creative commons

COMMONS DEED

저작자표시-비영리-변경금지 2.0 대한민국

이용자는 아래의 조건을 따르는 경우에 한하여 자유롭게

- 이 저작물을 복제, 배포, 전송, 전시, 공연 및 방송할 수 있습니다.

다음과 같은 조건을 따라야 합니다:

저작자표시. 귀하는 원저작자를 표시하여야 합니다.

비영리. 귀하는 이 저작물을 영리 목적으로 이용할 수 없습니다.

변경금지. 귀하는 이 저작물을 개작, 변형 또는 가공할 수 없습니다.

- 귀하는, 이 저작물의 재이용이나 배포의 경우, 이 저작물에 적용된 이용허락조건을 명확하게 나타내어야 합니다.
- 저작권자로부터 별도의 허가를 받으면 이러한 조건들은 적용되지 않습니다.

저작권법에 따른 이용자의 권리는 위의 내용에 의하여 영향을 받지 않습니다.

이것은 이용허락규약(Legal Code)을 이해하기 쉽게 요약한 것입니다.

Disclaimer

dCollection

이학박사 학위논문

Exploring the Effects of Body Position in Virtual Environments:

The Relationship with Spatial Cognition, Locomotion Method, Presence, and Cybersickness

가상현실에서 몸의 자세와 공간인지,
공간이동방법, 존재감, 사이버멀미의
상호작용에 대한 연구

2021 년 2월

서울대학교 대학원

인지과학 협동과정 전공

김 애 리

Exploring the Effects of Body Position in Virtual Environments:

The Relationship with Spatial Cognition, Locomotion Method, Presence, and Cybersickness

지도교수 이경민

이 논문을 이학박사 학위논문으로 제출함

2020 년 10 월

서울대학교 대학원

인지과학 협동과정 인지과학

김 애 리

김애리의 이학박사 학위논문을 인준함

2021년 1월

위 원 장 _____ 김 청 택 _____ (인)

부위원장 _____ 이 경 민 _____ (인)

위 원 _____ 윤 명 환 _____ (인)

위 원 _____ 이 준 환 _____ (인)

위 원 _____ 박 승 억 _____ (인)

Abstract

Exploring the Effects of Body Position in Virtual Environments:

The Relationship with Spatial Cognition, Locomotion Method, Presence, and Cybersickness

Aelee Kim
Interdisciplinary Program in Cognitive Science
The Graduate School
Seoul National University

Immersive virtual environments (VEs) can disrupt the everyday connection between where our senses tell us we are and where we are actually located. In computer-mediated communication, the user often comes to feel that their body has become irrelevant and that it is only the presence of their mind that matters. However, virtual worlds offer users an opportunity to become aware of and explore both the role of the physical body in communication, and the implications of disembodied interactions.

Previous research has suggested that cognitive functions such as execution, attention, memory, and perception differ when body position changes. However, the influence of body position on these cognitive functions is still not fully understood. In particular, little is known about how physical self-positioning may affect the cognitive process of perceptual responses in a VE.

Some researchers have identified presence as a guide to what constitutes an effective virtual reality (VR) system and as the defining feature of VR. Presence is a state of consciousness related to the sense of being within a VE; in particular, it is a 'psychological state in which the virtuality of the experience is unnoticed'. Higher levels of presence are considered to be an indicator of a more successful media experience, thus the psychological experience of 'being there' is an important construct to consider when investigating the association between mediated experiences on cognition.

VR is known to induce cybersickness, which limits its application and highlights the need for scientific strategies to optimize virtual experiences. Cybersickness refers to the sickness associated with the use of VR systems, which has a range of symptoms including nausea, disorientation, headaches, sweating and eye strain. This is a complicated problem because the experience of cybersickness varies greatly between individuals, the technology being used, the design of the environment, and the task being performed. Thus, avoiding cybersickness represents a major challenge for VR development.

Spatial cognition is an invariable precursor to action because it allows the formation of the necessary mental representations that code the positions of and relationships among objects. Thus, a number of bodily actions are represented mentally within a depicted VR space, including those functionally related to navigation, the manipulation of objects, and/or interaction with other agents. Of these actions, navigation is one of the most important and frequently used interaction tasks in VR environments. Therefore, identifying an efficient locomotion technique that does not alter presence nor cause motion sickness has become the focus of numerous studies.

Though the details of the results have varied, past research has revealed that viewpoint can affect the sense of presence and the sense of embodiment. VR experience differs depending on the viewpoint of a user because this vantage point affects the actions of the user and their engagement with objects. Therefore, it is necessary to investigate the association between body position, spatial cognition, locomotion method, presence, and cybersickness based on viewpoint, which may clarify the understanding of cognitive processes in VE navigation.

To date, numerous detailed studies have been conducted to explore the mechanisms underlying presence and cybersickness in VR. However, few have investigated the cognitive effects of body position on presence and cybersickness. With this in mind, two separate experiments were conducted in the present study on viewpoint within VR (i.e., third-person and first-person perspectives) to further the understanding of the effects of body position in relation to spatial cognition, locomotion method, presence, and cybersickness in VEs.

In Chapter 3 (Experiment 1: third-person perspective), three body positions (standing, sitting, and half-sitting) were compared in two types of VR game with a different degree of freedom in navigation (DFN; finite and infinite) to explore the association between body position and the sense of presence in VEs. The results of the analysis revealed that standing has the most significant effect on presence for the three body positions that were investigated. In addition, the outcomes of this study indicated that the cognitive effect of body position on presence is associated with the DFN in a VE. Specifically, cognitive activity related to attention orchestrates the cognitive processes associated with body position, presence, and spatial cognition, consequently leading to an integrated sense of presence in VR. It can thus be speculated that the cognitive effects of body position on presence are correlated with the DFN in a VE.

In Chapter 4 (Experiment 2: first-person perspective), two body positions (standing and sitting) and four types of locomotion method (steering + embodied control [EC], steering + instrumental control [IC], teleportation + EC, and teleportation + IC) were compared to examine the relationship between body position, locomotion method, presence, and cybersickness when navigating a VE. The results of Experiment 2 suggested that the DFN for translation and rotation is related to successful navigation and affects the sense of presence when navigating a VE. In addition, steering locomotion (continuous motion) increases self-motion when navigating a VE, which results in stronger cybersickness than teleportation (non-continuous motion). Overall, it can be postulated that presence and cybersickness are associated with the method of locomotion when navigating a VE.

In this dissertation, the overall results of Experiment 1 suggest that the cognitive influence of presence is body-dependent in the sense that mental and brain processes rely on or are affected by the physical body. On the other hand, the outcomes of Experiment 2 illustrate the significant effects of locomotion method on the sense of presence and cybersickness during VE navigation. Taken together, the results of this study provide new insights into the cognitive effects of body position on spatial cognition (i.e., navigation) in VR and highlight the important implications of locomotion method on presence and cybersickness in VE navigation.

Keywords: Body Position, Spatial Cognition, Locomotion Method, Presence, Cybersickness, Virtual Reality

Preface

This dissertation was submitted to the Interdisciplinary Program in Cognitive Science at Seoul National University in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

A paper based on the results of Experiment 1 was published in the International Journal of Human-Computer Interaction in June 2020 under the title ‘Exploring the Relative Effects of Body Position and Spatial Cognition on Presence when Playing Virtual Reality Games’.

Table of Contents

Abstract

Preface

Chapter 1. Introduction

1.1. An Introductory Overview of the Conducted Research 1

1.1.1. Presence and Body Position 1

1.1.2. Navigation, Cybersickness, and Locomotion Method 3

1.2. Research Objectives 6

1.3. Research Experimental Approach 7

Chapter 2. Theoretical Background

2.1. Presence 9

2.1.1. Presence and Virtual Reality 9

2.1.2. Presence and Spatiality 10

2.1.3. Presence and Action..... 12

2.1.4. Presence and Attention 14

2.2. Body Position 16

2.2.1. Body Position and Cognitive Effects 16

2.2.2. Body Position and Postural Control 18

2.2.3. Body Position and Postural Stability 19

2.3. Spatial Cognition: Degree of Freedom in Navigation 20

2.3.1. Degree of Freedom in Navigation and Decision-Making 20

2.4. Cybersickness 22

2.4.1. Cybersickness and Virtual Reality 22

2.4.2. Sensory Conflict Theory 22

2.4.3. Postural Instability Theory 23
2.5. Self-Motion 25
2.5.1. Vection and Virtual Reality 25
2.5.2. Self-Motion and Navigation in a VE 27
2.6. Navigation in Virtual Environments 29
2.6.1. Translation and Rotation in Navigation 29
2.6.2. Spatial Orientation and Embodiment 32
2.6.3. Locomotion Methods 37
2.6.4. Steering and Teleportation 38

