the Danish periodical Ingeniøren (The Engineer). As in the first study, all participants had prior experience with virtual WIP locomotion due to participation in previous studies and reported having normal or corrected-to-normal vision and hearing. Tickets for a movie theater were offered as compensation for participation.

4.3 Procedure

As it was the case in the first study, the participants performed 22 walks (11 different visual gains, repeated twice) at a fixed step frequency (1.8 steps per second) for each of the eight conditions (4 viewing conditions × 2 movement types). Also, a normal velocity was established for the individual participant, that is, the speed experienced when a visual gain of 1.0 was applied. However, rather than relying on equation 2 as before, the normal velocity was established prior to the first walk by asking the participants to walk in sync with the metronome on the treadmill at varying speeds without visuals being displayed. The normal velocity was then set based on the treadmill speed which the participants regarded as the most comfortable at the fixed step frequency. Moreover, before performing the first trial, the interpupillary distance (the horizontal separation of the eyes [9]) was estimated using the Oculus Rift configuration utility. Again the 11 visual gains ranged from 1.0 to 3.0, implying that the fastest speed would be three times as great as the established normal velocity. However, the presentation of the 22 visual speeds per condition varied across the two studies. Study II employed a presentation mode similar to the one used by Powell et al. [46], namely, an approach reminiscent of the method of limits. For each condition, the series of visual

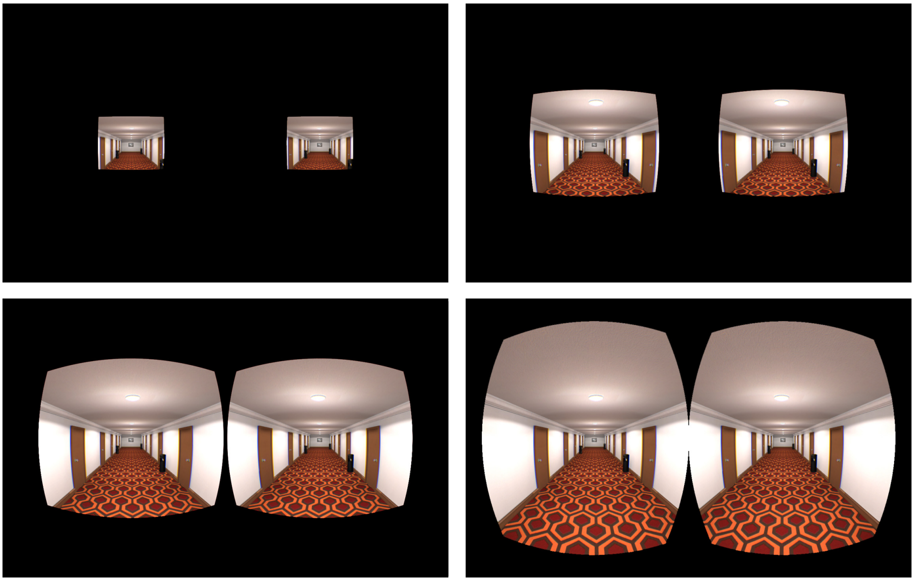

Fig. 4: The four viewing conditions used for Study II: Vertical FOVs of 25° (top left), 50° (top right) and 75° (bottom left), and the unrestricted FOV of the Oculus Rift (bottom right). The distortion constitutes the correction applied for each eye in order to account for the optics of the Oculus Rift developer edition.

gains were either commenced with the slowest visual gain (1.0) or the highest (3.0). After each walk, the gain would change in increments of 0.2. If the series started with the lowest gain, the gains would gradually increase until the highest gain was reached and then decrease until returning to the lowest gain again. The same logic applied if the first gain in the series was 3.0, albeit in this case, the gains would gradually descend before ascending. For each series it was randomly decided whether the first gain should be 1.0 or 3.0. For each walk the participants were asked to report whether they had found the virtual speed 'too slow', 'natural', or 'too fast'. These verbal judgments were given once the participants felt confident enough to do so or when the walk was over. Measures were taken to minimize the risk that the participants might resort to strategic thinking rather than perception when making their judgments. In addition to changing whether each session started with a high or a low visual gain, they were led to believe that both the speed of the initial walk and the change in speed between walks might vary. The actual procedure was revealed to the participants once the study was over and none indicated that they had been aware of the deception.

4.4 Study Stimulus

The virtual environment was identical to the one used in the first study, but the visual display differed. Instead of using the nVisor SX60, visual stimuli were delivered using the developer edition of the Oculus Rift which has a resolution of 640×800 (aspect ratio (AR) = 0.8) in each eye and a vertical FOV of 90°. The four different viewing conditions comprised the unconstrained view of the Oculus Rift (OR) and three constrained views with vertical FOVs of 25°, 50° and 75° (AR = 1.25). There were essentially two reasons why the Oculus Rift was used instead of the display from the first study. First, the Oculus Rift has a larger display FOV, thus making it possible to investigate the effects of a bigger range of FOVs. Second, it is likely to end up in the hands of consumers within the near future. The constrained viewing conditions were produced by means of virtual blinders placed just beyond the near clipping plane of the viewing frustum. Figure 4 illustrates the four viewing conditions. The aspect ratio of 1.25 was chosen since it is comparable to the one used in HMDs such as the nVisor SX60 and ProView SR80. The unconstrained viewing condition was included since it also was considered relevant to establish the range of perceptually natural walking speeds for the Oculus Rift. The orientation of the participants' heads was tracked using the 3DOF sensor embedded within the Oculus Rift. The virtual heights of the participants were based on an assessment of their actual heights. The participants stood on the treadmill and held on to the handlebars during all eight conditions. Finally, there was a minor difference in the auditory feedback provided in the two studies. The metronome sound used to dictate the step frequency in the first study was replaced by sampled footstep sounds played back at the same frequency as the metronome.

4.5 Results

For the 22 walks performed during each of the eight conditions the minimum and maximum visual gain rated 'natural' were identified. That is, the average value of the two lowest gains rated 'natural' (one during ascending gains and one during descending gains) signified the lower bound of the range of perceptually natural gains (the minimum). The upper bound (the maximum) was similarly established based on the average of the two highest gains rated 'natural'. The corresponding results are summarized in Tables 2 and 3 and visualized in Figures 5 and 6. Two-way repeated measures analyzes of variance (ANOVAs) were used to compare the results pertaining to the minimum and maximum reports ($\alpha = .05$). Mauchly's test indicated that the assumption of sphericity had been violated for viewing condition in relation to minimum gain ($\chi^2(5) = 20.13, p < .05$). Thus, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\epsilon = .61$). The assumption

Table 2: Walking – mean values ± one standard deviation pertaining to the maximum and minimum visual gains rated 'natural'.

	25°	50°	75°	OR
Maximum	2.64 ± 0.16	2.35 ± 0.22	2.16 ± 0.22	2.03 ± 0.17
Minimum	2.14 ± 0.16	1.89 ± 0.16	1.75 ± 0.13	1.67 ± 0.13

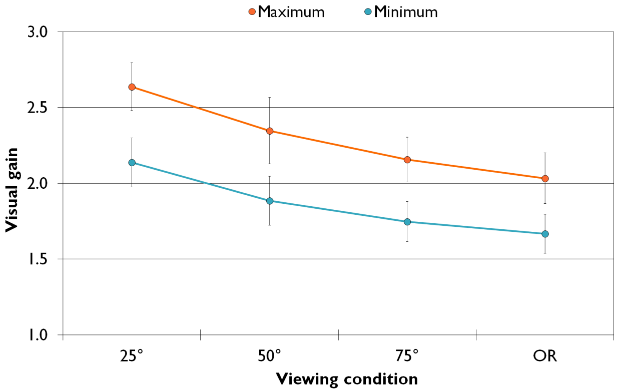

Fig. 5: Walking - results pertaining to the minimum and maximum visual gains rated 'natural'. Error bars indicate 95% confidence levels.

of sphericity was not violated in relation to the remaining measures. Subsequently, significant measures were analyzed by means of paired-sample, two-tailed t-tests using Bonferroni-corrected alpha values ($\alpha = .003$). That is, means pertaining to each of the four different FOVs for the walking condition were compared with the corresponding means for WIP, and the four means for each of the two movement types were compared with one another. Moreover, paired sample t-tests were used to compare the minimum and maximum gains and one sample t-tests were used to compare the minimum gains with the normal gain of 1.0.

In relation to the minimum gains rated 'natural' the performed ANOVAs revealed main effects for viewing condition ($F(1.82, 36.41) = 34.21, p < .001$) and movement type ($F(1, 20) = 8.26, p = .009$), but no significant interaction was found between the two. The ANOVAs related to the maximum gains rated as 'natural' similarly suggested a significant main effect for FOV($F(3, 60) = 62.62, p < .001$) and movement type ($F(1, 20) = 15.63, p < .001$), while no significant interaction was present in regards to the interaction between the two variables.

In relation to both the minimum and maximum gains rated 'natural', the post-hoc analysis revealed the following significant differences: For Walking, OR differed significantly from 50° and 25° differed significantly from all three

Table 3: WIP – mean values ± one standard deviation pertaining to the maximum and minimum visual gains rated 'natural'.

	25°	50°	75°	OR
Maximum	2.50 ± 0.20	2.20 ± 0.18	2.00 ± 0.20	1.99 ± 0.17
Minimum	2.03 ± 0.17	1.80 ± 0.13	1.66 ± 0.16	1.51 ± 0.12

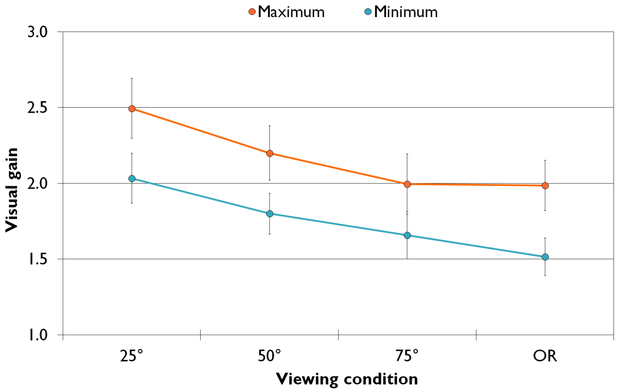

Fig. 6: WIP – results pertaining to the minimum and maximum visual gains rated 'natural'. Error bars indicate 95% confidence levels.

viewing conditions. In regards to WIP, OR also differed significantly from 50°, 75° differed significantly from 50°, and again 25° differed significantly from the remaining three viewing conditions. Table 4 presents an overview of the p-values obtained from the pairwise comparison of the means corresponding to the four viewing conditions. Despite the significant main effect of movement type, the post-hoc analysis did not reveal any significant differences in relation to the minimum and maximum gains. Finally, significant differences were found between the minimum and maximum gains of the

Table 4: P-values obtained from the pair-wise comparison of the mean minimum and maximum gains for the four viewing conditions. Significant difference are highlighted with bold (α = .003).

	Minimum		Maximum	
	Walking	WIP	Walking	WIP
OR-75°	.144	.0273	.048	.879
OR-50°	**.003**	**<.001**	**<.001**	**.002**
OR-25°	**<.001**	**<.001**	**<.001**	**<.001**
75°-50°	.021	**.002**	.007	**<.001**
75°-25°	**<.001**	**<.001**	**<.001**	**<.001**
50°-25	**.002**	**<.001**	**<.001**	**<.001**

individual types of movement in case of all viewing condition for both movement types. Also, the minimum visual gains of all four viewing conditions for both movement types differed significantly from the normal gain of 1.0.

4.6 Discussion

The two-way repeated measures analyzes did, as suggested, reveal a significant main effect for movement type in relation to the minimum and maximum gains. Based on the means alone (Tables 2 and 3), it would appear that the upper and lower bounds of the range of perceptually natural gains are slightly higher for Walking than WIP. This would suggest that individuals to a lesser degree underestimate visual speeds when walking in place, which in turn would imply that one would need to apply slightly smaller visual gains in order to produce perceptually natural walking speeds when users rely on WIP techniques for virtual locomotion. However, the post-hoc analysis did not reveal any significant differences. Thus, it is the belief that the current study does not provide sufficient evidence to suggest that there indeed is a difference in the upper or lower bounds of perceptually natural gains of the two movement types. From the perspective of developers relying on WIP techniques for facilitating virtual locomotion, the lack of significance may be viewed as a positive sign. Following the subtractive model introduced in section 2.2, the similarity in the perceptual distortion accompanying the two modes of locomotion might be regarded as an indication that the kinesthetic feedback generated while walking in place produces a similar degree of subtraction as the real thing.

The two-way repeated measures analyzes also revealed a significant main effect for viewing condition in relation to both minimum and maximum gains. Moreover, the post-hoc analysis revealed significant differences between the majority of the means (Table 4). Based on the means it is apparent that both the lower and higher bounds of the range of perceptually natural gains decreased as the FOV became larger. This suggests that the size of the display FOV is inversely proportional to the degree of underestimation of the virtual speeds for both treadmill-mediated IVR and WIP locomotion. In some capacity this may be viewed as evidence in favor of the hypothesis that lamellar flow is a prerequisite for accurate speed perception put forth by Banton et al [2]. As the participants became increasingly deprived of lamellar flow in the periphery, they became more likely to underestimate the virtual speed. However, the results should not be viewed as evidence in support of peripheral dominance. Instead, the findings correspond with research suggesting that the strength of self-motion illusions increase as a function of the stimulus size independently of whether the stimuli is presented in the central or peripheral vision [40].

Interestingly, no significant differences were found between the means related to the minima and maxima of the conditions with unconstrained FOV and a vertical FOV of 75°. Thus, it would seem that differences in the underestimation of the visual speeds might have decreased as the FOV became larger. It is worth recalling that the study performed by Pretto et al. [47] showed that participants underestimated the speed for circular FOVs smaller than 60° in diameter, leading the authors to conclude that FOVs of at least 60° should be used when motion perception is contingent upon visual flow information. It should be stressed that the two viewing conditions involving the unconstrained FOVs of the Oculus Rift also differed from the remaining conditions in terms of the aspect ratio. Thus, the differences between the means related to these two conditions may also have been influenced by the change in aspect ratio.

Leaving aside the results pertaining WIP for a moment, it is worth considering how the findings compare to existing research on treadmill-mediated walking. Kassler et al. [32] relied on a projection based setup, namely, the IVERT Treadmill System, which has 60° vertical and 175° horizontal FOV [22]. The visual gain identified by Kassler et al. (2.0) lies in the upper half of the range of the 50° condition (min = 1.89 and max = 2.35) and in the lower half of the range of the 75° condition (min = 1.75 and max = 2.16). Thus, the results appear to correspond relatively well. It should be noted that the different aspect ratios and the use of projection, rather than a HMD, make it difficult to directly compare the results of Study II and the ones obtained by Kassler et al.

In the study performed by Powell et al. [46], the participants were placed 2m in front of a 4.5m by 2m screen. Assuming that the screen is positioned at approximately at eye height, the vertical FOV would have been similar to that of the 50° condition, while the horizontal FOV was larger. Thus, the results are not directly comparable to the ones of the current study. Nevertheless, it is worth noting that mean gain resulting from the study by Powell et al. (1.96) falls within the range of the 50° condition (min = 1.89 and max = 2.35). However, the range (0.86) between the minimum (1.55) and maximum (2.41) identified by Powell et al. is higher than the range corresponding to the 50° condition (0.46). Indeed, the minimum identified by Powell et al. is lower than any of the minima revealed by Study II. In addition to the dissimilar visual displays, it is possible to offer three separate, albeit not mutually exclusive, explanations for the differences between results reported by Powell et al. and the ones of Study II. First, Powell et al. allowed the participants to vary the walking speed during each walk, whereas the participants in Study II walked at a fixed speed. Second, Powell et al. relied on a treadmill with sliding handrails, which allowed for more free movement of the upper extremity during the walks. Third, Powell et al. seemingly defined the minimum as the lowest gain rated 'normal' during each session. In Study II the minimum was defined as the mean of the two lowest gain perceived as natural (one during the ascending gains and one during the descending gains). If the minima and maxima had been defined as Powell et al. did, then they would have been lower and higher, respectively, i.e., for 25° (min = 1.95 and max = 2.77), for 50° (min = 1.70 and max = 2.50), for 75° (min = 1.60 and max = 2.38), and for OR (min = 1.55 and max = 2.18). Paired sample t-tests were used to perform pairwise comparisons of these minima and maxima with the corresponding results reported in Table 2. All comparisons revealed that the definition of minima and maxima used by Powell et al. led to significantly lower minima and higher maxima when applied to the data of Study II. In turn, this suggests that the method for identifying the range of perceptually natural gains used in Study II is considerably more conservative than the one proposed by Powell et al.

The study performed by Banton et al. [2] relied on a n-Vision Datavisor HMD with a diagonal FOV of 52° and a resolution of 640×480 in each eye. Their results suggest a considerably lower gain (1.57) than the minima established by Study II. It seems possible that this difference partially may be ascribed to methodological differences. In the study by Banton et al. the participants were asked to report whether the virtual speed should be faster or slower in order to match the speed of the treadmill. The visual speed was adjusted in increments of 0.5 mph until two response reversals were achieved. The matched gain was taken as the average of the two reversal speeds. However, rather than relying on an interleaved staircase procedure, which helps avoid trial-to-trial dependencies and observer strategies [34], the virtual and treadmill speed were identical at the beginning of all sessions. Indeed, the gain identified by Banton et al. is almost identical to the minimum gain (1.55) identified by Powell et al. [46].

Finally, the cited studies rely on virtual environments with markedly different appearances. While Powell et al. [46] did not find any significant differences across two environments, a study by Durgin et al. [18] suggests that the inclusion of near-space objects positively influences gain-matching performance. Thus, variations in the environments cannot be unequivocally ruled out as a factor influencing the results.

It is interesting to note that there are differences between the results of Study I and II. The aspect ratio of the nVisor SX60 HMD used in Study I is identical to the aspect ratio of the three simulated display FOVs of Study II. Since the nVisor SX60 has a vertical FOV of 34° one would expect the range of perceptually natural visual gains revealed by Study I (Table 1) to lie between the ranges corresponding to the 25° and 50° conditions of Study II (Tables 2 and 3). For both WIP and treadmill locomotion, the identified maxima correspond reasonably well. However, Study I indicated considerably lower minima than expected for both WIP and treadmill locomotion, and the ranges between minima and maxima were generally larger in Study I. These discrepancies may have been caused by variations in the ways that minima and maxima were identified. In Study I the minimum and maximum of each session were identified in the same way as they were by Powell et al. [46], i.e., they were defined as the lowest and highest gain rated 'natural'. Therefore, it is possible that the larger ranges between the lower and upper bounds may be attributed to this approach being less conservative than the one employed in Study II.

Another possible explanation is the dissimilarities between the HMDs used in Study I and II. A prominent difference between the two is their weights, i.e., the nVisor SX60 and the Oculus Rift developer edition weighs about 1050g and 380g, respectively. There exists evidence indicating that the mass and moments of inertia of HMDs may contribute to underestimations of virtual distances [74]. Thus, it cannot be ruled out that such mechanical attributes might also influence self-motion perception. Moreover, the Oculus Rift developer edition suffers from display latency and visual pixel seems, which may lead to motion blur when viewing dynamic scenes. Variations in display latency are not believed to have been of great influence since the head movement of the participants were minimal. Evidence suggests that graphical realism does not influence underestimations of virtual distances [64], and studies indicate that motion blur does not influence the perceived speed during a racing game [52]. Nevertheless, the limitations of the Oculus Rift developer edition cannot be ruled out as a factor influencing the participants' self-motion perception. Moreover, in neither of the two studies additional physical shrouds were used to prevent environmental stimuli from entering the displays. While both the HMDs include physical covering, they do not completely deprive the participants of exterior stimuli. This issue appears more prominent in relation to the physical blinders of the nVisor SX60. Jones et al. [31] found that adding a static white light in the far periphery of a HMD positively influences the wearer's distance judgments and perception of scale. Thus, it is plausible that peripheral stimulation influenced the participants' self-motion perception and perhaps even decreased the perceptual distortion of the optic flow speeds. This may in part explain why the underestimation of virtual speeds appear slightly lower than expected for the nVisor SX60. The above explanations are necessarily speculative in nature and suggest possible directions for future studies.

5 Conclusions and Future Work

This paper detailed two studies performed with the intention of exploring natural motion perception in relation to virtual WIP locomotion. Study I investigated whether there exist a tolerance in the range of perceptually natural visual gains which can be applied to virtual WIP locomotion. While the study did not reveal whether the range of perceptually natural gains differs across the two WIP techniques and the other two types of movement, it did yield results relevant to developers of IVR relying on WIP locomotion. The results suggest that there indeed exists a range of perceptually natural visual gains (1.58 to 2.40 for TIP and 1.65 to 2.44 for WIP). WIP and TIP did not differ significantly from one another, suggesting that similar virtual speeds may be perceived as natural in case of both gestures when wearing a HMD similar to the one used in Study I.

The purpose of the second study was two-fold: First, to uncover how the range in perceptually natural gains varies across different display FOVs. Second, to determine whether these variations are similar to the range in perceptually natural gains associated with treadmill mediated IVR. The results revealed significant main effects for both movement type and viewing condition, but no significant interaction between the two variables was found. The post-hoc analyses did not uncover any significant differences in regards to movement type, thus leaving open the question of whether the upper and lower bounds of the gains perceived as natural differ across the two types of movement. The results pertaining to variations in display FOV painted a clearer picture. They suggest that the size of the display FOV is inversely proportional to the degree of underestimation of the virtual speeds. However, no significant differences were found between the largest of the simulated display FOVs and the unconstrained FOV of the Oculus Rift. Thus, it is plausible that the influence of FOV size on the degree of underestimation decreases as the FOV becomes larger. Combined, the results of the two studies constitute a first attempt at establishing a set of guidelines specifying what virtual walking speeds WIP gestures should produce in order to facilitate natural walking experiences. Moreover, the results indirectly open up the possibility that previously identified detection thresholds for translation gains applied during redirected walking might vary depending on the display FOV.

With that being said, future studies should be performed in order to increase the utility of the proposed guidelines. To exemplify, it would be beneficial to investigate how properties of the visual stimuli (e.g. the geometric FOV, latency, resolution, weight, environmental motion cues and external peripheral stimulation) influence the range of perceptually natural visual gains. Research emanating from fields such as biomechanics has led to many insights regarding the relationship between gait parameters and walking speed. However, considering that the biomechanics of stepping in place differ from those of real walking, it is necessary for future studies to investigate how variations in gait parameters, such as step frequency and height, influence the perceived naturalness of walking speeds during WIP locomotion. Finally, the current studies were limited to forward translational motion, and it remains to be seen whether the results are applicable to walks involving rotational motion.

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Paper E

The Effect of Visual Display Properties and Gain Presentation Mode on the Perceived Naturalness of Virtual Walking Speeds

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Abstract

Individuals tend to find realistic walking speeds too slow when relying on treadmill walking or Walking-in-Place (WIP) techniques for virtual travel. This paper details three studies investigating the effects of visual display properties and gain presentation mode on the perceived naturalness of virtual walking speeds: The first study compared three different degrees of peripheral occlusion; the second study compared three different degrees of perceptual distortion produced by varying the geometric field of view (GFOV); and the third study compared three different ways of presenting visual gains. All three studies compared treadmill walking and WIP locomotion. The first study revealed no significant main effects of peripheral occlusion. The second study revealed a significant main effect of GFOV, suggesting that the GFOV size may be inversely proportional to the degree of underestimation of the visual speed. The third study found a significant main effect of gain presentation mode. Allowing participants to interactively adjust the gain led to a smaller range of perceptually natural gains and this approach was significantly faster. However, the efficiency may come at the expense of confidence. Generally the lower and upper bounds of the perceptually natural speeds were higher for treadmill walking than WIP. However, not all differences were statistically significant.

1 Introduction

Walking-in-Place (WIP) techniques constitute an inexpensive and convenient approach to facilitating relatively natural locomotion through virtual environments. The user performs stepping-like movements which serve as a proxy for real steps and enable the user to move through the virtual world while remaining physically stationary. The advantages of WIP techniques include convenience and cost-effectiveness [8]; good performance on simple spatial orientation tasks [33]; and generation of proprioceptive feedback similar, albeit not identical, to the one resulting from real walking [23]. Moreover, WIP locomotion has been shown to elicit a more natural walking experience and a stronger sensation of presence compared to interaction via more traditional peripherals [24, 30]. Combined these advantages suggest the need for finding the best possible WIP technique.

Numerous different interfaces and interaction techniques for WIP locomotion have been proposed (e.g., [3, 8, 12, 17, 18, 28, 31]). Even so, research on WIP locomotion has primarily sought to optimize the technical performance of this type of locomotion techniques (e.g., [8, 31]). Enabling users to control their virtual velocity in a manner that is both responsive and smooth is certainly an important technical challenge [32]. However, it is arguably also crucial to ensure that the experience of navigating virtual worlds is as natural as possible. Bowman et al. [2] describe naturalism, as the objective extent to which actions performed in order to accomplish a certain task correspond to their real world correlates; i.e., the action required to perform the same task in the real world. Thus, the very nature of WIP techniques renders a high degree of naturalism impossible since the biomechanics of real walking and stepping in place are fundamentally different.

Nevertheless, one may aspire to increase the perceived naturalness, of the interaction. Because the experience of walking is inherently multisensory [27], it has been argued that one might benefit from considering the sensorimotor loop in its entirety when attempting to increase the perceived naturalness of WIP techniques [18]. Thus, a central question becomes how to translate steps in place into virtual viewpoint movement. Wendt et al. [31] proposed a biomechanically informed WIP technique which is able to reproduce realistic walking speeds. Although the ability to faithfully reproduce real walking speeds is notable, it need not always be desirable. Nilsson et al. [19] documented that individuals tend to underestimate optic flow speeds during WIP locomotion and, therefore, find realistic walking speeds too slow. Notably, this phenomena is well-known in relation to treadmill-mediated IVR [6]. The direction of the perceptual distortion is identical across studies, i.e., the visual flow is generally perceived as slower than it really is. However, the magnitude of the underestimation varies across studies, and it remains uncertain whether the magnitude is the same for treadmill walking and WIP locomotion. Nilsson et al. [19], suggest that the discrepancies between the results of their two studies may be artifactual. That is, the discrepancies may be attributed to variations in visual display properties or possibly other methodological differences. This paper describes three studies investigating whether two different visual display properties and different gain presentation modes might influence the perceived naturalness of optic flow speeds during treadmill walking and WIP locomotion. The first study (Subsection 3.3) investigates whether variations in the amount of external peripheral stimulation influences the perceived naturalness of virtual walking speeds. The second study (Subsection 3.4) investigates the effects of geometric mini- and magnification, and the third study (Subsection 3.5) compares three different methods for presenting participants with visual speeds.

2 Related Work

It is well-documented that individuals walking on a treadmill tend to experience a reduction in the perceived optic flow speed of expanding flow fields. In other words, the speed perceived visually appears too slow compared to the speed of the treadmill (e.g., [29]). Moreover, variation between optic flow speeds and treadmill speeds are known to influence behavior (e.g., performance on subsequent blind walking tasks [15]).

Banton et al. [1] present four studies investigating the underestimation of optic flow speeds during treadmill-mediated IVR. The treadmill moved at a speed of 3.0mph, and the results suggested that a speed of 4.7mph (a gain of 1.57) was perceived as the best match. Generally, the studies led to the following findings: it was confirmed that geometrically correct optic flow is perceived as too slow during treadmill-mediated IVR; the perceptual distortion may be eliminated if walkers direct their gaze downwards or to the side; the distortion is unaffected by step length; and image jitter does not appear to be responsible for the distortion [1].

Kassler et al. [11] performed a study asking participants to match the speed of projected visuals to the speed of a treadmill by turning a knob. The results suggested a somewhat higher gain than the one reported by Banton et al. [1]. That is, the results indicate that a matched gain of 2.0 was constant across six treadmill speeds.

The variations in the reported gains may be attributed to the use of different displays or other methodological differences. However, it has also been suggested that there may exist a range of tolerance in the speeds that are perceived as natural [21]. Powell et al. [21] performed a study investigating whether normal gain perception is variant. This study also compared two visually distinct virtual hallways and two modes for presenting the gains. The results did not reveal any significant differences in the range of perceptually normal gains across the two environments or between the two presentation modes. However, they did suggest that there exists a tolerance in the range of perceptually normal gains.

Nilsson et al. [19] describe two studies intended to establish the range of perceptually natural walking speeds for WIP locomotion. The first study compared four different types of movement, namely, no leg movement, walking on a treadmill, and two forms of gestural input for WIP locomotion. The results suggested that WIP locomotion is accompanied by perceptual distortion in the same way as treadmill walking. The second study compared two movement types (treadmill walking and WIP) and four different display fields of view (the unconstrained view of the first Oculus Rift developer edition and three constrained views). The results suggested significant main effects of both movement type and field of view. However, the post-hoc analysis did not reveal any significant differences in regards to movement type. Notably, the first study revealed considerably lower minima than the second study, and the first study generally yielded smaller ranges between minima and maxima than the second study. When discussing why the results of the two studies differ from one another and related work, Nilsson et al. [19] note that the differences may be attributed to variations in the physical setup; e.g., some participants hold on to the handlebar whereas others wear a harness, and treadmill speeds may be constant or variant during each walk. Also, varying visual display properties may be responsible; e.g., the degree of peripheral stimulation or the head-mounted display (HMD) weight. Finally, different experimental procedures and methodologies may have led to the different results.

3 User Studies

Unanswered questions, such as the ones outlined in the previous section, served as part of the motivation for the three studies documented in the current paper. Study 1 (S1) investigated the effects of varying degrees of peripheral occlusion, study 2 (S2) investigated the effects of geometric mini- and magnification, and study 3 (S3) compared three different gain presentation methods. Moreover, all three studies compared treadmill walking with WIP locomotion since it remains uncertain whether different gains are perceived as natural by users relying on the two modes of locomotion.

3.1 Task and Environment

The variables being manipulated differed across the three studies, but the basic task and virtual environment remained the same. The participants were required to perform a series of virtual walks using a treadmill and WIP locomotion. During these walks they were exposed to a range of different visual gains, that is, scalar multiples of their normal walking speeds. The normal walking speeds were estimated prior to the first trial by asking the participants to walk on the treadmill while keeping their steps synchronous with a metronome tapping a 1.8 taps per second. This step frequency is just below the one accompanying normal gait speed for both men and women [20] and was chosen to ensure the safety and comfort of the participants. During this initial walk the participants could adjust the treadmill speed until they were

Fig. 1: The environment seen from the participants' perspective.

able to walk in sync with the metronome at a pace they found comfortable. This speed was used as an estimate of their normal walking speed at that step frequency. During the subsequent trials the participants were asked to judge what visual speeds they perceived as natural – a speed would qualify as natural if the participants, based on their prior experiences of walking, felt that the movement they performed could result in said speed. The same virtual environment was used for all three studies, namely, a seemingly infinite corridor (Figure 1). The vertical position of the virtual viewpoint was defined based on the participants' real heights. Since gaze direction may influence motion perception [1], the participants were instructed to keep their gaze fixed on the end of the corridor.

3.2 Study Stimuli and Setup

The visuals were displayed using a nVisor SX60 HMD, with a resolution of 1280×1024 and a diagonal FOV of 60° in each eye. The only auditory feedback was a metronome sound dictating at what step frequency the participants should walk. A 16 camera Optitrack motion capture system was used to track the position and orientation of a marker placed on the HMD. The cameras were placed along the circumference of a circle with a diameter of 7m. Twelve were placed at a height of approximately 2.9m and 4 were placed about 1.8m from the ground. The participants stood on the treadmill (ProForm 520 XLT) and held onto the handlebars during all conditions. Figure 2 shows a schematic drawing of the setup.

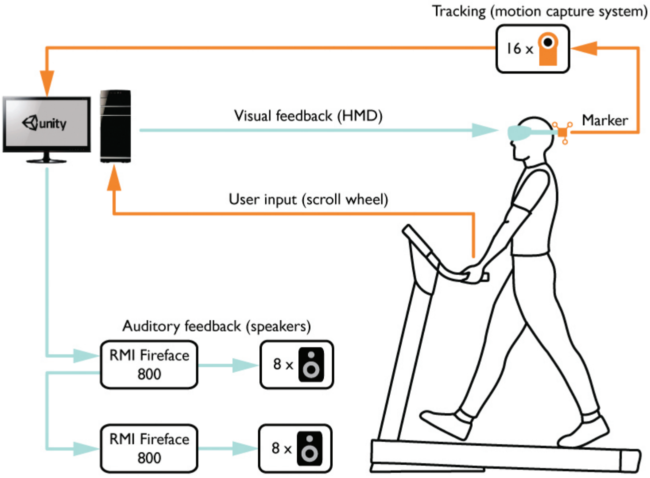

Fig. 2: Schematic drawing of setup used for the study.

3.3 Study 1 (S1): Peripheral Occlusion

The first study explored the effects of peripheral visual information on the perceived naturalness of virtual walking speeds. Jones et al. [10] performed studies suggesting that the addition of a static white light in the far periphery of a HMD improves the wearer's performance on distance judgment and visual scale tasks. Thus, it seems possible that external peripheral stimulation might also influence the perception of movement through virtual space. In order to investigate the effects of peripheral visual information, a within-subjects study was performed. The study design crossed two *movement types* (treadmill walking and WIP) with three *levels of peripheral occlusion* (no occlusion, the standard nVisor SX60 blinders and complete deprivation from peripheral visual information) resulting in a 2×3 factorial design.

Participants in S1

Twenty participants (15 males, 5 females) aged between 15-42 years (M=27.5 years, SD=7.0) took part in S1. They were recruited via a mailing list comprising volunteers from Aalborg University Copenhagen and readers of the Danish periodical Ingeniøren (The Engineer). All participants reported having normal or corrected-to-normal vision and hearing; 16 had prior experience with IVR; 14 had previously used WIP for virtual locomotion; and when asked how experienced they were at playing video games seen from a first person perspective the answers were distributed as follows: 2 'not experience at all', 5 'a little experienced', 6 'experienced' and 7 'very experienced'. A meal was offered as compensation for participating.

Method and Materials for S1

The study did, as described in Subsection 3.1, require the participants to perform a series of walks while identifying the visual speeds that felt natural. The participants performed 24 walks (4 walks for each of the 2×3 conditions) and were exposed to visual gains ranging from 0.1 to 4.0. Thus, the slowest speed was a tenth of the estimated normal walking speed while the highest

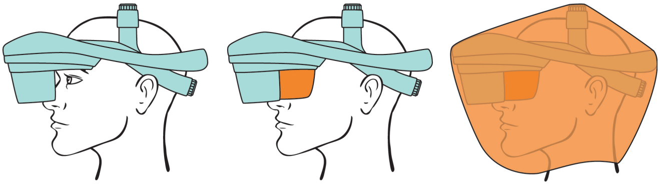

Fig. 3: The three levels of peripheral occlusion used in S1. From the left: The nVisor SX60 without any blinders, the display with standard blinders and the cloth shroud preventing all external peripheral stimulation.

was four times greater. In a vein similar to Kassler et al. [11], the participants were asked to perform a gain matching task informed by the method of adjustment (e.g., [7]). The order of the four starting speeds per condition was randomized. During each walk the participants were able to control the visual speed by manipulating the applied gain using a scroll wheel mounted on the right handlebar (Figure 2). The gain was changed in increments of 0.05 with 24 increments per revolution of the wheel. Thus, a full revolution resulted in a gain change of 1.2. Rather than asking the participants to identify a single point where they felt that visual speed matched their movement, they were asked to verbally indicate when the visual speeds reached the lower and upper limits of what felt natural.