Chapter 3. Experiment 1: Third-Person Perspective

3.1. Quantification of the Degree of Freedom in Navigation 40
3.2. Experiment
3.2.1. Experimental Design and Participants 41
3.2.2. Stimulus Materials 42
3.2.2.1. First- and Third-person Perspectives in Gameplay 43
3.2.3. Experimental Setup and Process 44
3.2.4. Measurements 45
3.3. Results 45
3.3.1. Presence: two-way ANOVA 45
3.3.2. Presence: one-way ANOVA 46
3.3.2.1. Finite Navigation Freedom 46
3.3.2.2. Infinite Navigation Freedom 47
3.3.3. Summary of the Results 48
3.4. Discussion 49
3.4.1. Presence and Body Position 49
3.4.2. Degree of Freedom in Navigation and Decision-Making 50
3.4.3. Gender Difference and Gameplay 51
3.5. Limitations 52

Chapter 4. Experiment 2: First-Person Perspective

4.1. Experiment

4.1.1. Experimental Design and Participants 53

4.1.2. Stimulus Materials 54

4.1.3. Experimental Setup and Process 55

4.1.4. Measurements 56

4.2. Results 57

4.2.1. Presence: two-way ANOVA 58

4.2.2. Cybersickness: two-way ANOVA 58

4.2.3. Presence: one-way ANOVA 60

4.2.3.1. Standing Position 60

4.2.3.2. Sitting Position 60

4.2.4. Cybersickness: one-way ANOVA 62

4.2.4.1. Standing Position 62

4.2.4.2. Sitting Position 62

4.2.5. Summary of the Results 63

4.3. Discussion 65

4.3.1. Presence

4.3.1.1. Presence and Locomotion Method 66

4.3.1.2. Presence and Body Position 68

4.3.2. Cybersickness

4.3.2.1. Cybersickness and Locomotion Method 69

4.3.2.2. Cybersickness and Body Position 70

4.4. Limitations 71

Chapter 5. Conclusion

5.1. Summary of Findings 72

5.2. Future Research Direction 73

References 75

Appendix A **107**
Appendix B **110**

국문초록 **111**

Chapter 1

1. Introduction

1.1. An introductory overview of the conducted research

Virtual reality (VR) offers a challenge to the everyday relationship between mind and body (Slater and Usoh 1994). It is through the body and sensory perception that we come to understand reality (Slater and Usoh 1994). Immersive virtual environments (VEs) can disrupt the everyday connection between where our senses tell us we are and where we are actually located. (Sanchez-Vives and Slater 2005). In computer-mediated communication, the user often comes to feel as if their body has become irrelevant and it is only the presence of their mind matters (Schultze, 2010). However, virtual worlds offer users an opportunity to become aware of and explore the role of the physical body in communication, as well as the implications of disembodied interactions (Dreyfus 2009; Ihde 2002; Schultze 2010).

1.1.1. Presence and Body Position

The essence of VR is that the user is transported bodily into a computer-generated environment (Slater and Usoh 1994). Therefore, an important aspect of the cognitive and perceptual responses to VR technologies is the user's sensation of being present inside the simulation (Lombard and Ditton 1997). Presence is a state of consciousness, the (psychological) sense of being in the VE (Slater and Wilbur 1997). Presence is defined as the subjective experience of being in one place or environment even when one is physically situated somewhere else (Witmer and Singer 1998). Presence is synonymous with the conscious feeling of one's body existing in and being distinct from a prefigured, external world, which can be both real and virtual (Schultze 2010; Waterworth and Waterworth 2003, 2006). Moreover, presence depends on the suitable integration of aspects relevant to the user's movement and perception, to their actions, and to their conception of the overall situation (Carassa et al. 2004). The bodily and cognitive activity of the user – their interaction with the

virtual world on various levels – is the true source of presence (Schubert et al. 1999; Steuer 1992).

In daily life, the experience of presence is strictly related to space (Riva et al. 2014; Spagnolli and Gamberini 2005). Evidence from clinical and experimental studies indicates that the spatial experience of an individual involves the integration of different sensory inputs within two different reference frames defined by their body model and related to its possibility of action (Longo et al. 2010; Previc 1998; Riva et al. 2014). The body is central to linking representations of space and of action, using perceptual information to plan movements and to predict their consequences (Bridgeman and Hoover 2008). Individuals conceive places in terms of the actions they could take in relation to them; they do not have a separate knowledge of the place's location relative to them and what they can do in it (Riva et al. 2014). Spatial cognition is an invariable precursor to action as it enables the formation of the necessary mental representations that code the positions and relationships among objects (Spence and Feng 2010). The actions that are represented mentally are bodily actions within the depicted space and are functionally related to navigation, the manipulation of objects, or the interaction with other agents (Schubert et al. 2001).

Human body knowledge is widely distributed in the adult brain (Dijkerman and Haan 2007). The brain holds several mental representations of the physical body (Serino and Haggard 2010), including descriptions of the parts of the body, their arrangement as a structural whole, and the positions of these parts in space at any given moment (Serino and Haggard 2010). In humans, postural control provides a stable body platform for the efficient execution of focal or goal-directed movements (Horak and Macpherson 1996). However, posture is no longer considered simply the summation of static reflexes but, rather, the complex interaction of sensorimotor processes and internal representations (Horak and Macpherson 1996). In addition, adopting a particular posture may activate mental states associated with that posture, such as the heightened alertness, attentional selectivity, and cognitive control (Smith et al. 2019). The postural control process appears to be distributed throughout the central nervous system (CNS) in a task- and context-dependent manner (Horak and Macpherson 1996). Therefore, many parts of the nervous system participate in the control of posture (Horak and Macpherson 1996), and many cognitive resources are required in postural control (Horak 2006; Teasdale and Simoneau 2001).

The relative effects of body position and cognition have been investigated for different types of cognitive task. The conclusions drawn from the analysis of these tasks indicate that body position can influence various cognitive processes, including executive function (Mehta et al. 2015), memory (Kerr et al. 1985; Mehta et al. 2015), attention (Barra et al. 2015; Caldwell et al. 2003; Rosenbaum et al. 2017), and cognitive performance (Isip 2014; Patston et al. 2017; Schulman and Shontz 1971). These findings suggest that at least some cognitive processes are embodied (i.e., body-dependent) in the sense that mental/brain processes rely on or are affected by the physical body (Wilson and Foglia 2011; Zhou et al. 2017).

Previous research on various cognitive functions has suggested that attention is closely associated with the cognitive processes underlying body position, presence, and decision-making. Attention can be defined as the information-processing capacity of an individual (Woollacott and Shumway-Cook 2002) and can be applied much more broadly than just to visual perception (Tsotsos et al. 2018). Postural control is known to recruit attentional resources (Barra et al. 2015; Kerr et al. 1985), and the interaction between posture and cognition is related to the allocation of attention (Barra et al. 2015; Dault et al. 2001; Redfern et al. 2004; Siu et al. 2009; Yardley et al., 2001). In addition, according to many VR researchers, attention is essential to the generation of a stronger sense of presence in VR (Schultze 2010; Weibel and Wissmath 2011; Wirth et al. 2007; Witmer and Singer 1998). Attention is also beneficial for decision-making because relevant features of the environment can be preferentially processed to enhance the quality of evidence (Nunez et al. 2017). During decision-making, the better a person can perceive the objects or events within their attentional focus, the more effectively various challenges and difficulties can be managed (Hüttermann et al. 2018).

1.1.2. Navigation, Cybersickness, and Locomotion Method

Navigation is one of the most important and frequently used interaction tasks in VR (Bowman et al. 2004; Langbehn et al. 2018). Thus far, various locomotion methods have been developed that aim to offer natural, usable, and efficient ways of navigating VEs (Al Zayer et al. 2020). However, the multimodal feedback provided by different locomotion techniques may lead to different levels of motion sickness,

presence, and usability, which in turn may affect task performance, effectiveness, and efficiency (Langbehn et al. 2018). Therefore, identifying an efficient locomotion technique that does not alter presence nor cause motion sickness represents a major challenge that has become the focus of numerous studies (Bowman et al. 2004; Kitson et al. 2017a; Cherni et al. 2020).

Many users experience symptoms of physical discomfort within a virtual environment (VE) (LaViola 2000; McCauley and Sharkey 1992), which is known as cybersickness (Stanney et al. 1997; Weech et al. 2020). Cybersickness is specifically associated with the use of VR systems (So 1999) and is characterized by symptoms such as nausea, disorientation, headaches, sweating, and eye strain (LaViola 2000; Davis et al. 2014). To date, many researchers have conducted studies on cybersickness (Farmani and Teather 2018), focusing on better understanding the mechanisms that cause it (Bonato et al. 2008; Davis et al. 2014; Hu et al. 1999; LaViola 2000), and proposing potential solutions (Dorado and Figueroa 2014; Fernandes and Feiner 2016). However, the issue is complicated because the experience of cybersickness varies greatly between individuals, the technology employed, the design of the environment, and the tasks performed (Johnson 2005; Davis et al. 2014). For this reason, a variety of locomotion methods have been tested to determine which are the most optimal (Bond and Nyblom 2019) for effectively navigating a VE without inducing cybersickness.