During two of the four walks per condition the initial speed corresponded to the a lowest possible gain (0.1) and during the remaining two it was the highest possible (4.0). Thus, half of the walks involved the participants increasing the virtual speed in order to identify the lower and upper limit of the perceptually natural speeds, whereas the other half required the participants to decrease the speed in order to do so. Both ascending and descending speeds were included in order to minimize errors caused by habituation and expectations, as it is often done when using the method of adjustment and similar psychophysical methods [13]. The three levels of peripheral occlusion were achieved by removing the standard blinders from the nVisor SX60, leaving the HMD untouched, and by including the blinders while covering the participants head in a thick cloth shroud (Figure 3). The lighting conditions in the room were identical for all participants. The order of the six conditions was pseudo-randomized; i.e., it was randomly decided if the participants initially were exposed to the three degrees of peripheral occlusion while walking on the treadmill or while walking in place. The participants were presented to the three degrees of peripheral occlusion in randomized order. In total the study took about 30 minutes and the participants were required to take a 5-minute break halfway through.

Results of S1

For each condition, the mean minimum and maximum gains perceived as natural were identified. The minimum and maximum of the individual participants were defined as the means of the four lower limits and upper limits, respectively. The corresponding means are visualized in Figure 4. Shapiro-Wilk's tests suggested that the obtained data were normally distributed, and Mauchly's tests indicated no violations of the assumption of sphericity. Two-way repeated-measures analyzes of variance (ANOVAs) were used to compare the corresponding means. Significant measures were subjected to post-hoc analyses by means of paired sample, two-tailed t-tests using Bonferroni-corrected alpha values. The ANOVAs did not reveal any significant interac-

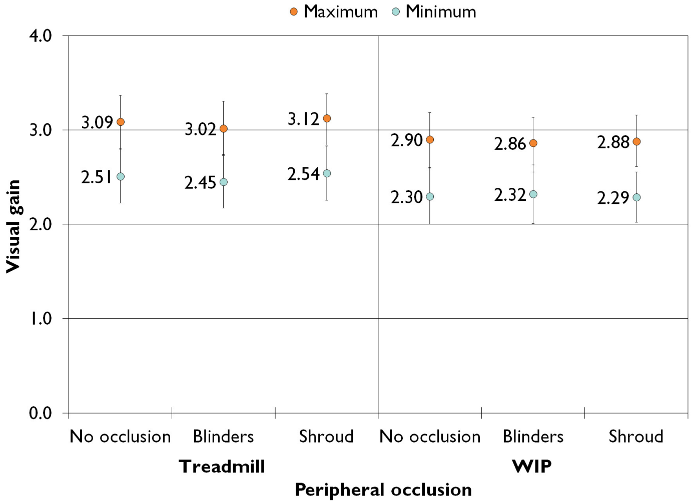

Fig. 4: Minimum and maximum visual gains perceived as natural for the three degrees of peripheral occlusion across Treadmill and WIP (S1). Error bars indicate 95% confidence intervals.

tion between movement type and peripheral occlusion for minima ($F(2, 38) = 1.274, p = .291$) or maxima ($F(2, 38) = .860, p = .431$). Moreover, no significant main effect was found for peripheral stimulation in regards to minima ($F(2, 38) = .221, p = .803$) or maxima ($F(2, 38) = 1.097, p = .344$). Finally, the main effect of movement type was borderline significant for both minima ($F(1, 19) = 4.118, p = .057$) and maxima ($F(1, 19) = 4.313, p = .052$). No post-hoc analyzes were performed due to lack of significant main effects.

Discussion of S1

The means presented Figures 4 along with the lack of any statistically significant differences suggest that the degree of peripheral occlusion might not have influenced what speeds the participants experienced as natural. The difference between the degrees of peripheral occlusion in the current study were considerably higher than the difference between the two studies reported by Nilsson et al. [19]. Thus, it seems unlikely that variations in the amount of peripheral occlusion were to blame for the varying results reported by the authors. However, it cannot be unequivocally ruled out that external peripheral stimulation might influence motion perception. It is possible that the effect was so subtle that the current study failed to identify it. In regards to movement type, the same pattern was apparent across all means; i.e., the means pertaining to treadmill walking were generally higher that then ones pertaining to WIP locomotion. However, the ANOVAs did not reveal significant differences.

3.4 Study 2 (S2): Geometric FOV

Steinicke et al. [26] describe that an important factor ensuring an undistorted view of the virtual environment is how the properties of the geometric field of view (GFOV) compares to the ones of the display field of view (DFOV). The DFOV is defined by the vertical and horizontal angles subtended by the visual display. Combined with the aspect ratio the GFOV describes the virtual counterpart to the DFOV, i.e., the vertical and horizontal boundaries of the virtual viewing volume. In order to obtain an undistorted perspective, the GFOV should be set up to match the DFOV. A GFOV which is larger than the DFOV forces more geometry to be displayed in the projected image and will result in *minification*. The opposite happens when the GFOV is smaller than the DFOV. The resulting distortion is referred to as *magnification* [26]. Interestingly, Steinicke et al. [26] have demonstrated that correctly projected geometry need not always be perceived as the most natural. To be exact, participants appear to find some amount of minification more natural than the undistorted view of virtual environments. The amount of minification appears to be dependent on the size of the DFOV. Moreover, work by Kuhl et al. [14] suggests that minification may help reduce underestimation of distances within IVR, and changes to the GFOV have also been shown to influence motion perception during driving simulations [16]. Consequently, it seems reasonable to assume that manipulating the GFOV will influence the underestimation of virtual walking speeds. In order to ascertain whether this indeed is the case, a within-subjects study was performed. The study was based on a 2×3 factorial design crossing two *movement types* (treadmill walking and WIP) with three different *vertical GFOV* (24°, 34° and 44°).

Participants in S2

The 20 people who participated in S1 also took part in S2. The participants were exposed to the two studies in randomized order.

Fig. 5: The three vertical GFOV used in S2: From the left 24° (magnification), 34° (undistorted) and 44° (minification). To make the distortion easily apparent two virtual objects are highlighted in blue and orange.

Method and Materials for S2

This study followed the same method as S1 (see Subsection 3.3). Thus, the participants performed a total of 24 walks (4 walks for each of the 2×3 conditions). The three different degrees of distortion of the view of the virtual environment were achieved by manipulating the GFOV. The nVisor SX60 has an aspect ratio of 1.25 and a vertical DFOV of 34°. In all three cases, the aspect ratio of the GFOV corresponded to the DFOV of the nVisor, but the vertical GFOV was manipulated. The first configuration used a vertical GFOV of 24° (magnification), the second used a vertical GFOV of 34° (undistorted), and the last used a vertical GFOV of 44° (minification). Figure 5 illustrates the three perspective projections. Counterbalancing was performed as in S1, and S2 similarly lasted for about 30 minutes including a mandatory 5-minute break halfway through the study.

Results of S2

The minima and maxima of each condition were identified as in S1 (see Subsection 3.3). Figures 6 summarize the results of S2. Shapiro-Wilk's tests indicated that normality could be assumed in relation to the minima, but the assumption had been violated for the maxima. Nevertheless, two-way repeated-measures ANOVAs were chosen for analysis of all data since comparable results were obtained when using a Friedman test to analyze the results pertaining to the maxima ($\chi^2(5) = 75.382, p < .001$).

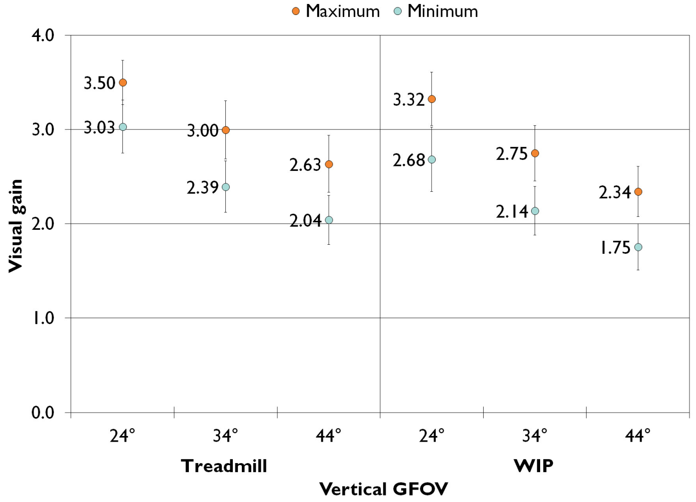

Fig. 6: Minimum and maximum visual gains perceived as natural for the three vertical GFOV across Treadmill and WIP (S2). Error bars indicate 95% confidence intervals.

Mauchly's tests indicated that the assumption of sphericity had been violated in relation to the minima for geometric FOV ($\chi^2(2) = 6.6701, p < .035$). Thus, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity for ($\epsilon = .76$) Similarly, a violation was found for maxima in regards to interaction between movement type and GFOV ($\chi^2(2) = 9.600, p < .008$) and the degrees of freedom were corrected in a similar manner ($\epsilon = .71$).

No significant interaction was found between the two variables in regards to minima ($F(2, 38) = .814, p = .451$) or maxima ($F(1.415, 26.886) = 1.079, p = .35$). A significant main effect of GFOV was found for both minima ($F(1.526, 28.989) = 220.252, p < .001$) and maxima ($F(2, 38) = 178.356, p < .001$). A significant main effect was found for movement type for minima ($F(1, 19) = 6.207, p = .022$), but not for maxima ($F(1, 19) = 4.180, p = .055$). As in S1, significant results were subjected to post-hoc analyzes by means of paired sample, two-tailed t-tests using Bonferroni-corrected alpha values.

The post-hoc analysis of the minima ($\alpha = .005$) revealed significant differences between all three GFOV for both treadmill walking and WIP. That is 24° was significantly higher than 34° and 44°, and 34° was significantly higher than 44°. All with a significant level of $p < .001$. Despite the significant main effect, the post-hoc test did not reveal any significant differences between the three GFOV across the two movement types. Since no significant main effect of movement type was found in regards to maxima, the post-hoc test only compared the three GFOV for either treadmill walking or WIP ($\alpha = .008$). Again, significant differences were found between all three GFOV; 24° was significantly higher than 34° and 44°, and 34° was significantly higher than 44°. All with a significant level of $p < .001$.

Discussion of S2

The ANOVAs did as suggested uncover significant main effects of GFOV for both minima and maxima and the subsequent post-hoc tests suggested that all three GFOV differed significantly from one another for both treadmill walking and WIP locomotion. For larger GFOV, the participants found speeds closer to the normal walking speed more natural. Thus, the size of the GFOV appears to be inversely proportional to the degree of underestimation of visual walking speeds in case of both movement types. It is worth nothing that the results generally are consistent with work suggesting that drivers exposed to a driving simulator are better at producing target speeds when the GFOV is larger than the DFOV [4]. Moreover, the results also correspond with the finding that some amount of minification is perceived as more natural than an undistorted view of the virtual world [26]. With that being said, from Figure 6 it would appear that a very large GFOV is required in order to achieve veridical performance; i.e., it would require an unnaturally high degree of minification for the participants to judge gains of 1.0 to be natural.

Finally, the results pertaining to movement type indicated that there was a significant main effect in relation to the minima. Even though the post-hoc tests did not reveal any significant differences, it is worth noting that all means pertaining to treadmill walking were higher than the corresponding means related to WIP as in S1.

3.5 Study 3 (S3): Gain presentation

The purpose of the third study was to compare three approaches to identifying the range of perceptually natural walking speeds during virtual locomotion. Powell et al. [21] found no significant differences when comparing two different approaches to presenting participants with gains. However, when discussing why their results differ from one another and other related work, Nilsson et al. [19] highlight that methodological differences might be to blame. Consequently, the current study sought to compare gain presentation methods similar to the ones which previously have been employed by Kassler et al. [11], Powell et al. [21], and Nilsson et al. [19]. To meet this aim, a within-subjects study was performed. The study design crossed two *movement types* (treadmill walking and WIP) with three *gain presentation modes* (different ways of presenting the visual speeds), resulting in a 2×3 factorial design.

Participants in S3

Twenty participants (16 males, 4 females) aged between 19-43 years (M=28.2 years, SD=7.0) took part in the study. They were recruited via the same mailing list used for S1 and S2. All participants reported having normal or corrected-to-normal vision and hearing. When asked how experienced they were at playing video games seen from a first person perspective the answers were distributed as follows: 3 'not experience at all', 2 'a little experienced', 7 'experienced' and 8 'very experienced'.

Method and Materials for S3

In case of all three gain presentation modes, the participants were exposed to visual gains ranging from 1.0 to 4.0. While the range of visual gains were identical across the three gain presentation modes, the manner in which the gains were presented varied. Even though the three gain presentation modes are reminiscent of existing psychophysical methods (i.e., the method of constant stimuli, method of limits and the method of adjustment [7]), we refrain from using identical labels in order to avoid ambiguity. Instead, we refer to the three as *Randomized Order*, *Reversed Staircases* and *User Adjustment*:

Randomized Order: The participants were exposed to 15 different gains ranging from 1.0 to 4.0 in increments of 0.2. As each gain was repeated twice, this yielded a total of 30 walks. The gains were presented in randomized order. During each walk the participants verbally reported whether they found the visual speed ‘too slow’, ‘natural’, or ‘too fast’ with respect to the movement they were performing.

Reversed Staircases: This gain presentation mode also involved exposure to visual gains ranging from 1.0 to 4.0 in increments of 0.2. However, the gains were organized into an ascending and a descending series. That is, if the series started with the lowest gain, the gains would gradually increase and if it started with 4.0, then it would gradually decrease. It was randomly decided whether the first series would be ascending or descending. Again the participants were asked to report whether they found the virtual speed ‘too slow’, ‘natural’, or ‘too fast’. Ascending series were terminated the first time a ‘natural’ report was followed by ‘too fast’, and descending series were terminated when a ‘natural’ rating was followed by ‘too slow’.

User Adjustment: The third gain presentation mode was largely identical to the method used in S1 and S2 (see Subsection 3.3). It is possible that the range of the presented gains might influence the participants’ judgments. Thus, to ensure a fair comparison the gain presentation mode also involved gains ranging from 1.0 to 4.0. Moreover, it was decided to reduce the number of repetitions to two in order to ensure that the participants were exposed to each gain the same number of times across the three conditions.

Counterbalancing was performed as in S1 and S2 (see Subsection 3.3). The study lasted for about 50 minutes including a mandatory 10-minute break after half of the conditions were completed.

Results of S3

In case of the Randomized Order the minimum was defined as the mean of the two lowest gains and the maximum was defined as the mean of the two highest. In case of Reversed Staircases the minimum and maximum were defined as the mean of the lowest gains rated ‘natural’ during the ascending series and the lowest gain rated ‘natural’ during the descending series. In case of the maximum the two highest gains rated ‘natural’ during the ascending and descending series were considered. Finally, for User Adjustment the minimum and maximum were defined as the means of two lower and upper limits, respectively. The corresponding results are summarized in Figure 7. Two-way repeated-measures ANOVAs were used to compare the corresponding means. Significant measures were compared using paired sample, two-tailed t-tests with Bonferroni-corrected alpha values. Shapiro-Wilk’s tests revealed no violations of normality. Mauchly’s tests indicated that the assumption of sphericity had been violated for gain presentation mode in relation to the maxima ($\chi^2(2) = 14.68, p < .01$). Thus Greenhouse-Geisser estimates of sphericity ($\epsilon = .64$) were used to correct degrees of free-

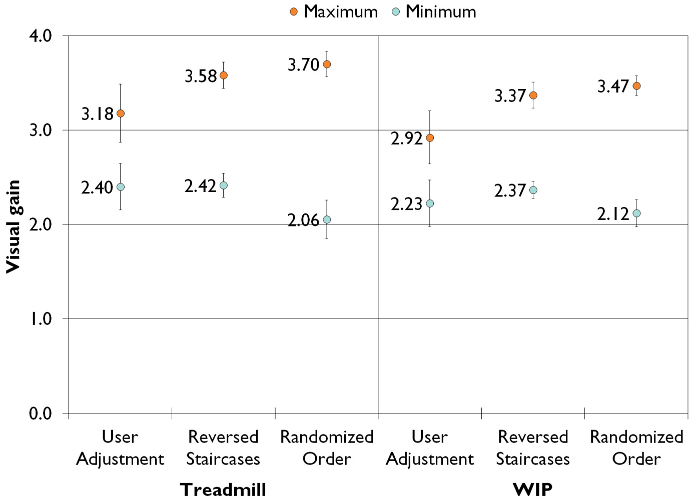

Fig. 7: Minimum and maximum visual gains perceived as natural for the three gain presentation modes across Treadmill and WIP across (S3). Error bars indicate 95% confidence intervals.

dom. For the range of natural gains sphericity could not be assumed in relation to the interaction between gain presentation mode and movement type ($\chi^2(2) = 9.33, p < .01$) and degrees of freedom were corrected using Greenhouse-Geisser estimates ($\epsilon = .71$). The ANOVAs did in no cases reveal significant interactions between gain presentation mode and movement type. In relation to the minima, a significant main effect was found for gain presentation mode ($F(2, 38) = 8.807, p = .001$), but none was found for movement type. For treadmill walking the post-hoc analyzes ($\alpha = .008$) suggested that the minimum pertaining to Randomized Order was significantly lower than the ones corresponding to User Adjustment ($p = .001$) and Reverse Staircases ($p < .001$). For WIP the minimum of Randomized Order was significantly lower than Reversed Staircases ($p < .001$). In regards to maxima, significant main effects were found for both gain presentation mode ($F(1.284, 24.395) = 4.968, p < .001$) and movement type ($F(1, 19) = 33.288, p < .001$). The post-hoc analyzes ($\alpha = .005$) indicated that the maximum resulting from User Adjustment was significantly lower than the other two maxima in regards to both treadmill walking and WIP ($p < .001$ in all cases). The maxima pertaining to Randomized Order differed significantly across the two motion types ($p < .001$), i.e., treadmill walking was significantly higher than WIP.

In case of all three gain presentation modes, the range of perceptually natural gains was defined as the differences between the minima and maxima for the participants (Figure 8). Shapiro-Wilk's and Mauchly's tests revealed no violations of normality and sphericity, respectively. Significant main effects were found for both gain presentation mode ($F(2, 38) = 40.790, p < .001$) and movement type ($F(1, 19) = 40.269, p < .001$). The post-hoc analyzes were similar for treadmill walking and WIP. That is, the ranges resulting from User Adjustment were significantly lower than the ranges resulting from the other gain presentation modes, and Reverse Staircases was significantly lower than Randomized Order ($p < .001$ in all cases). Finally, the range resulting from Randomized Order during treadmill walking was significantly larger than the corresponding range during WIP ($p < .001$).

The mean completion times are summarized in Figure 9. The assumption of normality was not satisfied for this measure as indicated by Shapiro-Wilk's tests ($p > .05$). Nevertheless, the two-way repeated-measures ANOVA was used since comparable results were obtained using a Friedman test

Fig. 8: Range of perceptually natural gains for the three gain presentation modes across Treadmill and WIP across (S3). Error bars indicate 95% confidence intervals.

Fig. 9: Completion time for the three gain presentation modes across Treadmill and WIP across (S3). Error bars indicate 95% confidence intervals.

($\chi^2(5) = 85.657, p < .01$). Mauchly's tests indicated no violations of the assumption of sphericity. No significant interaction between the variables was found ($F(2,38) = 1.375, p = .265$). A significant main effect was identified for gain presentation mode ($F(2,38) = 265.779, p < .001$), but not for movement type ($F(1,19) = 4.119, p = .057$). The post-hoc analysis ($\alpha = .005$) revealed significant differences between the gain presentation modes for both treadmill walking and WIP, i.e., User Adjustment was significantly faster than both other methods and Reverse Staircases was significantly faster than Randomized Order ($p < .001$ in all cases).

Discussion of S3

The variable gain presentation mode yielded significant main effects in relation to both minima and maxima across both treadmill walking and WIP (Figure 7). Notably, during treadmill walking Randomized Order led to a significantly lower threshold for natural gain perception than during the two other gain presentation methods, and during WIP the lower threshold was significantly lower for Randomized Order than Reverse Staircases. Moreover, the upper limit of the range of perceptually natural gains resulting from Randomized Order was significantly higher than the one corresponding to User Adjustment for both treadmill walking and WIP. In other words, it would appear that presentation of visual gains using Randomized Order generally caused the participants to find higher and lower gains natural. Indeed, this is also reflected in the results pertaining to the magnitude of the range of perceptually natural gains (Figure 8). The analysis indicated that the difference between the minima and maxima pertaining to Randomized Order was significantly larger than the ranges resulting from the two other gain presentation modes. This finding applied to both treadmill walking and WIP. Nilsson et al. [19] similarly found that random gain presentation led to lower minima and a larger range of perceptually natural gains than a method resembling Reversed Staircase. Despite these similarities, the results of S3 differs from those reported by Nilsson et al. [19] in important ways. S3 generally led to higher minima and maxima, and Randomized Order and Reversed Staircases led to larger ranges of natural gains than the comparable methods employed by Nilsson et al. [19]. It is possible to offer at least two different, albeit not mutually exclusive, explanations.

First, differences in the appearance of the virtual environments may be to blame. The study performed by Powell et al. [21] did not uncover any significant differences in gain perception across two environments; but work by Durgin et al. [5] indicated that the inclusion of near-space objects positively influences gain-matching performance. Variations in the environments can therefore not be unequivocally ruled out as a factor of influence. While the virtual environment used in S3 is largely identical to the one employed by

Nilsson et al. [19], the two differ in one notable way. Whereas, S3 relied on an infinite corridor, Nilsson et al. [19] used a corridor of 14m. This visual difference may have influenced the radial flow produced by the virtual motion and in turn the perception of speed.

Secondly, it is possible that differences in the range of presented gains may be responsible for the varying results. Both studies reported by Nilsson et al. [19] relied on gains ranging from 1.0 to 3.0 while the participants in S3 were exposed to gains ranging from 1.0 to 4.0. Thus, habituation and increased exposure time may have been a source of error causing the gains resulting from S3 to be unnaturally high. Here it is interesting to note that the results do not differ notably between S3 and the remaining two studies, even though S1 and S2 included gains ranging from 0.1 to 4.0. If habituation was of influence one might expect the results of the first three studies to suggest lower minima and maxima. However, it cannot be ruled out that habituation is of greater influence for lower gains than higher gains, and it is possible that habituation was less influential during User Adjustment since the participant more rapidly could skip across seemingly unnatural visual gains. Generally, it would seem that one should be careful when comparing the results of studies relying on different ranges of visual gains. While the different ranges in gains may be responsible for observed differences, variations in exposure time may constitute a confounding variable.

In addition to suggesting that the varying results found by Nilsson et al. [19] might be attributed to methodological differences, the results of S3 also provides interesting information about the use of User Adjustment, which was adapted from the psychophysical method dubbed the method of adjustment [7]. Particularly, User Adjustment was, as expected, significantly faster than both of the other methods and Randomized Order was significantly slower than Reversed Staircases. Indeed, the participants completed the task twice as fast when relying on User Adjustment compared to Randomized Order. While decreased completion times are a positive trait of the method, it should be stressed that it makes it impossible to unequivocally rule out that the differences between the three conditions was due to varying amounts of exposure to the IVR. In addition to being faster, it would appear that User Adjustment produced more conservative estimates than the other two since it yielded significantly smaller ranges of perceptually natural gain. It is interesting to note that the methods with the longest durations seemingly led to the largest ranges of perceptually natural gains (Figures 8 and 9). The caveat is that the 95% confidence intervals pertaining to User Adjustment are considerably larger than the ones obtained from the other measures (Figures 7). Notably, similar confidence intervals are apparent from the results of S1 and S2. Thus, while this method appears to be more conservative, this may come at the expense of confidence. The limitations of the method of adjustment are, however, not a novel insight. Versions of the method of adjustment has been used in relation to several studies of perception within IVR (e.g., [1, 22, 26]). However, Gescheider [9], describes that, while the method is used as a clinical device for diagnosing sensory loss, the method is rarely used to determine the limits of perception within psychophysical research. Instead, it is primarily used to produce preliminary perceptual thresholds which are further probed using more precise methods, such as, forced-choice methods which also have been used to study perception within IVR [25]. In sum, the choice of gain presentation mode appears to involve a trade-off between temporal resources and the required degree of precision. It should be noted that a limitation of S3, and the other two studies, is the relatively low number of times each visual gain was presented.

In regards to the influence of movement type, a significant main effect was found in relation to the maxima, but none was found for the minima. The post-hoc analysis only suggested that treadmill walking was significantly higher than WIP in relation to Random Order. Statistical insignificance notwithstanding, it is interesting to note that S3 showed the same pattern as the other two studies, i.e., with exception of one, all means pertaining to treadmill walking were higher than the corresponding means of WIP. Similarly, the magnitude of the range of perceptually natural gains was higher for treadmill than WIP, but the post-hoc analysis only revealed a significant difference in regards to Randomized Order. This suggests that the range of gains perceived as natural during WIP is smaller than during treadmill walking. At first glance, this might be viewed as an indication that the participants were more certain about their judgements when relying on WIP. However, this assumption is not supported by the results pertaining to completion time which suggested that movement type did not influence how long time it took the participants to assess the naturalness of the walking speeds. These assumptions necessarily remain speculative in nature but suggest possible directions for future studies.

4 Conclusions and Future Work

This paper detailed three studies exploring whether different degrees of peripheral occlusion, GFOV size, and gain presentation mode influence the perceived naturalness of visual walking speeds. All three studies compared treadmill walking and WIP locomotion.

S1 compared three different degrees of peripheral occlusion, but no main effect was found. However, it remains a possibility that the effect was so subtle that the employed method failed to identify it. While S1 compared three different types of peripheral occlusion, future studies might attempt to vary the amount and type of peripheral stimulation in a more controlled manner.

S2 investigated how three different levels of perceptual distortion influenced the perceived naturalness of virtual walking speeds. The results suggested that the size of the vertical GFOV is inversely proportional to the degree of underestimation of visual walking speeds. Notably, Steinicke et al. [26] found that different degrees of minification led participants to perceive the same virtual scene as natural across different DFOV. Therefore, it would be relevant for future studies to determine how different combinations of DFOV and GFOV influence motion perception.

S3 investigated the influence of different gain presentation modes. A significant main effect was found and the results indicate that random presentation of the visual gains led to the largest range of perceptually natural gains while user adjusted gains entailed the smallest range. The latter was also significantly faster, but resulted in larger confidence intervals. Thus, it would appear that the choice of gain presentation involves a trade-off between temporal resources and the required degree of precision. A primary limitation of the presented work is the limited number of repetitions per condition (i.e., the number of self-reports per condition). Thus, it would natural for future studies to involve more trials. Moreover, it would be relevant to consider traditional psychophysical methods (e.g., interleaved staircases and two-alternative forced-choice tasks).

The results pertaining to the effects of movement type obtained from all three studies collectively provided interesting indications. Even though some results were not statistically significant, it is interesting to note that the same pattern was apparent across all three studies. The lower and upper bounds of what speeds were perceived as natural were higher for treadmill walking than WIP for all but one of the paired conditions. Future meta-analysis may help solidify this claim. Moreover, future studies might address whether motion perception varies across different types of treadmills (e.g., between linear and omnidirectional treadmills) as well as during continuously varying gaze directions.

Finally, the studies yielded anecdotal evidence suggesting an interesting new direction for future studies. Two participants did, days after participating, independently of each other remark that the studies had influenced their everyday experience of walking speeds. They had started consciously attending to optic flow speeds when walking, and when doing so they sometimes felt that the walking speeds were too slow. This leaves the question: can part of the observed underestimation of virtual walking speeds be attributed to the participants explicitly focusing on the perceived naturalness of the speeds? If the perceived naturalness of optic flow speeds is influenced by the degree of attention explicitly allocated for visual motion perception, then future studies will need to rely on different tasks and measures.

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Paper F

The Influence of Step Frequency on The Range of Perceptually Natural Visual Walking Speeds During Walking-in-Place and Treadmill Locomotion

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Abstract

Walking-in-Place (WIP) techniques make relatively natural walking experiences within immersive virtual environments possible when the physical interaction space is limited in size. In order to facilitate such experiences, it is necessary to establish a natural connection between steps in place and virtual walking speeds. This paper details a study investigating the effects of movement type (treadmill walking and WIP) and step frequency (1.4, 1.8 and 2.2 steps per second) on the range of perceptually natural visual walking speeds. The results suggest statistically significant main effects of both movement type and step frequency but no significant interaction between the two variables.

1 Introduction

Walking-in-Place (WIP) techniques constitute a relatively natural alternative to real walking for users navigating an immersive virtual environment which is larger than the physical interaction space. When relying on WIP techniques for virtual locomotion the user performs stepping-like movements. These steps in place serve as a proxy for real steps and enable the user to move through the virtual world while remaining stationary with respect to the physical environment. The advantages of WIP techniques include, but need not be limited to, convenience and cost-effectiveness [5], good performance on simple spatial orienting tasks [19], and generation of proprioceptive feedback similar, albeit not identical, to the one resulting from real walking [13]. Moreover, virtual locomotion accomplished via such stepping motions have been shown to elicit a more natural walking experience and a stronger sensation of presence compared to interaction via more traditional peripherals [14], [16]. Combined these potential advantages suggest the need for finding the best possible WIP technique. Arguably, the challenge of doing so is twofold. First, it includes the technical challenge of enabling users to control their virtual velocity in a manner that is both responsive and smooth [18]. Second, it is necessary to investigate how to increase the perceived naturalness of WIP locomotion, i.e., how to make it feel as close to the real thing as possible [9]. A part of the second challenge is to ensure that there is a natural correspondence between the gesture being performed and the virtual velocity. Wendt, Whitton and Brooks [17] proposed a WIP technique informed by human gait principles which is able to produce walking speeds that correspond better with those of real walking. A state machine based on the human gait cycle makes it possible to estimate the user's step frequency multiple times during each step, and walking velocities are estimated based on the relationship between height and step frequency known from research on human biomechanics. While the ability to reproduce correct walking speeds is notable, faithful reproduction of real walking speeds need not always be desirable. Indeed, it has been demonstrated that individuals tend to underestimate optic flow speeds during both WIP locomotion and treadmill walking and, therefore, find exaggerated speeds more natural [10]. Thus, it is necessary to establish what visual gains, or optic flow multipliers [6], to use in order to facilitate natural walking experiences during WIP locomotion. The current paper describes a study investigating whether the perceptual distortion of optic flow speeds is consistent across different step frequencies for treadmill walking and WIP locomotion.

2 Related Work

Several studies suggest that individuals experience a reduction in the perceived optic flow speed of expanding flow fields when walking on a treadmill. That is, the visually perceived speed appears too slow compared to the speed of the treadmill (see, e.g., [15]). However, few studies address how this perceptual distortion is experienced by individuals relying on WIP techniques for virtual locomotion. Nilsson et al. [10] describe two studies intended to establish the range of perceptually natural walking speeds for WIP locomotion. The first study compared four different types of movement, namely, no leg movement, walking on a treadmill, and two forms of gestural input for WIP locomotion. The results suggested that WIP locomotion is accompanied by a perceptual distortion similar to the one experienced during treadmill walking. The second study compared four different display fields of view and two movement types (treadmill walking and WIP). The results revealed significant main effects of both movement type and field of view. However, the post-hoc analysis did not reveal any significant differences in regards to movement type. Banton et al. [1] describe a series of studies investigating the perceptual distortion of optic flow speeds during treadmill walking through immersive virtual environments. The studies confirmed that geometrically correct optic flow is perceived as too slow; they revealed that the perceptual distortion is eliminated when the gaze is directed either downwards or to the side; and they suggested that the distortion is unaffected by step length and image jitter [1]. Powell et al. [12] sought to investigate whether normal gain perception is variant. Moreover, the study compared two visually different virtual hallways and compared two modes for presenting the gain changes. The results revealed no significant differences in the range of perceptually normal gains between the two environments or between the two presentation modes. However, they did suggest that there exists a tolerance in the range of perceptually normal gains (i.e., a range of different visual speeds may be perceived as acceptable). In a study by Kassler et al. [6] participants were asked to match the optic flow speed of projected visuals to the speed of a treadmill by turning a knob. The results indicate that the same gains were perceived as a match across six different treadmill speeds. While the magnitude of the identified visual gains varies across studies, the direction of the perceptual distortion is identical. That is, the visual flow is generally perceived as slower than it really is. Durgin [4] describes that the relationship between perceived and actual speeds comply with an equation originally proposed by Barlow [2]. The equation stipulates that the perceived speed of optic flow is equal to the actual speed of the optic flow minus some amount of the self-motion experienced via other sensory channels:

$$\begin{aligned} &perceived\,visual\,velocity = \\ &\qquad actual\,visual\,velocity\ - K\ \times\ felt\,velocity \end{aligned} \tag{1}$$

where K is a constant, and felt velocity corresponds to velocity perceived non-visually. Considering that the proprioceptive feedback can serve as non-visual motion information, it seems possible that the degree of subtraction may vary between treadmill walking and WIP locomotion. Thus, the same visual speeds need not be perceived as natural during treadmill and WIP locomotion. However, existing research does not provide unequivocal evidence in favor of this assumption [10].

3 User Study

The objective of the current study was twofold: 1) To compare what gains were perceived as natural during treadmill walking and WIP locomotion. 2) To investigate whether the same visual gains would be perceived as natural across different step frequencies.

3.1 Study Design

To meet these aims, a within-subjects study was performed. The study design crossed two movement types (the WIP gesture and real walking on a treadmill) with three step frequencies (1.4, 1.8 and 2.2 steps per second), resulting in a 2×3 factorial design. The slowest and fastest step frequencies lie just below the ones reported during slow and fast walking for men and women [11].

3.2 Participants

Nineteen participants (12 males, 7 females) aged between 15-48 years (M=28.7 years, SD=8.3) took part in the study. They were recruited via a mailing list comprising volunteers from Aalborg University Copenhagen and readers of the Danish periodical Ingeniøren (The Engineer) All participants reported having normal or corrected-to-normal vision and hearing and were offered a meal as compensation for participating

3.3 Procedure

The participants performed a total of 24 walks (four walks for each of the six conditions) and were exposed to visual gains ranging from 0.1 to 4.0. Thus, the slowest visual speed was a tenth of the participants' normal walking speed and the highest speed was four times greater. The normal walking speeds were estimated prior to the first walk by asking the participants to walk on the treadmill while keeping their steps synchronous with a metronome tapping at 1.4, 1.8 and 2.2 taps per second. The speed of the treadmill was then adjusted until the participants were able to walk in sync with the metronome at paces they found comfortable. In a vein similar to Kassler et al. [6], the participants were asked to perform a gain matching task informed by the method of adjustment. During each walk the participants were able to control the visual speed by manipulating the applied gain using a scroll wheel mounted on the right handlebar. The gain was changed in increments of 0.05 with 24 increments per revolution of the wheel. Instead of asking the participants to identify a single point at which the visual speed matched their movement, they were asked to verbally indicate when the visual speed reached the lower and upper limits of what felt natural. During two of the four walks per condition, the initial speed corresponded to a gain of 0.1 and during the other two it was 4.0. Thus, one half of the walks involved the participant increasing the virtual speed in order to identify the upper and lower limit of the perceptually natural speeds, and the other half required the participants to decrease the speed in order to do so. Both ascending and descending speeds were included in order to minimize errors caused by habituation and expectations as it is often done when using the method of adjustment and similar psychophysical methods [7]. The order of the four starting speeds was randomized for each condition. Moreover, the order of the conditions involving step frequencies of 1.4 and 2.2 was randomized. The third condition was performed as part of another study performed conjointly with the current one. The two studies relied on the same setup and were performed in randomized order.