When moving in the real world, sensory cues gathered from multiple channels (e.g., proprioception, vision, vestibular, etc.) are used to continuously update the estimated state of the world and of the body (Calvert et al. 2004; Weech et al. 2019). However, in VR, people may not perceive certain sensory cues, such as proprioception and vestibular, because real walking is not possible due to the limitations of virtual interactions (e.g., space, hardware, tracking, etc.) (Warren 2018). It has been argued that the lack of proprioceptive and vestibular feedback during locomotion makes navigation in VEs more difficult (Chance et al. 1998; Ruddle and Lessels 2006; Riecke et al. 2010; Christou and Aristidou 2017). In a VE, the visual system detects cues that are consistent with self-motion, while the vestibular system indicates that the body is stationary with respect to gravity and position (Hettinger and Riccio 1992; Keshavarz et al. 2015; Farmani and Teather 2018). This causes conflict between visual, vestibular, and proprioceptive sensory

data, and can lead to undesirable side-effects, such as spatial disorientation and motion sickness (Keshavarz et al. 2014a; Lawson 2014; Hashemian and Riecke 2017).

Self-generated movements are crucial for exploring and interacting with a VE (Steinicke et al. 2013; Clifton and Palmisano 2019a). Previous studies have reported clear benefits from the use of body-based sensory information in VR locomotion (Klatzky et al. 1998; Kearns et al. 2002; Sun et al. 2004; Telford et al. 1995; Ruddle 2013; Nguyen-Vo et al 2019). In particular, several studies have shown that allowing physical rotation is beneficial for navigation and maintaining orientation (Ruddle and Lessels 2009; Riecke et al. 2010; Pausch et al. 1997; Moghadam et al. 2018). In addition, some studies have revealed that the integration of body motion cues increases presence (Bowman et al. 2004; Riecke and Feuereissen 2012) and the ability to orient oneself, while simultaneously reducing the effects of the simulator sickness (Bos et al. 2008; Zielasko et al. 2016).

1.2. Research Objectives

The primary goals of this dissertation are to provide new insights into the cognitive effects of body position on spatial cognition (i.e., navigation) in VR and to further the understanding of the implications of the choice of locomotion method on presence and cybersickness in VE navigation.

The specific objectives of this dissertation are as follows:

- To explore how physical self-positioning may affect the cognitive process of perceptual responses in a VE.
- To broaden the knowledge of the mechanisms underlying presence and cybersickness in VR.
- To investigate the cognitive linkage between body position and the degree of freedom in navigation (DFN) in a VE.
- To further the understanding of the association between body position, locomotion method, presence, and cybersickness during VE navigation.
- To identify the effects of translation (steering and teleportation) and rotation (embodied and instrumental) on presence and cybersickness when navigating a VE.
- To add to the understanding of the cognitive influence of navigation using third- and first-person perspectives in a VE.

1.3. Research Experimental Approach

In this dissertation, two separate experiments were conducted based on viewpoint within VR (i.e., third-person and first-person perspectives) to further the understanding of the association between body position, spatial cognition, locomotion method, presence, and cybersickness in a VE. In these experiments, body position and the DFN were the key experimental components, thus the following information is provided to clarify the experimental approach employed in this dissertation.

In VR, users are able to choose a number of play modes, such as standing, sitting, or walking (i.e., room-scale mode), which can lead to different levels of bodily involvement and spatial cognition (Kim et al. 2020). In general, standing and sitting are the most common player modes used by most home users due to physical space limitations and hardware restrictions. In addition to these modes, a half-sitting position should be considered because some users use VR applications on a bed or sofa with their legs outstretched, either for comfort or because they are physically unable to stand or sit. In experiment 1 (third-person perspective), standing, sitting, and half-sitting were selected as the possible positions for the VR games. The navigation method in experiment 1 did not require physical translation and rotation, which enables half-sitting participants to play VR games with full control of the game space. However, in experiment 2 (first-person perspective), two body positions (i.e., standing and sitting) were tested due to the locomotion methods employed. In experiment 2, physical movement was required for embodied rotation during VE navigation. It is difficult to rotate when the legs are outstretched, thus the half-sitting position was not included when navigating the VE using a first-person perspective.

Of the many factors associated with spatial cognition, these experiments focused on spatial navigation relating to the DFN in a VE. Experiment 1 (third-person perspective) used VR games that have visually distinct DFNs. In general, the characteristics of VR games differ depending on their design elements, such as visual features, viewing perspective, goals, game mechanisms and rules, interactions, and problem-solving tasks (Ahmad 2019). Of these characteristics, experiment 1 considered navigational possibilities to be the most important component when

selecting a VR game; as such, two VR games (Bomb Hero and Moss) were selected that provided the spatial experience (i.e., the DFN) required for experiment 1. On the other hand, in experiment 2 (first-person perspective), the DFN in a VE was determined by the locomotion method. Experiment 2 classified the locomotion method according to the type of translation (steering or teleportation) and rotation (embodied or instrumental) involved in the navigation motion; the combination of these methods thus determined the DFN. The locomotion methods were selected based on practical considerations. Steering and teleportation are the most dominant locomotion methods implemented with a controller for home VR use. For rotation, the body (i.e., embodied control) or a physical device (i.e., instrumental control) are the typical options available for VR users at home when navigating a VE. In line with this, experiment 2 tested four locomotion methods: steering + embodied control [EC], steering + instrumental control [IC], teleportation + EC, and teleportation + IC.

Chapter 2. Theoretical Background

2.1. Presence

2.1.1. Presence and Virtual Reality

VR is a real or simulated reality in which an individual has the belief that they are in an environment other than that which their real body is located (Slater and Usoh 1994). Ellis (1991) defined virtualization as "the process by which a human viewer interprets a patterned sensory impression to be an extended object in an environment other than that in which it physically exists". The aim of VR is to allow a person to perform perceptive-motor and cognitive activities in an artificial world that has been numerically created, which could be a fantasy world or a symbolic representation or simulation of some aspects of the real world (Á lvarez and Duarte 2017; Fuchs 2001).

With the advent and improvement of perceptually realistic, immersive, interactive, and engaging media, the experience of presence has become an area of scientific inquiry that has the potential to bridge the gap between media and the mind (Ijsselsteijn 2002). Presence is generally regarded as a vital component of VEs but in different ways (Nichols et al. 2000). For example, presence has been variously identified in previous research as a defining characteristic of a VE (Steuer 1992), one of several such characteristics (Sheridan 1992; Zeltzer 1992), an epiphenomenon (Welch et al. 1996), a design ideal (Draper et al. 1998) and, from an application perspective, a desirable outcome of VE participation (Wilson 1997; Nichols et al. 2000)

Presence has been studied by many researchers in recent years (Heeter, 1992; Held and Durlach, 1992; Loomis, 1992; Sheridan, 1992; Steur, 1992; Barfield and Weghorst, 1993; Barfield et. al., 1995; Slater and Wilbur 1997). Some researchers have identified presence as a guide to what constitutes an effective VR system (Slater et al. 1998) and as the defining feature of VR (Steuer 1992). The International Society of Presence Research defines presence in computer-mediated environments as a 'psychological state in which even though part or all of the individual's current experience is generated by and/or filtered through human-made technology, part or all of the individual's perception fails to accurately acknowledge the role of the

technology in the experience' (Riva 2009). In other words, presence is a 'psychological state in which the virtuality of the experience is unnoticed' (Lee, 2004). It is thought that participants who are highly present will experience a VE as a more engaging reality compared to the surrounding physical world and will consider the environment presented on the display as a place that has been visited rather than merely a series of observed images (Slater and Wilbur 1997).

Presence is a normal awareness phenomenon that requires directed attention and is based on the interaction between sensory stimulation, environmental factors that encourage involvement and enable immersion, and the internal tendency to become involved (Witmer and Singer 1998). In addition, the experience of presence can be described as the outcome of an intuitive metacognitive process that allows us to control our actions through the comparison between intentions and perceptions (Riva 2007; Riva and Mantovani 2012; Riva et al. 2014).

The subjective experience of information technology is profoundly affected by the extent to which the user feels that they are genuinely present within the mediated world that technology has made available to them (Riva et al. 2014). Thus, presence is considered a measure of success for a media experience, with higher levels of presence deemed more successful (Nowak and Biocca, 2003; Meehan et al. 2002; Bailey et al. 2012). This psychological experience of "being there" has increasingly became a crucial element of both the design and usage of recent interactive technologies (Riva et al. 2014); as such, presence is an important construct to consider when investigating the impact of mediated experiences on cognition (Bailey et al. 2012).