3.4 Study Stimuli

The visual stimulus was comprised of an infinite corridor (Figure 1). Since the underestimation of visual speeds may be influenced by gaze direction [1], the participants were instructed to keep their gaze fixed on the end of the corridor at all times. The virtual heights of the users were based on their real

Fig. 1: The environment seen from the participants' perspective.

heights. The visuals were delivered by means of a nVisor SX60 HMD, with a resolution of 1280×1024 and a diagonal FOV of 60° in each eye. The metronome sound dictating the step frequencies was the only auditory feedback present. A 16 camera Optitrack motion capture system was used to track the position and orientation of a marker placed on the HMD, thus providing information about the user's head movement. The cameras were placed along the circumference of a circle with a diameter of 7m. Twelve of the cameras were placed at a height of approximately 2.9m and the remaining 4 were placed about 1.8m from the ground. The participants stood on the treadmill (ProForm 520 XLT) and held onto the handlebars during all conditions. A schematic drawing of the system can be seen on Figure 2.

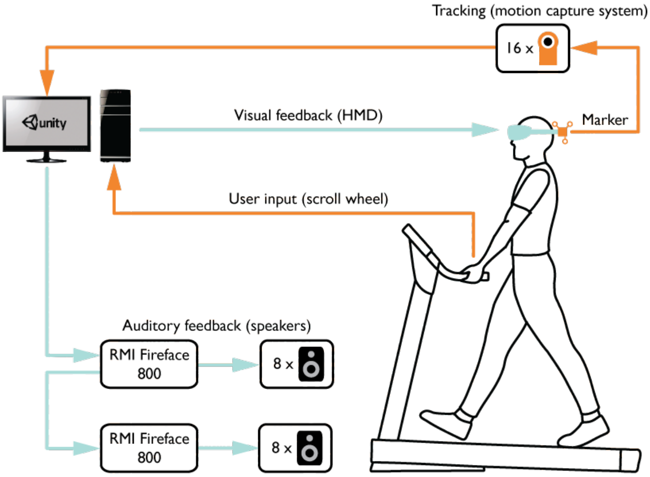

Fig. 2: Schematic drawing of setup used for the study.

4 Results

Since the objective of the study was to establish the range of perceptually natural visual gains, the maximum and minimum gains perceived as natural were identified. For each condition, the minimum and maximum were defined as the means of the four lower limits and upper limits, respectively.

The results are summarized in Figures 3 and 4. Repeated-measures analyzes of variance (ANOVAs) were used to compare the corresponding means. Significant measures were subjected to post-hoc analyzes by means of paired sample, two-tailed t-tests using Bonferroni-corrected alpha values ($\alpha = .005$). Shapiro-Wilk's tests suggested that the obtained data were normally distributed and Mauchly's tests indicated no violations of the assumption of sphericity.

In regards to the minima the ANOVA revealed significant main effects for both movement type ($F(1,18) = 16.789, p = .001$) and step frequency ($F(2,36) = 13.589, p < .001$), but no significant interaction between the variables was identified ($F(2,36) = 2.413, p = .104$). The post-hoc tests indicated that for treadmill walking the minimum pertaining to 2.2 steps per second was significantly higher than the minima corresponding to 1.8 ($p < .001$) and 1.4 ($p < .001$) steps per second. In relation to WIP, the minimum for 2.2 steps per second was significantly higher than the minimum for 1.4 steps per second ($p = 0.004$). Finally, a statistically significant difference was found between the conditions involving 2.2 steps per second across treadmill walking and WIP ($p < .001$). Similarly, in regards to the maxima significant

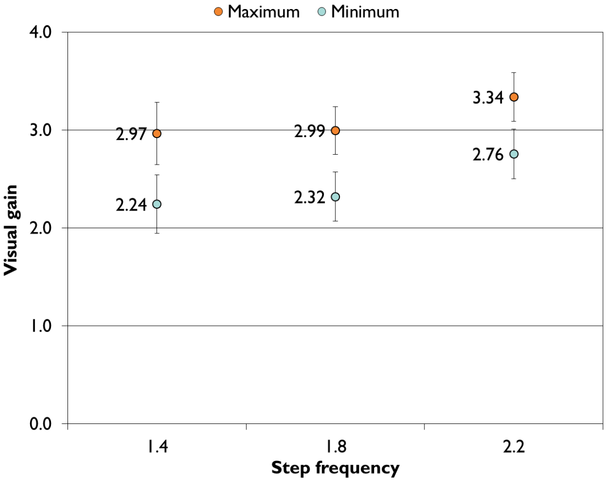

Fig. 3: Treadmill - results pertaining to the minimum and maximum gains perceived as natural. Error bars indicate 95% CIs.

main effects were found for movement type ($F(1,18) = 19.073, p < .001$) and step frequency ($F(2,36) = 6.443, p = .004$), but no significant interaction was uncovered ($F(2,36) = 1.355, p = .271$). For treadmill walking the post-hoc analysis revealed statistically significant differences between maximum for 2.2 steps per second and the maxima for 1.8 ($p < 0.001$) and 1.4 ($p = 0.004$) steps per second. No significant differences were found between the three step frequencies in relation to WIP. A significant difference was found between the conditions involving 2.2 steps per second across treadmill walking and WIP ($p < .001$)

5 Discussion

Significant main effects were found for both movement type and step frequency in relation to minima and maxima. With regards to the effects of movement type, the means suggest a pattern similar to the one described by Nilsson et al. [10]. That is, the upper and lower bounds of the range of perceptually natural gains were slightly higher for treadmill walking than WIP. However, the post-hoc analysis only revealed statistically significant differences in relation to 2.2 steps per second. It is possible that the employed method is to blame for the lack of significance. An increased number of walks per condition combined with alternative methods, such as the method of limits or the method of constant stimuli, might have reduced the variability in the data.

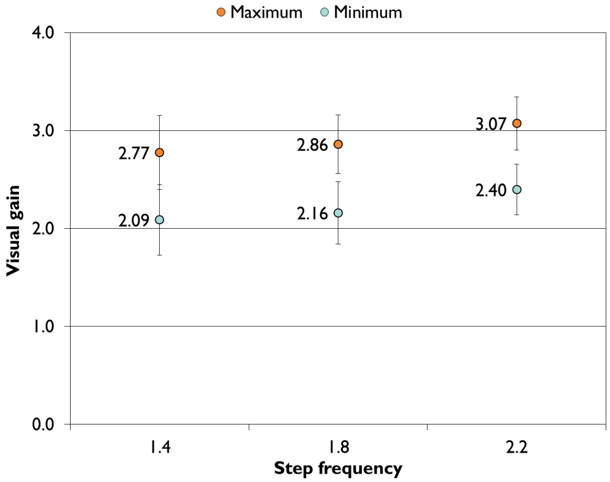

Fig. 4: WIP - results pertaining to the minimum and maximum gains perceived as natural. Error bars indicate 95% CIs.

Alternatively, it remains a possibility that the difference between treadmill walking and WIP only is present during high step frequencies. Future meta-analysis of the current and similar studies may shed more light on the extent to which movement type has an effect on gain perception.

As for the influence of step frequency, the means suggest that an increased step frequency may be accompanied by an increase in the underestimation of the visual speed. For treadmill walking statistically significant differences were found between the highest step frequency (2.2 steps per second) and the remaining two (1.4 and 1.8 steps per second) for both minima and maxima, while no difference was found between the two lowest step frequencies. As previously suggested, it is possible that the employed method is responsible for the lack of significance. Alternatively, it seems possible that the influence of step frequency is the most prominent when the frequency is high. In relation to WIP, a significant difference was only found between the minima of the highest step frequency and the lowest, while no difference were found in relation to the maxima. Thus, step frequency may have less of an influence on gain perception during WIP locomotion compared to treadmill walking. A possible explanation is that humans have an intuitive understanding of how variations in the step frequency and length influence the speed of self-motion. However, while walking in place the experience of these gait parameters may vary. Particularly, step length which roughly translates into step height. Notably, Bruno et al. [3] proposed that WIP algorithms may be improved by shifting focus from the temporal characteristics of the gait to the footstep amplitude (the step height).

Finally, it is worth highlighting that the results do not directly correspond with the ones reported by Kassler et al. [6] who found that the same gains were perceived as a match across six different treadmill speeds. The three step frequencies used in the current study entailed significantly different estimates of the participants' normal walking speeds ($(F(2, 36) = 265.85, p < .001)$), i.e., the step frequencies of 1.4, 1.8 and 2.2 steps per second led to mean speeds of 2.4 ± 0.3, 3.5 ± 0.4 and 4.6 ± 0.5 kmh, respectively. Possible, explanations for the different results include, the large variance in the per participant data reported by Kassler et al. [6], variations in the display type (HMD and screen-based), and the markedly different walking interfaces (a regular treadmill and an elaborate setup requiring the user to wear a harness).

6 Conclusion

This paper detailed a study investigating the influence of step frequency on the range of perceptually natural visual walking speeds during treadmill walking and WIP. The results revealed a statistically significant main effect of both step frequency and movement type. Future studies might further explore the influence of gait parameters on gain perception, e.g., by investigating whether the identified differences are equally pronounced across different step frequencies and by investigating the role of spatial gait characteristics (step length/height). Finally, since gender may influence spatial ability [8], future work might address whether the perceptual distortion is uniform for men and women.

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Paper G

The Perceived Naturalness of Virtual Walking Speeds During WIP Locomotion: Summary and Meta-Analyses

N. C. Nilsson, S. Serafin and R. Nordahl

The paper has been submitted to the journal
PsychNology

The layout has been revised.

Abstract

It is well-established that individuals tend to underestimate visually presented walking speeds when relying on treadmills for virtual walking. However, prior to the present studies this perceptual distortion had not been observed in relation to Walking-in-Place (WIP) locomotion, and a number of the factors contributing to the perceptual distortion have yet to be identified. In this paper we present a summary of seven of our studies investigating what factors that influence self-motion perception during virtual walks and two meta-analyses of the findings of the seven studies. The studies relate to how gait cycle characteristics, visual display properties, and methodological differences affect speed underestimation during treadmill and WIP locomotion. The studies suggested the following: A significant main effect was found for step frequency; both display and geometric field of view were inversely proportional to the degree of underestimation; varying degrees of peripheral occlusion and increased HMD weight did not yield significant main effects; and the choice of method (i.e., how the speeds were presented) had a significant effect on the upper and lower bounds of what speeds were perceived as natural. All seven studies compared treadmill and WIP locomotion and higher speeds were generally preferred during treadmill walking, but only some studies found a significant effect. Meta-analyses of the differences between the two movement types revealed a significant difference and provided pooled estimates of the magnitude of this difference.

1 Introduction

A major appeal of immersive virtual reality (IVR) is arguably that it enables users to experience a visceral sense of being in a place other than the one where they are physically located. However, a growing body of evidence suggests that perception of virtual environments is prone to distortions; i.e., perceived distances and speeds tend to be distorted and recent work suggests that participants may even misperceive time inside IVR [5]. In this paper, we present work pertaining to perceptual distortions of visually presented walking speeds. Particularly, the work deals with the factors influencing underestimations of speeds during virtual walks performed on a treadmill and using Walking-in-Place (WIP) techniques. When relying on WIP techniques the user performs stepping-like movements which serve as a proxy for actual steps. WIP techniques constitute an inexpensive and convenient approach to facilitating relatively natural locomotion through virtual environments when the physical interaction space is limited in size. However, no studies have explored whether walkers underestimate virtual speeds during WIP locomotion as they do when walking on a treadmill, and the factors contributing to the perceptual distortion have yet to be identified. This is important because presentation of perceptually natural walking speeds arguably is a prerequisite for facilitating natural walking experiences on behalf of users navigating virtual worlds using WIP techniques. Moreover, clarification of what factors that influence speed perception during virtual walking may provide valuable insights about human motion perception in general.

It is well-established that individuals walking on a treadmill tend to find the visually perceived speed too slow compared to the speed of the treadmill. Banton et al. [2] describe four studies investigating the underestimation of visual speeds during treadmill-mediated IVR. The studies led to the following findings: it was confirmed that geometrically correct optic flow is perceived as too slow; the perceptual distortion may be eliminated if walkers direct their gaze downwards or to the side; the distortion is not affected by step length; and image jitter does not appear to be responsible for the distortion [2]. Kassler et al. [17] asked participants to match the speed of projected visuals to the speed of a treadmill by turning a knob. Across six treadmill speeds the results indicated that the participants chose visual speeds that were twice as fast as the treadmill. Notably, the degree of underestimation varies across studies. This may be due to methodological differences (e.g., different visual displays), but it has also been suggested that there may exist a range of different speeds which are perceived as natural at a given treadmill speed [27]. In order to investigate this, Powell et al. [27] performed a study asking participants to differentiate between speeds that were 'too slow', 'normal', or 'too fast' while exposed to two visually distinct virtual hallways and two ways presenting the speeds. No significant differences in the range of perceptually normal gains were found across the two environments or between the two presentation modes. However, the results suggested that there exists a tolerance in the range of perceptually normal gains. It has been proposed that distortions of visual speeds during virtual walks, at least in part, can be explained by the way in which multi-sensory motion information is processed by the brain. To be exact, Durgin [11] has proposed that a subtractive model may account for why virtual speeds are perceived as slower by walkers than individuals standing still. Durgin [11] describe that the perceived speed of the visual flow may be equal to the actual speed of the visual flow minus some amount of the motion information originating within other modalities (e.g., proprioceptive information about limb movement). A reduction in the signal representing visual information may be advantageous because small variations in the speed will seem larger than when compared to the actual speed [11].

The current paper details a summary of seven of our studies pertaining to self-motion perception during treadmill and WIP locomotion, and two meta-analyses allowing us to draw conclusions that were not possible based on the studies themselves. The first two studies pertain to the influence of gait cycle properties: Study 1 (S1) compared different movement types for virtual locomotion [24], and Study 2 (S2) compared varying step frequencies [25].

The following four studies relate to the influence of visual display properties: Study 3 (S3) explored the influence of the display field of view (FOV) [24], Study 4 (S4) investigated the effects of geometric mini- and magnification [21], Study 5 (S5) compared different degrees of peripheral occlusion [21], and Study 6 (S6) investigated the effects of head-mounted display (HMD) weight [20]. The final study investigated the influence of study method; i.e., Study 7 (S7) compared the three different ways of presenting visual speeds to the participants used during S1 to S6 [21]. All studies compared treadmill and WIP locomotion, but the results are equivocal in regards to the significance and magnitude of the observed difference. Consequently, we present two meta-analyses that help shed light on whether the two movement types lead to different degrees of speed underestimation.

2 User Studies

The seven studies presented throughout the following do, to the best of our knowledge, represent the only existing investigations of how motion is perceived during WIP locomotion. While each study set out to investigate how different factors influence the perceived naturalness of virtual walking speeds during WIP locomotion, there are a number methodological commonalities.

2.1 Participant Recruitment

All participants were recruited via a mailing list comprising volunteers from Aalborg University Copenhagen and readers of the Danish periodical Ingeniøren (The Engineer). They reported having normal or corrected-to-normal vision and hearing, and they were offered either movie tickets (S1 and S3) or meals as compensation for participating (S2 and S4-S7).

2.2 Task and Environment

In all studies the participants were required to perform a number of walks through a virtual environment using a treadmill and WIP locomotion. During the walks the participants were exposed to a range of visual gains (scalar multiples of their normal walking speeds). With the exception of S1, the participants' normal walking speeds were estimated prior to the first trial by asking them to walk on the treadmill at a step frequency of 1.8 steps per second. The participants then adjusted the treadmill speed until they found a speed they found comfortable. This comfortable speed was used as an estimate of their normal walking speed at 1.8 steps per second, and it was used as the visual speed representing a gain of 1.0. The step frequency of 1.8 steps per second lies just below the one accompanying normal gait speed for both men and women [26], and it was therefore believed to ensure the safety

Fig. 1: From the left: The corridor used for S1 and S3, and the corridor used during S2 and S4-S7.

and comfort of the participants. Throughout all walks, the participants were observed in order to ensure that they did in fact walk at the requested step frequency.

During the studies the participants were asked to judge if they found the visually presented speeds to be natural or not. A speed would qualify as natural if the participants, based on their prior experiences of walking, felt that the movement they performed could result in said speed.

In all seven studies the participants were tasked with walking down a virtual corridor. The corridors used for the studies were visually similar but differed in length. The corridor used for S1 and S3 was 14m long whereas the corridor used for S2 and S4-S7 was infinitely long (Figure 1). The participants' real heights were used to determine the vertical position of the virtual viewpoint. Since gaze direction may influence motion perception [2], the participants were instructed to keep their gaze fixed on a painting on the back wall (S1 and S3) or the end of the corridor (S2 and S4-S7).

2.3 Study Stimuli and Setup

The setup was largely identical for all seven studies. The visuals were generated using Unity 3D (www.unity3d.com), and a nVisor SX60 HMD was used deliver the stimuli in all studies except S2. The HMD has a resolution of 1280×1024 and a diagonal FOV of 60° in each eye. The only auditory feedback was the sound of a metronome dictating at what step frequency the participants should walk. The participants head movement was tracked using a 16 camera Optitrack motion capture system (www.optitrack.com). In S2 and S4-S7 a scroll wheel mounted on the right handlebar allowed the participants to control the visual speed. During all conditions, the participants stood on a treadmill (ProForm 520 XLT) and held onto the handlebars during all walks.

2.4 Statistical Analyses

The results of S1, which relied on a single factor design, were analyzed by means of repeated-measures analyzes of variance (ANOVAs). The remaining studies relied on factorial designs, and the results were analyzed using two-way repeated-measures ANOVAs. All ANOVAs were performed using a significance level of $\alpha = .05$. Shapiro-Wilk's test and Mauchly's tests were used to test the assumptions of normality and sphericity, respectively. In case of all studies, significant measures were subjected to post-hoc analyzes using paired-sample, two-tailed t-tests with Bonferroni-corrected alpha values.

3 Gait Cycle Properties

The subtractive model described by Durgin [11] suggests that perception of walking speeds may be influenced by both external sensory information (e.g., visual motion cues) and internal sensory information, such as proprioceptive and kinesthetic information about limb positions and movements [33]. Thus, it seems possible that variations in the movements performed by the walker could influence the perceived naturalness of virtual walking speeds. S1 and S2 investigated the influence of movement type and step frequency, respectively.