2.1.2. Presence and Spatiality

Presence is a highly activity-dependent and context-dependent process that is both embodied and environmentally and temporally embedded, integrating multimodal sensory data, ongoing actions and intentions, and cognitive and emotional processes (Ijsselsteijn 2002). Because presence is a multi-faceted phenomenon (Kim and Biocca 1997), it is difficult to define in one specific sentence. However, a common concept is the sense of "being there," (Slater and Wilbur 1997), which suggests that the essential perceptual framework for presence is based on spatiality. When we work or play within VEs, traveling through them and interacting with virtual objects,

it is common for a certain sense of “being in the VE,” i.e., presence, to develop (Schubert et al. 2001). In the process of developing presence, a mental model of the virtual three–dimensional space is constructed, consisting of the possible actions in this space (Schubert et al. 1999). When users are present in a VE, the outcome of the cognitive processes can be conceptualized as a special type of mental model of the virtual space, in which the location of the body is construed as being contained in the space rather than looking at it from outside (Biocca 1997; Regenbrecht et al. 1998; Schubert et al. 2001).

Presence in an immersive VE involves the commitment of the person’s entire neurology to the suspension of disbelief that they are somewhere else rather than where their physical body actually is (Slater and Usoh 1993). In the case of presence in an immersive VE, that “somewhere else” is computer-generated (Slater and Usoh 1993). Presence is both a subjective and objective description of a person's state with respect to an environment (Slater and Wilbur 1997). The subjective element relates to their evaluation of their degree of “being there”, the extent to which they think of the VE as “place-like” (subject to the suspension of disbelief) (Slater and Wilbur 1997). A number of definitions of presence in VR have been suggested by many researchers (Barfield and Weghorst 1993; Biocca 1997; Sheridan 1992; Slater and Wilbur 1997; Witmer and Singer 1998; Zeltzer 1992), many of which include the notion of spatiality. For example, presence has been defined as a state of consciousness, i.e., the (psychological) sense of being in a VE (Slater and Wilbur 1997), and presence in a VE necessitates a belief that the participant no longer inhabits the physical space but now occupies the computer-generated VE as a “place” (Barfield and Weghorst 1993; Slater et al. 1994). Other researchers have described presence as the sense of being in a place that is different from the physical one (Witmer and Singer 1998; Sheridan 1992; Zeltzer 1992) and as a compelling sense of being in a mediated space other than where the physical body is located (Biocca 1997; Riva et al. 2014; Schubert et al. 1999). From these perspectives, the essential concept of presence, “being there,” can be conceptualized and developed from the construction of a spatial-functional mental model of the VE (Schubert et al. 2001). Thus, it is apparent that the sense of presence is deeply associated with spatial cognition and should be understood in the context of spatiality in VEs.

2.1.3. Presence and Action

An individual is considered present in a space if they can act and interact in it (Riva 2009; Schultze 2010). Presence is tied to successfully supported actions within an environment (Zahorik and Jenison 1998). These approaches suggest that reality is grounded in action rather than in mental filters and that ‘‘the reality of experience is defined relative to functionality, rather than to appearances’’ (Flach and Holden 1998; Usoh et al. 2000).

To date, various authors have suggested that presence plays a role in the monitoring of action (Riva and Mantovani 2012). Riva (2009) suggested that presence is a core neuropsychological phenomenon whose goal is to produce a sense of agency and control; in other words, subjects are ‘‘present’’ if they are able to enact their intentions in an external world. Slater et al. (2009) proposed that ‘‘humans have a propensity to find correlations between their activity and internal state and their sense perceptions of what is going on out there’’ (Riva and Mantovani 2012). In addition, Zahorik and Jenison (1998) argued that ‘‘presence is tantamount to successfully supported action in the environment’’. Specifically, it means that, when the environmental response is perceived as lawful, that is, commensurate with the response that would be made in the real-world environment in which our perceptual systems have evolved, then the action is said to successfully support our expectations (Zahorik and Jenison 1998).

A virtual environment, like any other environment, is perceived and understood by mentally combining potential patterns of action in the virtual space; as such, understanding the world means conceptualizing it in terms of actions (Schubert et al. 2001). The success of perception depends not on its geometric accuracy but on the extent to which it leads to appropriate behavioral decisions and the successful guidance of actions (Witt and Sugovic 2013). This perspective of presence argues that “being there” is grounded in the ability “to do there” (Sanchez-Vives and Slater 2005; Schultze 2010).

The capability of action within a VE has frequently been linked to the feeling of presence in VR (Sanchez-Vives and Slater 2005; Slater 2009). There is evidence that the ability to interact with VE (Welch et al.1996) and control one’s own locomotion in a virtual landscape (Stanney et al. 2002; Clemente et al. 2014; Weech et al. 2019) enhances presence.

Welch et al. (1996) conducted two experiments that examined the effects of pictorial realism, observer interactivity, and the delay of visual feedback on the sense of presence. Subjects were presented pairs of VEs for a simulated driving task that differed in one or more ways from each other. This experiment hypothesized that maximal presence occurs when the user felt capable of moving about in the VE and manipulating its content. It was found that the act of controlling the car increased the subjective sense of presence more than the delay in the visual feedback reduced it.

Stanney et al. (2002) investigated the interrelations between VE design characteristics (user control over movement, scene complexity, and exposure duration) and VE performance, presence, and cybersickness. Their results indicated that, under complete control, participants performed significantly faster on locomotion and choice reaction tasks, achieved higher overall performance scores, and experienced a greater sense of presence. These findings suggest that providing users with complete control allows for effective performance in both stationary tasks and those requiring head movement only. Overall, this improved performance may be beneficial for promoting presence in VE systems.

Clemente et al. (2014) conducted a study to measure the level of presence experienced while navigating a VE in comparison with less immersive conditions using a wireless portable electroencephalogram (EEG) device as an objective indicator of brain activation. They compared three experimental conditions: photographs, video, and free navigation through a VE using either a desktop screen or a high-resolution power wall screen. Significant differences were found between the navigation and video conditions in the activity of the right insula for the theta band. They also found a higher activation of the insula for the alpha and theta bands when navigating the VE when comparing the two screen types. Insula activation is related to stimulus attention and self-awareness processes, directly related to the sense of presence.

Furthermore, choosing a form of locomotion for a VR environment that is closer to real human locomotion is likely to increase both subjective presence (Usoh et al. 2000) and behavioral presence (Slater et al.1998; Soler-Domínguez et al. 2020).

In a study by Usoh et al. (2000), one group of ten subjects searched for a box in a real office environment, while a second group of ten subjects carried out the same task in a VE that simulated the same office. The subjects in the real office moved through the environment on foot, while the participants in the VE moved through in their gaze direction at a constant velocity by pressing the thumb button on a 3D mouse. The results of the Slater-Usoh-Steed questionnaire (Slater et al. 1998; Usoh et al. 1999) revealed a small, statistically significant difference between the real environment and the VE, with the individuals in the real environment reporting a higher presence.

Slater et al. (1998) examined the influence of two factors on presence in VEs - body movement and task complexity. They found a significant positive association between reported presence and body movement, particularly head yaw and the extent to which the subjects bent down and stood up. This study suggests that the reported presence of a participant in a VE is likely to be positively associated with the movement of the entire body (such as crouching down and standing up) and head movements (looking around and looking up and down) that are appropriate for the context offered by the VE.

Several studies have also indicated that physical movement has a positive effect on presence (Kitson et al. 2015; Hale and Stanney 2014; Slater et al. 1998; Nutt 2014; Kohn and Rank 2016). Specifically, previous studies have identified advantages in terms of spatial orientation and the feeling of presence for methods that involve more realistic physical inputs during movement (Suma et al. 2007; Chance et al. 1998; Ruddle and Lessels 2009; Riecke et al. 2010; Chrastil and Warren 2012; Moghadam et al. 2018).

2.1.4. Presence and Attention

Attention allocation and the establishment of a mental model of the mediated environment appear to be prerequisite conditions for the sensation of presence (Weibel and Wissmath 2011; Wirth et al. 2007), which occurs as part of a feedback loop between task characteristics and attention allocation (Bystrom et al. 1999; Weibel and Wissmath 2011). The nature of the task itself may indirectly influence the level of presence because a particularly engaging task may lead the user to

allocate more attentional resources to the VE, thus bringing about a greater sense of presence (Bystrom et al. 1999). How sharply users focus their attention on a VE partially determines the extent to which they become involved in that environment and how much presence they report (Witmer and Singer 1998). Whether there is a threshold for the allocation of attentional resources that must be reached before presence is experienced remains an open question, but it is reasonable to assume such a threshold exists (Witmer and Singer 1998). The more attention the users pay to the virtual rather than the actual world, and the more absorbed and emotionally engaged they become in the virtual space, the greater their sense of presence (Schultze 2010).

2.2. Body Position

It is often claimed that the "states of the body modify states of the mind" (Wilson and Golonka 2013). The body can be viewed from many different perspectives (e.g. semantic, emotional, spatial, motor, tactile, visual, and proprioceptive) and described in terms of many pairs of opposing properties (e.g. conscious/unconscious, conceptual/nonconceptual, dynamic/static, innate/acquired) (Gallagher 2005). The body is the repository of the sensory apparatus, which in turn leads to the fundamental representation systems based on the senses (e.g., visual, auditory, and kinesthetic) (Slater and Usoh 1994). Before a unified perception of the world can be formed, sensory signals must be processed with reference to body representation (Harris et al. 2015). The various attributes of the body, such as shape, proportion, position, and movement can be derived from the various sensory systems and can affect the perception of the world (Harris et al. 2015). When changing body position, an individual is aware of the outstretched or bent position of their limbs and of their upright position even with their eyes shut (Á dám 1980). Receptors in the skin also participate in signaling changes in body position; it is difficult to separate the senses of touch and pressure from the perception of body position (Á dám 1980).

The body processes the information given by proprioceptive and kinesthetic sensations without any need for conscious or reflective awareness (Dolezal 2009). Specifically, we use tactile input to localize and experience the various qualities of touch and proprioceptive information to determine the position of different parts of the body with respect to each other, which provides fundamental information for action (Dijkerman and Haan 2007). Proprioceptive information is interpreted by the postural control system in a flexible manner within the context of behavioral requirements (Horak and Macpherson 1996). This input helps define a postural reference frame for the body and its configuration and interrelates body space with extrapersonal space (Horak and Macpherson 1996).

2.2.1. Body Position and Cognitive Effects

Numerous studies on body position have indicated that there is an association between body position and cognitive effects. For example, children performed three manual dexterity tasks (tracking, aiming, and tracing) more quickly and more

accurately when standing compared to when sitting (Britten et al. 2016), while coding task performance in terms of processing speed was higher when standing compared to sitting (Patston et al. 2017). In addition, the Stroop effect was found to be weaker when participants were standing in terms of color naming, arrow direction judgment, and response time compared to a seated position (Rosenbaum et al. 2017). Cognitive psychomotor performance has also been reported to be maintained at nearly well-rested levels when standing upright, whereas reaction time and attention noticeably deteriorated when participants were seated (Caldwell et al. 2003). Another study has found that performance was better in an alternative-uses task and a figural-combination task when standing up than when sitting or lying (Zhou et al. 2017), while solving a complex anagram task was more difficult for subjects in a supine position than subjects in other positions (standing, sitting-erect, and sitting-bent), with the best performances given by subjects who sat erect (Schulman and Shontz 1971). Furthermore, participants in a standing position reported impaired spatial but not nonspatial memory performance when compared to their performance in a sitting position (Kerr et al. 1985). In education research, college students who took a math exam in a standing position produced better results compared to those in a sitting position (Isip 2014), and high school students showed significant improvements in executive function and working memory capabilities after the continued use of stand-biased desks (Mehta et al. 2015). Based on the results of the research summarized here, it can be predicted that the effects of body position on cognition will influence the sense of presence when navigating a VE.

Of the various cognitive functions (e.g., executive function, memory, and attention), this research considered attention a key function to be explored, with evidence suggesting that it affects the cognitive process of body position and presence. Previous research has indicated that the interaction between posture and cognition is related to a general limitation of attention (Barra et al. 2015; Dault et al. 2001; Redfern et al. 2004; Siu et al. 2009; Yardley et al. 2001) rather than the specific interference with spatial processing (Barra et al. 2015; Kerr et al. 1985; Maylor et al. 2001; Maylor and Wing 1996). The conclusion that postural balance demands attentional resources is consistent across all of these studies, despite the very different nature and difficulty of the cognitive tasks tested (Barra et al. 2015).

Presence experience (i.e., the sense of presence) results from the interpretation of the mental model of the VE, which is an outcome of cognitive processes (Schubert et al. 2001). In particular, two cognitive processes are involved in the emergence of presence: the construction of a mental model and attention allocation (Schubert et al. 2001). Individuals experiencing a VE can concurrently attend to aspects of the VE and events in their physical environment (Witmer and Singer 1998). Therefore, presence may vary depending in part on the allocation of attentional resources, with greater allocation leading to a heightened sense of presence (Witmer and Singer 1998). As a consequence, presence appears to be a matter of focus (Fontaine 1992; Witmer and Singer 1998) and can be achieved by allocating attentional resources (Carassa et al. 2004). Hence, we hypothesized that attention is an essential cognitive function that needs to be considered when investigating the cognitive effects of body position and presence during VE navigation.

2.2.2. Body Position and Postural Control

Body position requires postural control, especially when in a standing position. Postural control has been defined as the control of the body's position in space for the purposes of balance and orientation (Woollacott and Shumway-Cook 2002). Postural control provides stability, exhibited in the form of balance in a variety of body configurations (e.g., seated or in a bipedal stance) (Wade and Jones 1997). Maintaining stability, even in a non-moving stance, is a dynamic and rather than static task because the body is never completely motionless (Horak and Macpherson 1996). Researchers have found an interaction between postural control and cognitive task performance, indicating that postural control is not a fully automatic process but may require active cognitive processes (Chen et al. 2018; Woollacott and Shumway-Cook 2002; Yogev-Seligmann et al. 2008), including complex information processing, such as perception, decision-making, and motor control (Chen et al. 2018; Watson 1999). In addition, maintaining an upright stance may tax cognitive factors, such as attentional processes, when the standing conditions are challenging or when attentional interference between postural control and cognitive processes is high (Huxhold et al. 2006; Wollacott 2000). The degree of attention or cognitive involvement required to control posture increases with task difficulty (Donker et al.

2007). In this regard, the attentional demands of balance control vary depending on the complexity of the task and the type of secondary task being performed (Woollacott and Shumway-Cook 2002).

2.2.3. Body Position and Postural Stability

Postural stability has been found to be related to cybersickness in HMD-based VR (Arcioni et al. 2018; Widdowson et al. 2019). Past research has shown that people who display greater postural instability are more likely to subsequently report feeling sick when they are exposed to visual motion stimulation (Stanney et al. 1998; Riccio and Stoffregen 1991; Chang et al. 2012; Owen et al. 1998; Stoffregen and Smart 1998; Stoffregen et al. 2008; Arcioni et al. 2018). These predictions have been found to hold for many different types of visual motion stimulation (Arcioni et al. 2018), including visual stimulation with large moving rooms (Stoffregen and Smart 1998), handheld devices (Stoffregen et al. 2014), console video games (Chang et al. 2013), and cave automated virtual environments (CAVEs) (Chardonnet et al. 2017). However, the results from studies on sickness and postural instability are often discordant. Some have found that participants who navigate a VE while sitting become sick without any prior instability (Dennison et al. 2016; Kim et al. 2005; Dennison and D'zmura 2018), while other studies found that sickness occurred in both standing and sitting positions (Merhi et al. 2007; Clifton and Palmisano 2019a).

2.3. Spatial Cognition: Degree of Freedom in Navigation

Spatial cognition refers to the capacity and the cognitive processes necessary to move in an environment without becoming lost (Á lvarez and Duarte 2017). Spatial cognition is essential to represent, organize, understand, and navigate an environment (Choi 2013; Spence and Feng 2010) and involves more than just perception; it involves integrating perception with memory, decision-making, and task execution (Tsotsos et al. 2018). In planning a move, the brain must select one of the many possible movements (Seegelke and Schack 2016). Known as the degree of freedom problem (Bernstein 1967), there are multiple ways in which a movement can be performed to achieve the same action goal (Seegelke and Schack 2016). The local goals of a player's actions depend on their general goals and on how they interpret them, and these guide the perception of possible opportunities for action (Carassa et al. 2004). Thus, the possibility of choosing between alternative courses of action, that is, the degree of freedom in navigation (DFN) granted to the user, needs to be taken into account (Carassa et al. 2004) when navigating a VE.

2.3.1. Degree of Freedom in Navigation and Decision-Making

Most actions performed in a video game involve decision-making behaviors and triggering actions that are not found in other media experiences (Tamborini and Skalski 2006). As reported by Fabricatore (2007), when playing a game, a player interacts with a virtual universe that receives the player’s inputs and responds by changing its status. Information regarding the outcome of the interaction is then conveyed to the player, and this is collected and used by the player to decide what to do next. This interactive cycle of the play experience is thus centered on a decision-making process that relies on the information conveyed to the player.

A decision is a commitment to a proposition or plan of action based on information and values associated with the possible outcomes (Shadlen and Kiani 2013). According to Harris (1998):

> Making a decision implies that there are alternative choices to be considered, and in such a case we want not only to identify as many of these alternatives as possible but to choose the one that has the highest

> probability of success or effectiveness and best fits with our goals, objectives, desires, values, and so on. (p.1)

Decisions can follow from perception and lead to action, but other directions within this interaction are possible (Oliveira et al. 2009). The processes by which information that is gathered from the sensory systems are combined and used to influence how we behave in the world is referred to as perceptual decision-making, which is influenced not only by the sensory information at hand but also by factors such as attention, task difficulty, the prior probability of the occurrence of an event and the outcome of the decision, and the means by which a choice is enacted (Heekeren et al. 2008).