3.1 Study 1 (S1): Movement Type

S1 investigated if visual walking speeds are underestimated during WIP locomotion, and if the underestimation is the same across different movement types for virtual locomotion. The study relied on a within-subjects design and compared four different types of user motion: Stationary (the user remained still with both feet on the ground), Tapping-in-Place (TIP) (the user alternately tapped each heel against the ground without breaking contact with the toes), Walking-in-Place (WIP) (the user alternately lifted each foot of the ground), and Treadmill (the user walked on a treadmill).

Method and Materials for S1

Twenty-two participants (18 males, 4 females) aged between 20-58 years (M= 28.9 years, SD=8.9) took part in the study. The participants performed 22 walks for each conditions (11 different gains, repeated twice). The gains ranged from 1.0 to 3.0, in increments of 0.2. Thus, the slowest speed was equal to the estimated normal speed, whereas the highest speed was three times greater.

The normal walking speed of the individual participant was derived based on an approach proposed by Wendt et al. [34] as part of their algorithm for

Gait-Understanding-Driven Walking-in-Place. This technique takes advantage of the fact that walking speed generally can be expressed as the product of step frequency and step length. Because, step length and height are correlated, the normal walking speed can be estimated based on the height of the walker if the step frequency is known. We established the height of the user during calibration, and all walks were performed at 1.8 steps per second. The metronome dictating the step frequency was also audible during the condition where the participants remained stationary.

In a vein similar to Powell et al. [27], the participants were asked to verbally report if they found the virtual speed of each walk 'too slow', 'natural', or 'too fast'. The participants made their verdict when they felt confident enough to do so or when the walk was over. Unlike Powell et al. [27], we chose to randomize the order of the gains in order to prevent the participants from basing their judgements on strategic thinking rather than perception (e.g. by considering the number of walks it took before the first occurrence of perceptually natural stimuli during previous sessions).

Results of S1

For each condition, the lowest and highest gains rated 'natural' were identified. The corresponding results are summarized shown in Figure 2. The ANOVA revealed a significant difference between the minimum gains ($F(3, 21)$ $= 3.75, p = .02$), but no significance was found maximum gains. The post-hoc analysis ($\alpha = .008$) revealed a significant difference between TIP and Treadmill ($p < .003$). Paired sample t-tests revealed significant differences between all minima and maxima for each movement type and one sample t-tests showed that all minima differed significantly from the normal gain (in all cases $p < .001$).

Discussion of S1

The results pertaining to TIP and WIP suggest that the speed underestimation known from treadmill-mediated virtual walking, also is present when participants are stepping in place. Moreover, the results support the finding that there exist a range of perceptually natural gains for treadmill walking Powell et al. [27] and suggest that this also is the case for WIP locomotion.

The results are less conclusive when it comes to the difference between the four movement types. Following the subtractive model described by Durgin [11] stationary participants ought to find lower speeds natural. The absence of kinesthetic and proprioceptive motion information should entail a lower degree of subtraction, and thus lead to the speeds being perceived as faster, compared to treadmill walking where the subtraction of internal sensory information is present. There is at least one possible explanation for the seeming contradiction between the theory and the current results. Since the step

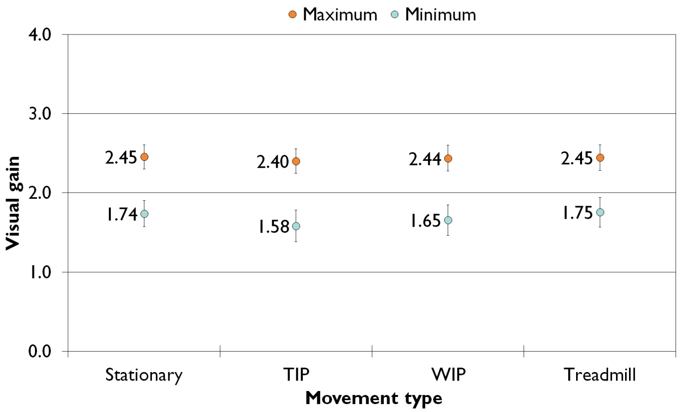

Fig. 2: Minimum and maximum visual gains perceived as natural for the four movement types. Error bars indicate 95% confidence intervals.

frequency was audible during the stationary condition, we cannot rule out that the metronome tapping served as nonvisual motion information and entailed some degree of subtraction. Moreover, methodological issues may have influenced the results reported for the treadmill condition. Prior to the treadmill condition, the speed of the treadmill was adjusted until the participants were able to walk comfortably in sync with the metronome. The ratio between step length and frequency is normally constant over a large range of walking speeds. However, this ratio tends to be lower when walking on a treadmill, i.e., shorter and more frequent steps [12]. This may have produced a mismatch between the treadmill speeds and estimate of the natural walking speed.

As for WIP, it is hard to predict whether the degree of subtraction would be higher or lower compared to treadmill walking. On the one hand, the WIP gesture is dissimilar from actual steps, which might lead us to suspect a lower degree of subtraction. On the other hand, studies indicate that walkers tend to find the WIP gesture more physically straining than real walking [22, 23]. If physical effort plays into the subtraction, then one would expect WIP to lead to a higher degree of subtraction and thus lower perceptually natural gains.

3.2 Study 2 (S2): Step Frequency

The objective of S2 was to determine if the range of perceptually natural gains varies across different step frequencies and across treadmill and WIP locomotion. A within-subjects study based on a 2×3 factorial design was performed. The study crossed two *movement types* (treadmill and WIP) with three *step frequencies* (1.4, 1.8 and 2.2 steps per second).

Method and Materials for S2

Nineteen participants (12 males, 7 females), aged between 15-48 years (M = 28.7 years, SD = 8.3), took part in S2. The participants performed 24 walks (4 walks for each of the 2×3 conditions) and were exposed to gains ranging from 0.1 to 4.0. Thus, the slowest speed was a tenth of the estimated normal walking speed while the highest was four times greater. Rather than varying the gains between walks as in S1, the participants were asked to perform a gain matching task informed by the method of adjustment in a manner similar to the approach used by Kassler et al. [17]. During each walk the participants were able to manipulate the applied gain using a scroll wheel mounted on the right handlebar. The gain was changed in increments of 0.05 with 24 increments per revolution of the wheel. Thus, a full revolution resulted in a gain change of 1.2. While adjusting the speeds, the participants were asked to verbally indicate when the visual speeds reached the lower and upper limits of what felt natural. During two of the four walks per condition, the initial speed was equal to the lowest possible gain (0.1) and during the remaining two it was the highest possible (4.0). Thus, half of the walks required the participants to increase the virtual speed when identifying the lower and upper limit of what speeds they found natural, and the other half required the participants to decrease the speed. A combination of ascending and descending speeds was used so as to minimize errors from habituation and expectations, as it is often done when using the method of adjustment and similar psychophysical methods [18]. The order of the four starting speeds per condition was randomized. The order of the conditions with step frequencies of 1.4 and 2.2 was randomized. The condition involving a step frequency 1.8 steps per second was performed as part of S6 which was performed conjointly with S2. The two studies were performed in randomized order. The normal walking speeds at the three step frequencies were established prior to the first trial as described in Section 2.2. Finally, it was randomly decided if the initial movement type at each step frequency would be treadmill walking or WIP.

Results of S2

For each condition, the lower and upper bounds of the range of perceptually natural gains (the minima and maxima) were defined as the means of the four lower limits and upper limits, respectively. The results are summarized in Figure 3. In relation to the minima significant main effects were found for both movement type ($F(1, 18) = 16.789, p = .001$) and step frequency ($F(2, 36) = 13.589, p < .001$), but no significant interaction was found ($F(2, 36) = 2.413, p = .104$). For treadmill walking the post-hoc tests ($\alpha = .005$) revealed significant differences between the step frequencies of 2.2 and 1.8 ($p < .001$) and between 2.2 and 1.4 ($p < .001$). For WIP significant differ-

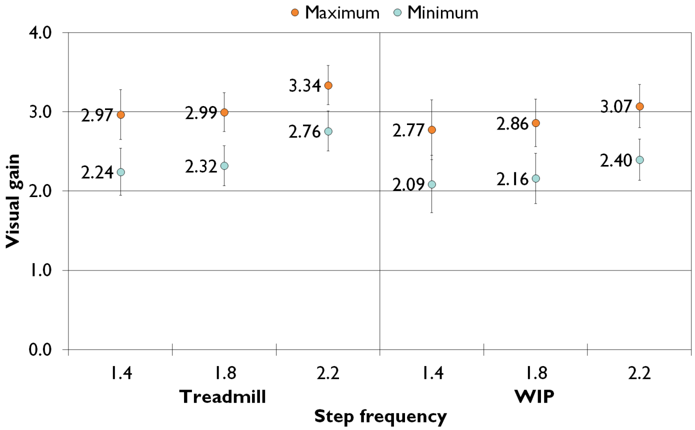

Fig. 3: Minimum and maximum visual gains perceived as natural for the three step frequencies across treadmill and WIP. Error bars indicate 95% confidence intervals.

ences were found between step frequencies of 2.2 and 1.4 ($p = 0.004$). Across treadmill walking and WIP, a significant difference was found between the conditions involving 2.2 steps per second ($p < .001$).

Similarly, in regards to the maxima significant main effects were found for movement type ($F(1,18) = 19.073, p < .001$) and step frequency ($F(2,36) = 6.443, p = .004$), but no significant interaction was found ($F(2,36) = 1.355, p = .271$). For treadmill walking the post-hoc analysis ($\alpha = .005$) yielded significant differences between the step frequencies of 2.2 and 1.8 ($p < 0.001$) and between 2.2 and 1.4 ($p = 0.004$) No significant differences were found for WIP. A significant difference was found between the conditions involving 2.2 steps per second across treadmill walking and WIP ($p < .001$).

Discussion of S2

With regards to the effects of movement type, the means suggest a notable pattern. Across the board, the means pertaining to treadmill were higher than the corresponding means for WIP. However, the post-hoc analysis only found a significant difference in relation to 2.2 steps per second. It is possible that the lack of significant can be attributed to the limited sample size or the employed method. An increased number of walks per condition combined with alternative psychophysical methods, such as the method of limits or the method of constant stimuli, might have reduced the variability in the data. However, it we cannot rule out the possibility that the difference between treadmill walking and WIP only is present during high step frequencies.

In relation to step frequency, the means suggest that higher step frequencies may entail a higher degree of underestimation of the visual speed. For treadmill walking significant differences were found between the highest step frequency (2.2 steps per second) and the remaining two (1.4 and 1.8 steps per second) in relation to both minima and maxima, but no difference was found between the two lowest step frequencies. Again, it is possible that the sample size and method are responsible for the lack of significance. Moreover, it is possible that the influence of step frequency is strongest when the frequency is high.

Notably, the three step frequencies used in the current study led to significantly different estimates of the participants' normal walking speeds ($F(2, 36) = 265.85, p < .001$). The step frequencies of 1.4, 1.8, and 2.2 steps per second led to mean speeds of 2.4 ± 0.3, 3.5 ± 0.4, and 4.6 ± 0.5 kmh, respectively. Thus, the current results do not directly correspond with the previous finding suggesting that the same gain may be applicable across six treadmill speeds [17]. Possible reasons for the varying results include, variations in the visual display type (HMD and screen-based), the markedly different walking interfaces (a regular treadmill and setup requiring the user to wear a harness), and the high variance in the per participant data in the study by Kassler et al. [17]. Moreover, a study performed by Banton et al. [2] suggests that the perception of visual speeds is not influenced by stride length. The authors compared two step lengths (normal steps and very short steps) across three treadmill speeds. No main effect of step length was found ($p = .073$), but for the shorter step length the degree of underestimation appears slightly reduced at 3mph and to a lesser extent at 2mph. Since decreasing the step length at a fixed treadmill speed should result in an increased step frequency, these insignificant differences appear to be in line with the current findings.

4 Visual Display Properties

The properties of IVR displays are likely to influence our perception of the virtual environment, including our perception of self-motion. S3 to S6 sought to investigate whether certain display properties affect the perceived naturalness of walking speeds during treadmill and WIP locomotion.

4.1 Study 3 (S3): Display Field of View

Considering that optic flow is central to motion perception, it seems natural that our sensation of speed will be influenced by the extent to which our visual field is occupied by virtual stimuli indicating motion. Particularly, the perceived naturalness of virtual speeds may be influenced by the size of the display field of view (DFOV); i.e., the vertical and horizontal angles subtended by the visual display [32]. Riecke [30] describes that a primary factor contributing to compelling self-motion illusions is the solid angle subtended by the visual motion stimuli. Even though it has been possible to elicit self-

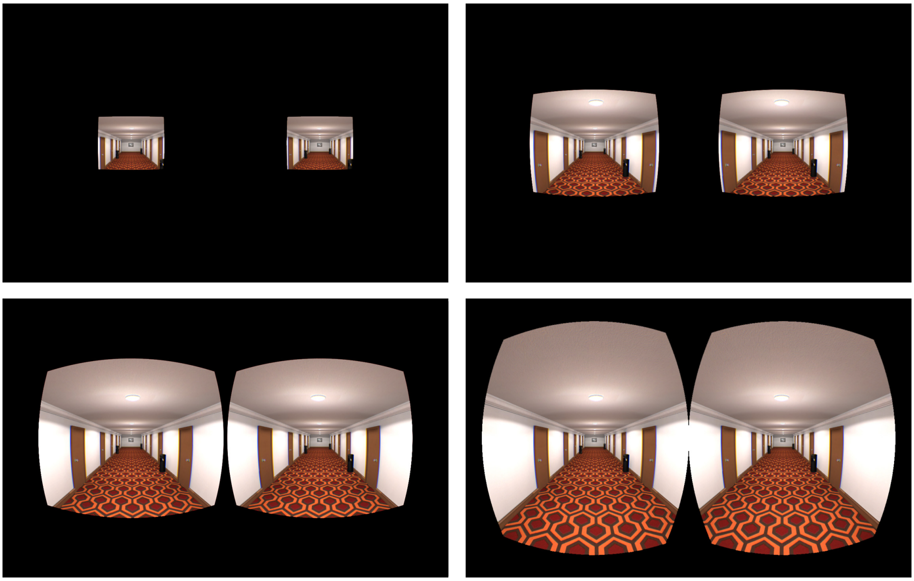

Fig. 4: The four viewing conditions used for S3: Vertical FOVs of 25° (top left), 50° (top right) and 75° (bottom left), and the unrestricted FOV of the Oculus Rift (bottom right). The distortion constitutes the correction applied for each eye in order to account for the optics of the Oculus DK1.

motion illusions with FOV as small as 7.5° [1], larger FOV generally lead to enhanced illusions, and full-field stimulation may elicit illusions that are so compelling that they become indistinguishable from the real thing [4, 9]. To investigate how different DFOV affect natural gain perception, we performed a within-subjects study crossing two *movement types* (treadmill and WIP) with four viewing conditions (four DFOV sizes).

Method and Materials for S3

Twenty-one participants (18 males, 3 females) aged between 18-44 years (M= 28.6 years, SD=6.0) took part in the study. The employed method resembled the one used in S1 (Section 3.1) with the primary difference being the way in which the gains were presented. The participants performed 22 walks (11 different visual gains, repeated twice) for each of the eight conditions (2 movement types × 4 viewing conditions). The normal velocity of each participant was established during a walk on the treadmill prior to the first trial as described in Section 2.2. The gain presentation mode was similar to one used by Powell et al. [27]. For each condition, a series of gains was presented, either beginning with the lowest (1.0) or the highest possible gain (3.0). After each walk, the gain would change in increments of 0.2. If the series started with the lowest gain, the gains would gradually increase until the highest gain was reached and then decrease until returning to the lowest gain again. The opposite logic applied if the initial gain was 3.0. It was randomly decided whether the first gain would be 1.0 or 3.0 for each series. As in S1, the participants were asked to report whether they found the visual speed 'too slow', 'natural', or 'too fast'. In order to reduce the risk that the participants relied on strategy rather than perception when making their judgements, we gave them the impression that both the speed of the initial walk and the change in speed between walks might vary. Unlike the remaining studies, S3 used the first Oculus Rift Developer Kit (henceforth Oculus DK1). This HMD has a resolution of 640×800 (aspect ratio (AR) = 0.8) in each eye and a vertical DFOV of 90°. The four different viewing conditions comprised the unconstrained view of the Oculus DK1 and three constrained views with vertical DFOV of 25°, 50° and 75° (AR = 1.25). The constrained viewing conditions were produced by placing virtual blinders just beyond the near clipping plane of the viewing frustum. Figure 4 illustrates the four viewing conditions. An AR of 1.25 was chosen for the constrained conditions because it is comparable to the one used in HMDs such as the nVisor SX60 and ProView SR80. The orientation of the participants' heads was tracked using the 3DOF sensor embedded within the Oculus DK1. Since this sensor is prone to drift over time, the orientation was reset between each walk.

Results of S3

For each condition the lower bound of the natural speeds (the minimum) was defined as the average value of the two lowest gains rated 'natural' (one during the series with ascending gains and one during the series with descending gains). The upper bound (the maximum) was similarly established based on the average of the two highest gains rated 'natural'. The corresponding results are summarized in Figure 5. Mauchly's test indicated that the assumption of sphericity had been violated for viewing condition in relation to minimum gain ($\chi^2(5) = 20.13, p < .05$). Thus, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\epsilon = .61$).