Of the many cognitive functions, attention can be directed toward the features and/or location of a stimulus, and attention can benefit decision-making when the subject is cued to these characteristics (Davis and Graham 1981; Eriksen and Hoffman 1972; Nunez et al. 2017; Shaw and Shaw 1977). Previous research has highlighted the importance of a well-controlled distribution of visual attention during decision-making (Hüttermann et al. 2018; Orquin and Loose 2013). The integrated model of visual attention, visual short-term memory, and perceptual decision-making proposed by Smith and Ratcliff (2009) predicts that attention operates on the encoding of the stimulus and that greater encoding increases the drift rate during the decision-making process (Nunez et al. 2017).

2.4. Cybersickness

2.4.1. Cybersickness and Virtual Reality

Despite the advances in VR technology, many people still report experiencing cybersickness during its use (Dużmańska et al. 2018; Gavgani et al. 2017; Guna et al. 2019; Rebenitsch and Owen 2016; Saredakis et al. 2020). The occurrence of cybersickness reduces the range of possible VR applications and highlights the need for scientific strategies to optimize virtual experiences (Litleskare and Calogiuri 2019). Major symptoms of cybersickness include, but are not limited to, headache, disorientation, fatigue, pallor, nausea, drowsiness, and incapacitation (Kennedy et al 2001; Kolasinski 1995; Widdowson et al. 2019). Cybersickness may arise from nonvisual or multisensory stimulation and can be caused by multiple factors (Kennedy and Fowlkes 1992; Widdowson et al. 2019) related to the individual, the device (Kolasinski and Gilson 1998; Seay et al. 2002; Toet et al. 2008; Davis et al. 2015), or the task (Stanney and Kennedy 1997; Bonato et al. 2008; Kemeny et al. 2017; Farmani and Teather 2020). In particular, in terms of the user, age and gender (Arns and Cerney 2005; Park et al. 2006; Farmani and Teather 2020), illness, and position within the simulator are factors that influence the severity of cybersickness (Mousavi et al. 2013).

2.4.2. Sensory Conflict Theory

There are two prevailing theories regarding the causes of cybersickness: sensory conflict and postural instability. (Litleskare and Calogiuri 2019). The sensory conflict theory postulates that cybersickness is caused by the sensory conflict between visual, vestibular, and proprioceptive inputs (Reason and Brand 1975; Litleskare and Calogiuri 2019). This theory suggests that the conflict between sensory inputs (e.g., visual motion without concordant vestibular stimulation) leads to conflict in the neural mechanisms responsible for interpreting and responding to orientation and self-motion (Money 1990; Stanney et al. 2003). The visual and vestibular senses provide information about an individual's orientation and perceived motion (Kolasinski 1995; Davis et al. 2014). A mismatch of these senses can frequently occur in virtual worlds (Kolasinski 1995; Davis et al. 2014), and this

is thought to play a causal role in cybersickness (Oman 1990; Reason 1978; Rebenitsch and Owen 2016; Weech et al. 2018a; Weech et al. 2020).

Reason (1978) argued that the brain probably evaluates incoming sensory signals for consistency by computing the components of sensory signals that are new and unexpected given knowledge of ongoing movement commands (Oman 1990). In line with this, Reason (1978) noted that any stimulus situation or environment that effectively changed the rules relating motor outflow to sensory return would thus be expected to produce prolonged sensory conflict and result in motion sickness (Oman 1990).

Weech et al. (2018a) investigated the effects of the mismatch between the visual and vestibular senses by examining whether noisy vestibular stimulation through bone vibrations can reduce the symptoms of simulator sickness. They carried out two experiments in which participants performed a spatial navigation task in VR. Experiment 1 was conducted using a high-end projection-based VR display, whereas experiment 2 used a consumer head-mounted display (HMD). During each trial, vestibular stimulation was either: 1) absent, 2) coupled with high angular acceleration of the projection camera, or 3) applied randomly throughout each trial. The results of the two experiments indicated that participants exhibited less simulator sickness compared with the control when the vibration was coupled with the angular acceleration of the camera. Overall, this study suggests that noisy vestibular stimulation can influence simulator sickness in VR if it is applied when vestibular signals are expected (i.e., coupled with high visual acceleration).

Some unresolved issues surrounding this theory include why the body cannot process the information and why some individuals are affected more frequently or severely than others under identical stimuli (LaViola 2000; Harrington et al. 2019).

2.4.3. Postural Instability Theory

The second explanation for cybersickness is the postural instability theory, which is based on the idea that the main goal of humans is to maintain postural stability within the environment (Riccio and Stoffregen 1991; Davis et al. 2014). The theory suggests that prolonged instability and the lack of control arise from a variety of factors such

as low-frequency vibrations, weightlessness, changing relationships with gravitoinertial forces, and altered specificity (Harrington et al. 2019). It has also been suggested that, whenever the environment changes in an abrupt or significant way and postural control strategies have not been learned, postural instability occurs (Davis et al. 2014). In many VEs, visual changes that are unrelated to the normal constraints on body motion lead to a conflict with normal postural control strategies, resulting in cybersickness symptoms (Davis et al. 2014). However, the relationship between cybersickness and postural instability is not conclusive. Some past studies have found a positive connection (Munafo et al. 2017; Arcioni et al. 2018; Merhi et al. 2007; Chardonnet et al. 2017), while others have found no relationship (Dennison and D'Zmura 2018; Cobb 1999) between cybersickness and postural instability. Additionally, some studies have observed that individuals who experience stronger cybersickness tend to demonstrate lower postural sway (Dennison and D'Zmura 2017; Sadiq et al. 2017; Weech et al. 2018).

2.5. Self-Motion

The perception of self-motion refers to the subjective experience of moving through space, which, under most natural conditions, occurs when a person is actually moving (Campos et al 2009). Perceiving and controlling self-motion requires the integration of multisensory cues (e.g., vision, audition, proprioception, and vestibular sense) to derive knowledge about the state of the body in space (Weech et al. 2018b). Proprioceptive feedback is used to determine the position and orientation of the limbs and head, while vestibular feedback generates a sense of linear acceleration (translation) and rotation in space (Christou and Aristidou 2017). The proprioceptive and vestibular systems have direct and important ties to spatial cognition (Waller and Hodgson 2013). It may therefore be that non-visual cues contribute to successful navigation and that, when they are lacking, as in some VR systems, this leads to lower spatial cognition (Christou and Aristidou 2017).

2.5.1. Vection and Virtual Reality

Visual-vestibular cue mismatch has been linked to a reduced sense of vection (Wong and Frost 1981; Weech and Troje 2017) or to enhanced vection (Kim et al. 2012; Palmisano et al. 2012; Weech et al. 2019). Vection describes the sensation of illusory self-motion in the absence of physical movement through space (Dichgans and Brandt 1973; Palmisano et al. 2015; Keshavarz et al. 2015). Vection in VR has been found to be a common factor contributing to both presence and cybersickness (Slater et al. 1996; Weech et al. 2019). Several studies have found positive correlations between vection and presence (Keshavarz et al. 2018; Riecke et al. 2006; Clifton and Palmisano 2019a), while others have confirmed that vection acts as an intervening factor between presence and cybersickness (Stanney et al. 1998; Sadowski and Stanney 2002; Hettinger et al. 2014; Hettinger et al. 1990; Keshavarz et al. 2014b; Keshavarz et al. 2015; Weech et al. 2019). Sensory conflict due to vection is often argued to be the prime cause of cybersickness (Hill and Howarth 2000; Keshavarz et al. 2014a; Palmisano et al. 2011; Weech et al. 2018a; Zacharias and Young 1981; Clifton and Palmisano, 2019a).

Hill and Howarth (2000) examined whether motion sickness is lower with repeated exposure to motion and whether participants can become habituated to the visual appearance of motion. Overall, their findings support the idea that nausea, a component of virtual simulator sickness, is primarily a consequence of the appearance of motion in the VE, leading to a form of vection-induced motion sickness resulting from the feeling of self-motion.

Palmisano et al. (2011) reviewed viewpoint jitter effects on vection, postural sway, eye movements, and motion sickness. Their review of recent studies on simulated viewpoint jitter indicated that jittering self-motion displays, which are thought to generate significant and sustained visual–vestibular conflict, lead to superior vection compared to non-jittering displays, which are thought to generate only minimal/transient sensory conflict.

Zacharias and Young (1981) compared three models to investigate the association between visual, vestibular, and self-motion. A parallel channel linear model with separate visual and vestibular pathways that sum in a complementary manner was proposed. A dual-input describing function supported this model, with vestibular cues dominating at higher frequencies. The describing function model was extended to a non-linear cue conflict model, in which cue weighting depended on the level of agreement between the visual and vestibular cues. The results of this study confirmed that self-motion is estimated by combining complementary visual and vestibular cues; in particular, low-frequency visual cues are used to augment high-frequency vestibular cues to affect the wideband sensory system.

However, vection does not always lead to the emergence of sickness symptoms (Weech et al. 2019). Previous studies have found positive (Dichgans and Brandt 1978; Berthoz et al. 1979; Palmisano et al. 2014; Hettinger and Riccio 1992; Hettinger et al. 1990; Keshavarz et al. 2014a), negative (Palmisano et al. 2017b), or no relationship (Palmisano et al. 2017a) between vection and cybersickness (Clifton and Palmisano, 2019a).

2.5.2. Self-Motion and Navigation in a VE

When walking in the real world, vestibular, proprioceptive, and efferent copy signals and visual information create consistent multi-sensory cues that indicate self-motion, i.e., acceleration, speed, and the direction of travel (Bruder et al. 2015). The proprioceptive and vestibular systems have direct and important ties to spatial cognition (Waller and Hodgson 2013). It may be, therefore, that non-visual cues contribute to successful navigation and that, when they are lacking, as in some VR systems, this leads to lower spatial cognition (Christou and Aristidou 2017). In addition, the issue of conflicting or degraded sensory information in VEs has additional practical importance given that discrepancies in sensory information are widely believed to be responsible for the onset of simulator sickness (Harm 2002; Yardley 1992) and are also thought to impact the user's sense of presence and immersion in a VE (Biocca et al. 2000; Waller and Hodgson 2013).

Many researchers (Klatzky et al. 1998; Rieser 1989; Wang 2004; Ruddle and Lessels 2006) have argued that the perceptual and performance discrepancies between real and virtual movement stem from the lack of physical locomotion cues, such as vestibular and proprioceptive cues (Kitson et al. 2017a). Thus, traveling through immersive VEs by means of intuitive, multimodal methods of generating self-motion is becoming increasingly important when seeking to improve the naturalness of VR-based interaction (Bruder et al. 2015).

Klatzky et al. (1998) investigated four conditions: walking without vision (proprioceptive cues), imagining oneself walking along a verbally described path (neither proprioceptive nor visual cues), watching someone else walk and trying to take that person's perspective (visual cues not coupled with self-locomotion), and watching optical flow fields generated by a virtual display to correspond to physical walking (visual cues typically coupled with self-locomotion). Their findings revealed that physical turns are important to update the user's perceived heading and that, when proprioceptive cues for a change in heading are lacking, the user fails to update the heading representation that governs the response turn.

Rieser (1989) studied orientation using a task in which the participants estimated the direction to a target object in a room after closing their eyes and imagining a change in their position or orientation from their starting point. It was

found that performance was slower for imagined rotations than for physical rotations, and response latencies increased as a function of the angular deviation of the target from the direction that the participant was physically facing. A possible explanation for this is that imagined movements are not associated with vestibular signals or afferent and efferent proprioception (Avraamides et al. 2004).

Ruddle and Lessels (2006) investigated the importance of visual information and rotational and translational body-based information in complex spatial tasks. They conducted an experiment in which participants searched a computer-generated virtual room for targets. Three conditions were compared in their study: a visual-only group (visual information only), a walking group (visual information and full body-based information), and a rotating group (visual information and rotational body-based information only). The results indicated that the walking group performed the task with near-perfect efficiency, irrespective of whether a rich or impoverished visual scene was provided, while the visual-only and rotating groups were significantly less efficient and frequently searched parts of the room at least twice. These findings suggest that full physical movement (translation and rotation) plays a critical role in navigational searches.

It has been suggested that provoking small physical movements at the onset of a visually simulated passive motion strengthens the illusion of self-motion for both translation and rotation (Riecke et al. 2006; Wong and Frost 1981; Riecke 2008). Research has also found that motion cueing in VR can increase the feeling of self-motion or vection (Harris et al. 2002; Kitson et al. 2015). Motion cueing is an approach that simulates proprioceptive and vestibular cues as closely as possible when walking is not feasible (Kitson et al. 2015). Several locomotion interfaces that employ motion cueing for VR navigation have been proposed and investigated (Nguyen-Vo et al. 2019), such as walking-in-place (Skopp et al. 2014; Langbehn et al. 2015), redirected walking (Razzaque et al. 2001; Nescher et al. 2014; Zank and Kunz 2016), gesture-based (Ferracani et al. 2016; Wilson et al. 2016), and leaning-based interfaces (Kruijff et al. 2016; Harris et al. 2014; Kitson et al. 2017a).

2.6. Navigation in Virtual Environments

Navigation is broadly defined as the ability of humans to find their way and move from one point to another (Balakrishnan and Sundar 2011). Most sensory systems are able to provide information about the spatial structure of the surrounding environment, their location within that environment, and their movement through it (Waller and Hodgson 2013). Spatial environments vary considerably in terms of their size and complexity (Irish and Ramanan 2019), thus different types of movement are required for successful navigation.

2.6.1. Translation and Rotation in Navigation

When navigating a world, motion can be described as a combination of translation and rotation (Sunkara et al. 2016). To perform specific tasks, translation, rotation, or both need to be estimated (Sunkara et al., 2016). Translation and rotation are the basic constituents of all locomotion in the sense that even the most complex trajectories can be decomposed into a combination of elementary translations and rotations (Riecke 2008). Locomotion in VEs can be physical, i.e., exploiting physical motion cues for navigation and translating natural movement into VR motion through some form of body tracking, or it can be artificial, i.e., utilizing input devices to direct VR motion and navigation (Kim et al. 2010; Boletsis 2017). Therefore, translation and rotation in VR navigation can be achieved through either physical implementation or locomotion devices.

During navigation, people update their knowledge of their position and orientation, which involves combining body-based information about the translational and rotational movements with other, principally visual, sensory information (Ruddle and Lessels 2006). Previous research on the relative importance of translational versus rotational body-based information has been inconclusive (Ruddle and Lessels 2006). Several studies conducted using basic spatial tasks such as inter-object pointing (Presson and Montello 1994; Rieser 1989; Mou et al. 2004), path integration (Klatzky et al. 1998; Avraamides et al. 2004), and exhaustive searching (Pausch et al. 1997) have found that the rotational component of movement is critical (Presson and Montello 1994; Rieser 1989; Mou et al. 2004; Ruddle and Lessels 2006), while others have highlighted the important role of

translational body-based cues (Ruddle and Lessels 2006, 2009; Cherep et al. 2020). Additionally, in more complex spatial tasks that involve estimating the direction to a target along a route, full (i.e., translational and rotational) body-based information appears to have an advantage over rotational information on its own (Chance et al. 1998; Waller et al. 2004).

Physical translation and rotation are fundamental components of navigation behavior in the real world, yet evidence is mixed about their relative importance for complex navigation in VR (Riecke et al. 2010). Some studies have reported that performance in VR spatial orientation tasks appears to benefit from physical locomotion within the environment (Avraamides et al. 2004; Chance et al. 1998; Klatzky et al. 1998; Pausch et al 1997; Ruddle and Lessels, 2006; Waller et al. 2004; Wraga et al. 2004; Riecke et al. 2010).

Chance et al. (1998) investigated the effects of different locomotion techniques on a spatial orientation task when navigating a virtual maze. In this study, subjects controlled their motion in the maze using three locomotion modes: (a) walking mode, in which the subjects walked normally in the experimental room, (b) visual turning mode, in which the subjects moved through the environment using a joystick to control their turning, and (c) real turning mode, in which the subjects physically turned in place to steer while translating in the virtual maze. They found that, in general, a technique more similar to real walking (physical translation and/or rotation) led to better spatial orientation than when the self-motion was virtual (i.e., when the subject's view was translated or rotated while the subject remained still) (Bowman et al. 1999).

Klatzky et al. (1998) designed a triangle-completion task to examine the updating of perceived heading under conditions of physical movement and imagined movement induced in various ways. Four conditions were examined: walking without vision, imagining oneself walking along a verbally described path, watching someone else walk and trying to take that person's perspective, and watching optical flow fields generated by a virtual display to correspond to physical walking. Their results revealed that, without a physical turn, subjects failed to update their perceived heading to include rotation.

In a study by Pausch et al. (1997), participants in a virtual room searched for items by turning around the room using a head-tracked VR system or a hand-tracked joystick. The participants were better able to keep track of the search space with the body-based movement than with the joystick even though optical information was held constant across conditions. Collectively, these findings suggest that sources other than retinal inputs may be critical to spatial updating during self-movement (Wraga et al. 2004).

Waller et al. (2004) examined a task which compared two conditions: participants either walked a route while viewing video images on a HMD or viewed recorded video while remaining physically stationary in the laboratory. It was found that the walking participants estimated the direction significantly more accurately than those who were provided with no body-based information.

Wraga et al. (2004) conducted four experiments to study observers' ability to locate objects in a virtual display while rotating to new perspectives. In this study, the participants rotated themselves in a swivel chair (active rotation) or were rotated in the chair by the researcher (passive rotation). The results revealed that active rotation had advantages over passive rotation. Overall, this study suggests that spatial updating during viewer rotation is superior to that during rotation of the display about the self, providing direct evidence that self-movement plays a key role in spatial updating tasks involving rotational movement within a full perceptual context.