In regards to the minima Significant main effects were found for DFOV ($F(1.82, 36.41) = 34.21, p < .001$) and movement type ($F(1, 20) = 8.26, p = .009$), but no significant interaction was found. Similarly, in relation to the maxima significant main effects were found for DFOV ($F(3, 60) = 62.62, p < .001$) and movement type ($F(1, 20) = 15.63, p < .001$), while no significant interaction was between the two variables was found. Despite the significant main effect of movement type, the post-hoc analysis did not reveal any significant differences in relation to the minimum and maximum gains. However, for DFOV the post-hoc analyzes ($\alpha = .003$) revealed the following signifi-

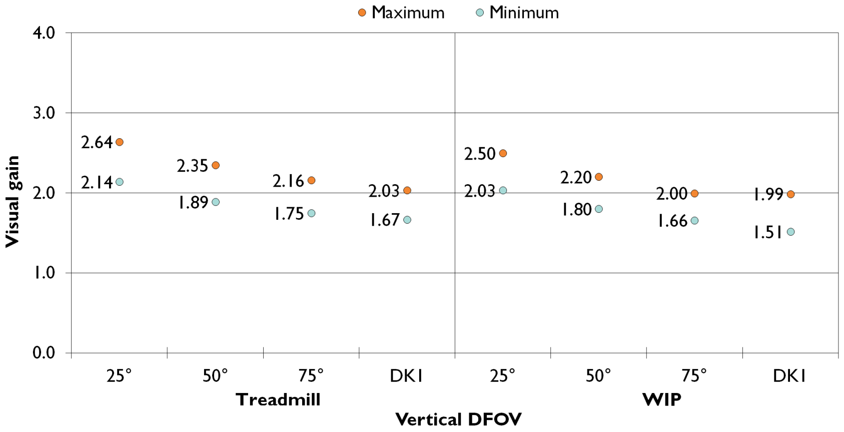

Fig. 5: Minimum and maximum visual gains perceived as natural for the four display FOV across treadmill and WIP. Error bars indicate 95% confidence intervals.

cant differences for both minima and maxima: For Treadmill, Oculus DK1 differed significantly from 50° ($p < .001$) and 25° differed significantly from all three viewing conditions. For WIP, Oculus DK1 also differed significantly from 50°, 75° differed significantly from 50°, and 25° differed significantly from the remaining viewing conditions.

Discussion of S3

Significant main effects of movement type were found for both minima and maxima. Despite the lack of significant post-hoc tests, it is worth noting that the upper and lower bounds of the range of perceptually natural gains are slightly higher for treadmill walking than WIP as in S1 and S2. Significant main effects of viewing condition were found in relation to both minimum and maximum, and the post-hoc analysis suggested that most of the means differed significantly from one another. Judging from the means it would appear that the size of the DFOV is inversely proportional to the degree of underestimation of the virtual speeds for both treadmill and WIP locomotion. However, the differences between the unconstrained view of the Oculus DK1 and the vertical DFOV of 75° were not significant. One interpretation is that the degree to which an increase in DFOV affects speed underestimation diminishes as the FOV becomes larger. Notably, Pretto et al. [28] found that seated participants underestimate optic flow speeds, produced using white dots on a dark background, when a circular FOV was smaller than 60° in diameter while no effect was found for larger FOV. That being said, the Oculus DK1 also differed from the remaining conditions in terms of the aspect ratio. Therefore, the varying aspect ratios could have been of influence.

Fig. 6: The three vertical GFOV used in S4. From the left: 24° (magnification), 34° (undistorted) and 44° (minification). To make the distortion easily apparent two virtual objects are highlighted in blue and orange.

4.2 Study 4 (S4): Geometric Field of View

The geometric field of view (GFOV) describes the virtual counterpart to the DFOV; i.e., the GFOV determines the vertical and horizontal bounds of the virtual viewing volume along with the aspect ratio [32]. In order to ensure an undistorted view of the virtual environment, the GFOV should match the DFOV. If the GFOV is larger than the DFOV, more geometry is forced into the projected image, and this will result in *minification*. If the GFOV is smaller than the DFOV, the opposite happens. The resulting distortion is referred to as *magnification* [32]. Even though a match between the GFOV and DFOV is necessary for an undistorted perspective, it has been demonstrated that users wearing a HMD do not always find this undistorted projection to be the most natural. Steinicke et al. [32] present a study suggesting that some amount of minification may be perceived as more natural than the undistorted view. The size of the DFOV appears to influence what amount of minification will be perceived as natural. Moreover, changes to the GFOV have been shown to influence motion perception during driving simulations [19], and it has been demonstrated that undistorted views tend to cause drivers to underestimate virtual speed [10]. Thus, it seems reasonable to assume that changes to the GFOV will influence the degree of underestimation experienced during virtual walking. A within-subjects study was performed in order to explore to what extent this is the case. The study was based on a 2×3 factorial design crossing two *movement types* (treadmill and WIP) with three different *vertical GFOV* (24°, 34° and 44°).

Method and Materials for S4

Twenty participants (15 males, 5 females) aged between 15-42 years (M=27.5 years, SD=7.0) took part in S4. This study relied on the same method as S2 (Section 3.2). The three different degrees of perspective distortion were achieved by manipulating the GFOV. The aspect ratio of the GFOV was kept consistent with the one of the nVisor SX60 (AR = 1.25), but three different ver-

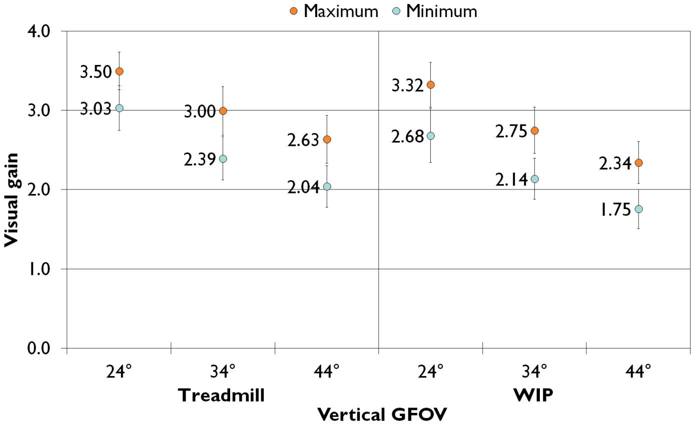

Fig. 7: Minimum and maximum visual gains perceived as natural for the three vertical GFOV across treadmill and WIP. Error bars indicate 95% confidence intervals.

tical GFOV was used: 24° (magnification), 34° (undistorted) and 44° (minification). Figure 6 illustrates the three perspective projections. It was randomly decided if the participants initially were exposed to the three degrees of distortion while walking on the treadmill or while walking in place, and the participants were presented to the three degrees of distortion in randomized order.

Results of S4

The minima and maxima were identified as in S2 (Section 3.2). Figure 7 summarize corresponding results. Shapiro-Wilk's tests indicated that normality had been violated for the maxima. Nonetheless, two-way repeated-measures ANOVAs were used for analysis of all data since a Friedman's test revealed comparable results in regards to maxima ($\chi^2(5) = 75.382, p < .001$). Mauchly's tests indicated that sphericity could not be assumed in relation to the minima for geometric FOV ($\chi^2(2) = 6.6701, p < .035$). Thus, degrees of freedom were corrected using Greenhouse-Geisser estimates ($\epsilon = .76$) A violation was also found for maxima in regards to the interaction between movement type and GFOV ($\chi^2(2) = 9.600, p < .008$) and the degrees of freedom were corrected ($\epsilon = .71$).

No significant interaction was found between the two variables in regards to minima ($F(2, 38) = .814, p = .451$) or maxima ($F(1.415, 26.886) = 1.079, p = .35$). A significant main effect of GFOV was found for both minima ($F(1.526, 28.989) = 220.252, p < .001$) and maxima ($F(2, 38) = 178.356, p < .001$). A significant main effect was found for movement type for minima ($F(1, 19) = 6.207, p = .022$), but not for maxima ($F(1, 19) = 4.180, p = .055$).

The post-hoc analysis of the minima ($\alpha = .005$) revealed significant differences between all three GFOV for both treadmill walking and WIP; i.e., 24° was significantly higher than 34° and 44°, and 34° was significantly higher than 44° (all $p < .001$). The post-hoc tests did not reveal significant differences between the GFOV across the two movement types. Since no significant main effect of movement type was found in regards to maxima, the post-hoc test only compared the three GFOV for either treadmill walking or WIP ($\alpha = .008$). Significant differences were found between all GFOV; i.e., 24° was significantly higher than 34° and 44°, and 34° was significantly higher than 44° (all $p < .001$).

Discussion of S4

The identified differences between the three GFOV sizes suggest that GFOV size may be inversely proportional to the degree of speed underestimation in case of both movement types; i.e., speeds closer to the normal walking speed were perceived as more natural for larger GFOV. This finding is consistent with the work pertaining to driving simulations [10]. Also, the results appear to be consistent with the finding that some amount of minification is perceived as more natural than an undistorted view of the virtual world [32]. However, the means (Figure 7) suggest that a very large GFOV would be required in order to achieve veridical performance; i.e., it would require an unnaturally high degree of minification in order for the participants to judge gains of 1.0 to be natural. Finally, a significant main effect of movement type was found for the minima. Despite insignificant post-hoc tests a pattern similar to the preceding studies was apparent; i.e., all means pertaining to treadmill walking were higher than the corresponding means related to WIP.

4.3 Study 5 (S5): Peripheral occlusion

It has been demonstrated that the addition of a static white light in the far periphery of a HMD may positively influence performance on distance judgment and visual scale tasks [16]. Consequently, it seems conceivable that external peripheral stimulation may affect motion perception during virtual walks. S5 investigated the effects of peripheral occlusion on the perceived naturalness of virtual walking speeds. The study relied on a within-subjects, 2×3 factorial design and crossed two *movement types* (treadmill and WIP) with three degrees of peripheral occlusion (no occlusion, the standard nVisor SX60 blinders and complete deprivation from peripheral visual information).

Method and Materials for S5

The 20 people who participated in S4 also took part in S5. The participants were exposed to the two studies in randomized order. This study relied on

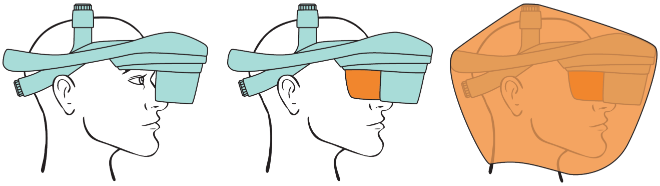

Fig. 8: From the left: The nVisor SX60 without blinders, with blinders and with the shroud preventing peripheral stimulation.

the same method as S2 and S4 (Section 3.2). The three degrees of peripheral occlusion were achieved by removing the standard blinders from the nVisor SX60, leaving the HMD untouched, and by including the blinders while covering the participants head in a thick cloth shroud (Figure 8).

Results of S5

The minima and maxima were identified as in S2 and S4 (Section 3.2). Figure 9 summarize corresponding results. No significant interactions were found between movement type and peripheral occlusion for minima ($F(2, 38) = 1.274, p = .291$) or maxima ($F(2, 38) = .860, p = .431$). Also, no significant main effect was found for peripheral stimulation in regards to minima ($F(2, 38) = .221, p = .803$) or maxima ($F(2, 38) = 1.097, p = .344$). The main effects of movement type were nearly significant for minima ($F(1, 19) = 4.118, p = .057$) and maxima ($F(1, 19) = 4.313, p = .052$).

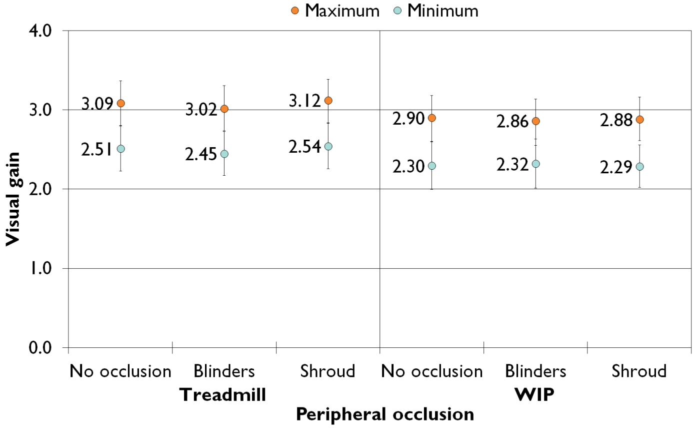

Fig. 9: Minimum and maximum visual gains perceived as natural for the three degrees of peripheral occlusion across treadmill and WIP. Error bars indicate 95% confidence intervals.

Discussion of S5

The means (Figure 9) combined the absence of significant main effects does not support the assumption that that peripheral occlusion might influence what speeds the participants experienced as natural. With that being said, it cannot be ruled out that the effect simply was so subtle that the current study failed to identify it.

While no significant main effect was found, the results pertaining to movement type, showed the same pattern as the previous studies; i.e., the means pertaining to treadmill walking were generally higher that then ones pertaining to WIP locomotion.

4.4 Study 6 (S6): HMD weight

Willemsen et al. [35] performed a study suggesting that the mass and moments of inertia of HMDs may contribute distance underestimations within IVR, even though these display properties cannot fully account for the perceptual distortion. Moreover, work by Proffitt et al. [29] demonstrated that perception of space may be influenced by locomotor effort. Thus, it was regarded as interesting to explore if whether variations in HMD weight influence perception of self-motion. We performed a within-subjects study based on a 2×2 factorial design crossing two *movement types* (treadmill and WIP) with two *HMD weights* (the nVisor SX60 and an altered version which was twice as heavy).

Method and Materials for S6

The same nineteen participants who took part in S2 (Section 3.2) also participated in S6. The participants were exposed to the two studies in randomized order. This study relied on the same method as S2, S4 and S5 (Section 3.2). The HMD weight was manipulated using two versions of the nVisor SX60; i.e., the original display (1050g) and a version with added weights (2050g). Figure 10 illustrates the two versions of the HMD.

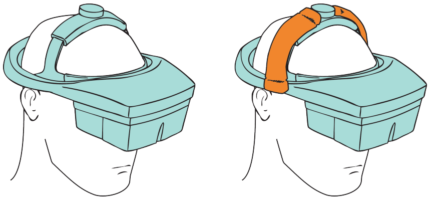

Fig. 10: The unaltered nVisor SX60 and the version with two 500g sandbags (highlighted with orange) mounted on the display.

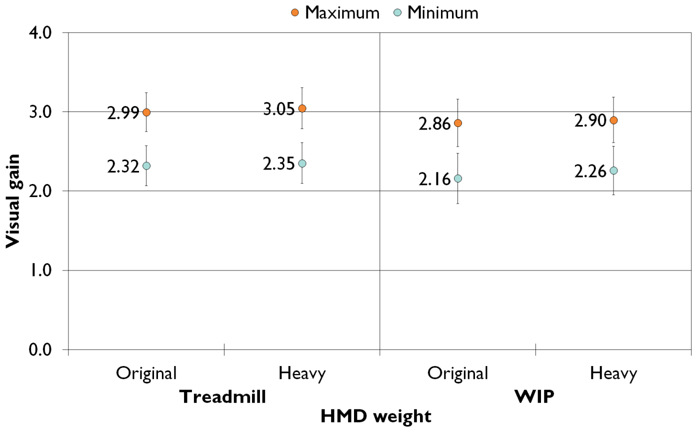

Fig. 11: Minimum and maximum visual gains perceived as natural for the two HMD weights across treadmill and WIP. Error bars indicate 95% confidence intervals.

Results of S6

The minima and maxima were identified as in S2, S4 and S5 (Section 3.2). The corresponding results are presented in Figure 11. In relation to minima, a significant main effect of movement type was found ($F(1,18) = 4.658, p = .045$). No significant main effects were found for HMD weight ($F(1,18) = 1.091, p = .310$) or the interaction between the two variables ($F(1,18) = .515, p = .482$). The minima pertaining to treadmill walking were generally higher than the minima for WIP. However, despite the significant main effect of movement type, the post-hoc analysis ($\alpha = .025$) revealed no significant differences. Similar results were found for maxima. A significant main effect of movement type was found ($F(1,18) = 8.812, p = .008$), but the main effect of HMD weight was not significant ($F(1,18) = .893, p = .357$) and no interaction was found ($F(1,18) = .028, p = .868$). The post-hoc tests ($\alpha = .025$) suggested that treadmill walking was significantly higher than WIP for the means pertaining to the heavy HMD ($p = .019$).

Discussion of S6

The results revealed no difference in the amount of underestimation of virtual speeds across the two HMD weights. However, the study only compared a relatively heavy display with an even heavier version of the same display. Thus, they do not reveal whether there is a difference in case of lighter displays. Even though the post-hoc analyses related to movement type only found a significant difference between the two conditions involving the heavy display, the minima and maxima pertaining to treadmill walking were generally higher than the ones pertaining to WIP locomotion as in S1 to S5.

5 Gain Presentation Method

The purpose of the seventh study was to compare three different approaches to identifying the range of perceptually natural walking speeds during virtual locomotion.

5.1 Study 7 (S7): Gain Presentation Method

While Powell et al. [27] found no significant differences when comparing two different approaches to presenting visual gains, it cannot be ruled out that the choice of method might be of influence. S7 relied on a within-subjects, 2×3 factorial design crossing two *movement types* (treadmill and WIP) with three *gain presentation modes* (GPMs) (different ways of presenting the visual speeds).

Method and Materials for S7

Twenty participants (16 males, 4 females) aged between 19-43 years (M=28.2 years, SD=7.0) took part in the study. The three GPMs compared in S7 are largely identical to the ones employed in S1 to S6 and bear semblance with existing psychophysical methods [13]):

Randomized Order: The participants were exposed to 15 gains, repeated twice, yielding a total of 30 walks. The gains ranged from 1.0 to 4.0 in increments of 0.2 and were presented in randomized order. The participants verbally reported whether they found the visual speed 'too slow', 'natural', or 'too fast'. This approach resembles the one used in S1.

Reversed Staircases: This GPM is similar to the previous one. However, the gains organized into an ascending and a descending series; i.e., if the series started with 1.0, the gains would gradually increase, and if it started with 4.0, then it would gradually decrease. Ascending series were terminated the first time a 'natural' report was followed by 'too fast', and descending series were terminated when a 'natural' rating was followed by 'too slow'. It was randomly decided whether the first series would be ascending and a descending. This approach resembles the one used in S3.

User Adjustment: The third GPM is similar to the method used in S2 and S4 to S6; i.e., the participants were adjusting the gain, which could range from 1.0 to 4.0, while walking. As in the other GPMs the participants performed one walk with ascending gains and one descending gains.

Results of S7

The minima and maxima were defined as follows: For Randomized Order the minimum and maximum were defined as the mean of the two lowest gains and highest gains, respectively. For Reversed Staircases the minimum

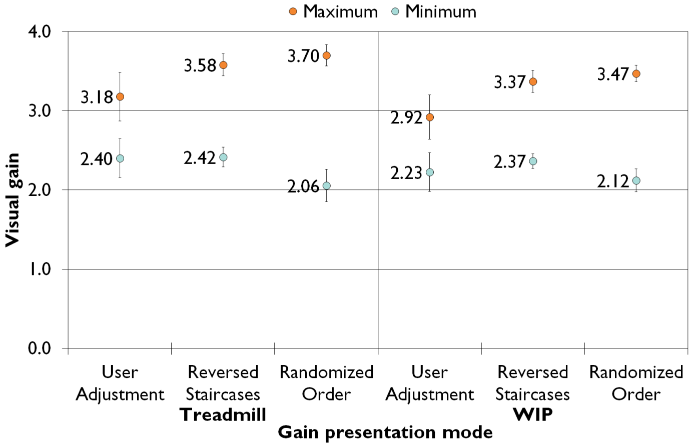

Fig. 12: Minimum and maximum visual gains perceived as natural for the three gain presentation modes across treadmill and WIP. Error bars indicate 95% confidence intervals.

was defined as the mean of the two lowest gain rated 'natural' (one for ascending and the descending series). The maxima was similarly was based on the two highest gains rated 'natural'. For User Adjustment the minimum and maximum were defined as the means of two lower and upper limits, respectively. The corresponding results are summarized in Figure 12. Mauchly's tests indicated that the assumption of sphericity had been violated for GPM in relation to the maxima ($\chi^2(2) = 14.68, p < .01$), and degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\epsilon = .64$). No significant interactions between GPM and movement type were found. In relation to the minima, a significant main effect was found for GPM ($F(2,38) = 8.807, p = .001$), while none was found for movement type. For treadmill walking the post-hoc analyzes ($\alpha = .008$) suggested that the minimum of Randomized Order was significantly lower than the ones corresponding to User Adjustment ($p = .001$) and Reverse Staircases ($p < .001$). For WIP the minimum of Randomized Order was significantly lower than Reversed Staircases ($p < .001$). In regards to the maxima, significant main effects were found for GPM ($F(1.284, 24.395) = 4.968, p < .001$) and movement type ($F(1,19) = 33.288, p < .001$). The post-hoc analyzes ($\alpha = .005$) suggested that the maximum resulting from User Adjustment was significantly lower than the other two maxima in regards to both treadmill walking and WIP (all $p < .001$). The maxima pertaining to Randomized Order differed significantly across the two motion types ($p < .001$).

Discussion of S7

The results suggest that for both treadmill walking and WIP, Randomized Order caused the participants to find higher and lower gains natural compared to the two other GPMs. Notably the same appear to be the case when comparing the results of S1 and S3, which relied on methods resembling Randomized Order and Reversed Staircase, respectively. Despite this similarity, it is notable that S7 generally led to higher minima and maxima compared to S1 and S3. It seems possible that differences in the range of presented gains are responsible for the varying results. S1 and S3 relied on gains ranging from 1.0 to 3.0 while S7 relied on gains from 1.0 to 4.0. Thus, habituation and increased exposure time may account for the difference. Notably, the results of S7 do not differ considerably from those of S2, S4, S5 and S6 which involved gains from 0.1 to 4.0. Thus, habituation appears to be less of an issue during User Adjustment. A possible explanation is that the participants could skip across the unnatural lower gains more rapidly, and varying exposure times may therefore be the confounding variable. Nevertheless, S7 points to an interesting difference between the three GPMs. User Adjustment yielded smaller ranges of perceptually natural gains and may, therefore, produce more conservative estimates than the other two. The caveat is that the 95% confidence intervals pertaining to User Adjustment are considerably larger than the ones resulting from the other measures. Hence, even though User Adjustment appears more conservative, this may come at the expense of confidence. The limitations of this approach are not unknown within psychophysical research where forced-choice methods are commonly used [14]. Notably, forced-choice methods have also been used to study perception within IVR [31].

The results pertaining to the effects of movement type were not all significant but showed the same pattern as the remaining studies; i.e., with exception of one, all means pertaining to treadmill walking were higher than the corresponding means of WIP.

6 Meta-Analyses

All of the presented studies investigated the extent to which walkers underestimate virtual speeds during treadmill and WIP locomotion. Interestingly, the same tendency was present across all studies, namely, when walking on a treadmill the participants tend to find higher speeds natural compared to when they were walking in place. However, the results are equivocal in regards to the statistical significance of this effect. Four in seven studies found a significant effect of movement type for minima or maxima. Even if a greater majority of the studies had yielded significant main effects, the frequency of significant tests does not provide us with the whole picture. Meta-analyses enable us to combine the findings of several studies through quantitative analysis and thereby achieve greater precision with respect to the observed effect. Traditionally, meta-analysis have been performed as part of large-scale literature reviews, but the value of applying meta-analysis on a smaller scale has been recognized [8]. Two meta-analyses of the difference between treadmill and WIP locomotion were performed: one for the lower threshold of perceptually natural gains and one for the upper threshold. S1 to S7 do, to the best of our knowledge, represent the only comparisons of gain perception across treadmill walking and WIP locomotion. Thus, no additional studies were included in the meta-analyses.

The results of these meta-analyses are presented as forest plots illustrating the individual effect sizes as confidence intervals (CIs), and the meta-analytic combination, the summary effect size, as another CI [8]. The following subsections describe how the effect size of each study was determined, how composite effect sizes were calculated in order to ensure independence and better weighting of the studies, and finally the results of the meta-analyses are presented.

6.1 Effect size

The effect size of interest was obviously the extent to which the perceived naturalness of visual gains differs across treadmill walking and WIP locomotion. Since we cannot be certain that this difference is identical for the lower and upper thresholds of normal gain perception, the effect sizes for the two are treated separately. Specifically, as a measure of effect size we relied on the mean difference (M_{diff}) between the lower and upper thresholds for treadmill walking (T) and Walking-in-Place (WIP); i.e., the mean of the differences between the n pairs of thresholds for each condition:

$$M_{diff} = \frac{1}{n} \sum_{i=1}^{n} T_i - WIP_i \tag{1}$$

The corresponding CIs were based on the variance (V_{diff}) of these paired differences. Because S1 relied on a single factor design this study yielded one effect size, namely, the M_{diff} between the Treadmill and WIP conditions. The remaining studies were based on factorial designs since they also involved manipulation of a second variable. Thus, the remaining studies yielded as many effect sizes as there were levels in the second variable being manipulated. To exemplify, S3 relied on a 2×4 factorial design crossing the two movement types (Treadmill and WIP) with four different display FOV. Each of the four display FOV enabled a comparison between Treadmill and WIP. Thus, this study yielded four effect sizes. The same logic applies to the remaining factorial designs crossing the two movement type with other factors.

An overview of the conditions in the seven studies can be seen in the rightmost column of Table 1.

Table 1: Grouping of effect sizes based on studies and conditions.

Group ID	Study no.	Study designs	Conditions
Group I	S1	Single factor design	4 movement types*
Group II	S3	2×4 factorial design	2 movement types × 4 display FOV
Group III	S7	2×3 factorial design	2 movement types × 3 gain presentation methods
Group IV	S2	2×3 factorial design	2 movement types × 3 step frequencies**
	S6	2×2 factorial design	2 movement types × 2 HMD weights
Group V	S4	2×3 factorial design	2 movement types × 3 geometric FOV
	S5	2×3 factorial design	2 movement types × 3 degrees of peripheral occlusion

* This study compared four different movement types, but the meta-analyses only included the difference between treadmill walking and WIP.

** The study relied on a 2×3 factorial design. However, in practice the participants were only exposed to two conditions since the condition with the unaltered HMD from S6 represented one of the three step frequencies.

6.2 Composite effect sizes

Each of the seven studies did, as suggested, yield more than one effect size. However, Borenstein et al. [3] describe that we cannot treat these effect sizes as separate studies in the meta-analyses for two reasons: 1) It would lead us to assign greater weight to studies with more outcomes than studies with fewer outcomes. 2) Considering the effect sizes as the outcome of separate studies would lead us to erroneously treating them as independent, despite several effect sizes resulting from the reports made by the same participants. Since all seven studies were based on within-subject designs, it was necessary to collapse the effect sizes resulting from each study into composite effect sizes. Moreover, in two cases participants took part in two studies entailing that independence could not be assumed. Thus, in those two instances it was necessary to collapse the effect sizes across studies. Table 1 provides an overview of how the effect sizes were collapsed across studies and conditions into five groups. Each group supplied one composite effect size for the meta-analyses. The composite effect sizes ($\bar{Y}$) and variances ($V_{\bar{Y}}$) were determined based on an approach described by Borenstein et al. [3]. That is, the composite effect sizes for the groups were given as the mean effect size of the studies in that group:

$$\bar{Y} = \frac{1}{m} \sum_{j=1}^{m} Y_j \tag{2}$$

where m is the number of effect sizes per group. According to Borenstein et al. [3], the corresponding composite variance ($V_{\bar{Y}}$) of the effects sizes $j = 1$, ... m can be defined as:

$$V_{\bar{Y}} = \left(\frac{1}{m}\right)^2 \left(\sum_{j=1}^{m} V_j + \sum_{j \neq k} (r_{jk} \sqrt{V_j} \sqrt{V_k})\right) \tag{3}$$

where r_{jk} is the correlation coefficient describing the amount of correlation between the j^{th} and k^{th} variances (V_j and V_k).

6.3 Results of Meta-Analyses

The meta-analyses were performed by means of the ESCI software which runs under MS Excel [7] and relied on the random effects model, which assumes two sources of variability; i.e., variability caused by sampling error and variability caused by differences at a study level [36]. Heterogeneity, the extent to which sampling variability cannot reasonably account for the variability of the studied effect sizes [8], was evaluated based on I^2. In line with recommendations presented by Burcharth et al. [6], we regarded I^2 values of 25% 50% and 75% as indicative of 'low', 'moderate', and 'high' heterogeneity [15], and only considered the results usable if $I^2 < 75\%$.

Figure 13 illustrates the data and forest plots making up the meta-analyses of the extent to which the lower and upper bounds of natural gain perception differ between treadmill walking and WIP locomotion.

Since the effect size was defined as $T - WIP$ positive differences suggest that the participants found higher speeds to be natural during treadmill walking compared to WIP. In case of both composite effects (blue squares) and the summary effect sizes (orange diamonds) statistical significance at 95% CI is visible from the figure; i.e., if the CI overlaps with the vertical line at zero.

The meta-analysis pertaining to the lower threshold of natural gain perception found that the minima was higher during treadmill walking compared to WIP with a summary effect size of 0.128 (95% CI[0.069, 0.186], $p < 0.001$, $I^2 = 50.4\%$). The meta-analysis of the upper threshold similarly suggested that that the maxima was higher for treadmill walking with a summary effect size of 0.159 (95% CI[0.094, 0.224], $p < 0.001$, $I^2 = 63.3\%$).

6.4 Discussion of Meta-Analyses

Both of the performed meta-analyses suggested that there indeed is a difference in the upper or lower limits of perceptually natural gains of the two movement types. Particularly, the meta-analyses were able to confirm the

MINIMA:	$\bar{Y}$	95% CI	Weight (%)	n
Group I	0.100	[-0.005, 0.205]	18.8	22
Group II	0.108	[0.039, 0.118]	27.0	21
Group III	0.053	[-0.037, 0.143]	22.1	20
Group IV	0.192	[0.097, 0.288]	20.9	19
Group V	0.248	[0.099, 0.407]	11.1	20
Summary	**0.128**	**[0.069, 0.186]**		

Test for heterogeneity: $X^2 = 8.06$, df = 4 (p = .09), $I^2 = 50.4\%$

Test for overall effect: $Z = 6.03$ (p < .001)

MAXIMA:	$\bar{Y}$	95% CI	Weight (%)	n
Group I	0.009	[-0.129, 0.147]	14.3	22
Group II	0.125	[0.059, 0.191]	25.8	21
Group III	0.232	[0.152, 0.313]	23.2	20
Group IV	0.184	[0.109, 0.259]	24.4	19
Group V	0.216	[0.060, 0.371]	12.5	20
Summary	**0.159**	**[0.094, 0.224]**		

Test for heterogeneity: $X^2 = 10.91$, df = 4 (p = .03), $I^2 = 63.3\%$

Test for overall effect: $Z = 4.79$ (p < .001)

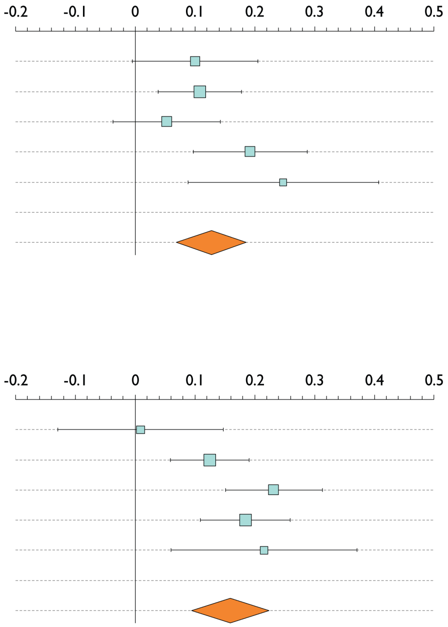

Fig. 13: Meta-analyses (data and forest plots) for the minima(top) and maxima (bottom). The composite effect sizes ($\bar{Y}$) of the groups are represented with blue squares and the error bars signify the corresponding 95% CIs. The sizes of the squares are scaled based on the weight assigned to the individual groups of *n* participants. The pooled estimates and 95% CIs are determined via the random-effects model and are visualized by the orange diamonds. The figure shows significant overall effects.

suspicion about the direction of the effect raised by S1 to S7: the participants perceived higher speeds to be natural when walking on the treadmill compared to when they were walking in place. Moreover, the meta-analyses provided estimates of magnitudes of the observed difference. That is, the CIs of the summary effects suggested that we with reasonable confidence can assume that the difference between the gains that are perceived as natural was between 0.069 and 0.186 for the minimum, and the difference was between 0.094 and 0.224 for the maximum. Here it is worth considering the magnitude of the effect size relative to the identified ranges between the upper and lower bounds of perceptually natural gains of the studies. The mean range between minima and maxima across all studies is 0.67 (SD=0.31) for treadmill walking and 0.65 (SD=0.23) for WIP and the only ranges larger than 1.0 were found in S7 for the conditions Reverse Staircases and Randomized Order. Thus, it would seem that the effect of movement type is relatively large compared the range of gains perceived as natural by the participants. However, compared to the actual thresholds the effect appear rather small. The lowest identified gain across the seven studies (1.51) was found for the unconstrained view of the Oculus DK1 during WIP locomotion in S3, and the highest gain (3.70) was found for treadmill walking in the condition Randomized Order of S7.

From a perceptual standpoint the results of the meta-analyses are of interest since they suggest that the type of gesture being performed may influence how we perceive visual motion in IVR. Assuming that subtraction of non-visual motion information contributes to speed underestimation [11], this may suggest that WIP leads to a larger degree of subtraction than treadmill walking. Possibly, due to the higher exertion accompanying WIP locomotion Nilsson et al. [22]. From the perspective of developers this result is interesting because it suggests that the perceptually natural gains identified based on treadmill walking need not be directly applicable in relation to WIP locomotion and vice versa.

7 Conclusions

This paper detailed seven studies and two meta-analyses pertaining to the underestimation of virtual walking speeds during treadmill and WIP locomotion.

S1 and S2 investigated how the perceptual distortion of visual speeds is influenced by gait cycle properties; i.e., different movement types and step frequency. S1 found no significant difference between the compared movement types, but S2 found a significant main effect of step frequency. An increase in step frequency appear to result in increased speed underestimations, but a significant difference was only found between the highest step frequency and the two lowest ones in case of both treadmill and WIP locomotion.

S3 to 6 investigated the effects of four different visual display properties: DFOV, GFOV, peripheral occlusion and HMD weight. For both treadmill and WIP locomotion, the results suggest that the size of both the DFOV and GFOV are inversely proportional to the degree of underestimation of the virtual speeds for. No significant main effects of peripheral occlusion and HMD weight were identified.

S7 compared three different ways of presenting visual speeds to the participants. When the participants were allowed to adjust the virtual speeds, they found a lower range of gains to be natural compared to when the speeds were varied between walks either randomly or in ascending and descending series. While user adjusted speeds may provide a more conservative estimate of the range, this appear come at the expense of confidence due to the increased variability in the data introduced by this method.

All seven studies compared treadmill and WIP locomotion. Across the studies a pattern was visible; i.e., the participants seemed to find higher speeds natural during treadmill walking compared to WIP. However, the results were equivocal in regards to the significance of this effect. Through meta-analyses of the difference between the upper and lower bounds of the perceptual natural speeds for treadmill and WIP locomotion, we were able to demonstrate that there indeed is a difference between the two movement types and present pooled estimates of the magnitude of this difference.

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SUMMARY

Recent technological advances may soon bring immersive virtual reality (IVR) out of the laboratory and into the homes of consumers. This means that IVR systems will be deployed in settings where the physical interaction space is very limited in size. If users wish to navigate virtual environments on foot, these spatial constraints are problematic since they make real walking infeasible. Walking-in-Place (WIP) techniques constitute a convenient and inexpensive approach to facilitating walking within virtual environments.

This thesis focuses on the factors influencing the degree of perceived naturalness of WIP locomotion; i.e., the degree to which the user's experience of walking through a virtual environment using WIP locomotion is mistakable for the experience of real walking. I take the degree of correspondence between the sensorimotor loops of real walking and WIP locomotion as my point of departure, and explore how to facilitate perceptually natural actions (steps in place) and natural self-motion perception (virtual walking speeds). The primary contributions of the presented work are the findings of ten studies and two meta-analyses documented in the seven papers.

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