However, Riecke and colleagues (2005) found no significant benefit of adding physical rotation via a motion platform (Moghadam et al. 2018), while other study reported path integration may be performed accurately even if no body-based information is provided (Riecke et al. 2002; Ruddle and Lessels 2006). In addition, Chance and colleagues (1998) reported that walking through a virtual maze, physical translation and rotation allowed subjects to update spatial awareness better than physical translation and joystick rotation (Williams et al. 2007), while Ruddle and Lessels (2006, 2009) stated that actual walking is far more useful than physical rotation in terms of user performance in complex tasks (i.e., navigational search tasks) (Ruddle and Lessels 2006, 2009; Hashemian and Riecke 2017). On the other hand, Riecke and colleagues (2010) reported that body-based rotation yielded a

comparable performance to actual walking in terms of search efficiency and time (Riecke et al. 2010; Hashemian and Riecke 2017).

2.6.2. Spatial Orientation and Embodiment

More natural locomotion techniques lead to a greater sense of presence (Schuemie et al. 2005; Weech et al. 2019). Previous research has indicated that a participant's sense of presence in a VE is enhanced when they are able to move through that environment using a method that is similar to one they would naturally use in the real world as opposed to having to rely on an indirect metaphor for locomotion (Slater et al. 1995; Usoh et al. 1999; Whitton et al. 2005; Zanbaka et al. 2004; Interrante et al. 2007).

Schuemie et al. (2005) investigated three locomotion techniques (i.e., walk-in-place, hand-controlled viewing, and gaze-directed steering) that were systematically varied for several tasks in different VEs. A number of variables were measured to show the effects on presence, fear, avoidance, and simulator sickness. In this study, they found that the more natural locomotion technique (i.e., walk-in-place) contributed to higher levels of presence and fear than the other two techniques.

Slater et al. (1995) studied a walking-in-place (WIP) technique that enabled a real physical walking movement in 3D VEs. In this interaction paradigm, the user walked in place in the real world, providing proprioceptive feedback while remaining in the real space. To evaluation this WIP technique, two experimental studies were conducted to assess its impact on presence in comparison to a mouse-button method of navigation in VR. The results showed that, on average, the participants who moved through the environment using the proposed WIP technique reported a significantly higher sense of presence than those who used the mouse-button method.

Usoh et al. (1999) compared three locomotion methods (i.e., walking, WIP, and flying) in a VE. They found that presence was higher for virtual walkers than for flyers, and higher for real walkers than for virtual walkers. Overall, the evidence suggested that real walking is significantly more effective than either virtual walking or flying in terms of simplicity, straightforwardness, and naturalness as a mode of locomotion.

Whitton et al. (2005) explored locomotion interfaces for users who virtually moved on foot in a VE. They characterized task behavior and task performance using different visual and locomotion interfaces. A combination of one of three locomotion interfaces (real walking, WIP, or joystick flying), and one of three visual conditions (head-mounted display, unrestricted natural vision, or field-of-view-restricted natural vision) were applied in each of five experimental conditions. The outcomes of the first study showed that WIP produces higher levels of presence than moving by pushing a button. The second study revealed that both real walking and WIP yielded significantly higher levels of presence than did joystick flying, though real walking produced a higher sense of presence than WIP.

Zanbaka et al. (2004) investigated four different locomotion methods (i.e., real walking, virtual walking using six-degrees-of-freedom tracking, virtual walking using three-degrees-of-freedom tracking, and a joystick with a monitor) in a VE and monitored their effect on cognition. The results of this study suggest that, for applications where problem-solving and the interpretation of the material is important or where the opportunity to train is minimal, having a large tracked space so that the participant can walk around the VE provides benefits conventional virtual travel techniques.

Thus, much of the more recent navigation work has focused on engaging the user in physical movement as it seems to result in better spatial awareness of the VE compared to using a joystick (Hashemian and Riecke 2017; Kitson et al. 2017b; Suma et al. 2012; Waller and Hodgson 2013; Wilson et al. 2016; Coomer et al. 2018).

Prior work suggests that the type of visual cue (Teramoto and Riecke 2010; Riecke et al. 2007; Riecke et al. 2005) and motion (Klatzky et al. 1998; Rieser 1989) may influence the ease of maintaining orientation when updating the viewpoint (Moghadam et al. 2018). In addition, numerous studies have demonstrated (Moghadam et al. 2018) how different forms of viewpoint control can influence sickness (Sargunam et al. 2017; Ragan et al. 2012b; Chance et al. 1998), spatial understanding (Ragan et al. 2013; Ruddle and Lessels 2009; Bowman et al. 1999), and cognitive processing (Ragan et al. 2012a; Marsh et al. 2013; Bruder et al. 2015).

Sargunam et al. (2017) examined semi-natural view rotation for use in situations where physical rotation is limited. They tested rotation amplification, which increases the mapping between physical and virtual view rotations, and the results showed significant sickness effects with amplified or modified rotation in HMDs.

Ragan et al. (2012b) compared two travel techniques — steering and target-based — and two display conditions—a high-fidelity setup (a four-wall display with stereoscopy and head-tracking) and a lower-fidelity setup (a single wall display without stereoscopy or head-tracking). The higher degree of navigational control afforded by steering allowed faster performance in a data-relationship task than did target-based travel. However, steering also increased the risk of simulator sickness with the high-fidelity setup.

Chance et al. (1998) compared techniques that differed in their similarity to real walking in the physical world. In this study, three locomotion modes were compared: (a) walking mode, in which the subjects walked normally in the experimental room, (b) visual turning mode, in which subjects moved through the environment using a joystick to control their turning, and (c) real turning mode, in which the subjects physically turned in place to steer when translating in the virtual maze. The results showed that the walking mode had the lowest ratings for motion sickness, which is consistent with the widely held view that one of the causes of motion sickness is the discrepancy between vestibular signals and other informational inputs specifying body motion.

Ragan et al. (2013) studied the effects of the field of regard (FOR), stereoscopy, and head-tracked rendering on the performance of a task involving precise spatial inspections of complex 3D structures. The results of this study revealed that the condition with a high FOR, head tracking, and stereoscopy had fewer errors than all other conditions, while the condition with a low FOR, no head tracking, and no stereoscopy had the lowest average time overall. Overall, this study suggests that the addition of the higher fidelity system features leads to improvements in performance when making small-scale spatial judgments.

Ruddle and Lessels (2009) investigated how body-based information regarding the translational and rotational components of movement helped participants to perform a navigational search task (finding targets hidden inside

boxes in a room-sized space). In this study, three conditions were compared: physical walking with an HMD, physical turning but pressing a button to translate with an HMD, and no body-based information using a desktop display. Behavioral data indicated that both translational and rotational body-based information is required to accurately update one's position during navigation and confirmed the effects of the walking interface on the ability to navigate a VE.

Bowman et al. (1999) explored the effects of virtual travel techniques on the spatial orientation of users in a VE. System-automated, pointing, and route-planning techniques were compared in this study. The system-automated technique gave users no control over their path, while the pointing technique allowed users to continuously specify their direction of motion. Finally, the route-planning technique allowed users to set a path before moving, and they were then moved along that path by the system. In all cases, the translation of the user's viewpoint was virtual, but the user's gaze direction was controlled by physical head rotations. The results showed that techniques using virtual translation along with physical rotation could reasonably maintain spatial orientation as measured by an object-pointing task.

Ragan et al. (2012a) conducted a study that focused on two design issues for effective educational VEs: the level of environmental detail and the method of navigation. This study compared user-controlled steering to automatic animated transitions not controlled by the user for a memory task where participants viewed textually displayed information in the environment. The findings of this study suggest that manual navigation may have negatively affected the learning activity, though neither environmental detail nor navigation type significantly affected learning outcomes. Overall, a variety of learning and memory outcomes were consistently higher with the automatic travel technique, but the differences were not significant (Moghadam 2018).

Marsh et al. (2013) studied the cognitive resource demands of locomotion user interfaces that varied in their naturalness and the impact of a restricted field of view (FOV) on cognitive working memory demands while moving in a VE. The results revealed that locomotion with a less natural interface increased spatial working memory demands, and locomotion with a lower FOV increased general attentional demands. These findings provided insight into the cognitive strategies employed for specific types of concurrent tasks performed in VEs.

Bruder et al. (2015) investigated the mutual influence of redirected walking and verbal/spatial working memory tasks using a dual-task method in a VR laboratory. This study analyzed how curvature gains correlated with spatial and verbal working memory demands. The outcomes of this study revealed a significant influence of redirected walking on verbal and spatial working memory tasks, and also found a meaningful influence of cognitive tasks on walking behavior.

When considering body-based information, a distinction needs to be made between the rotational and translational components of movement (Ruddle and Lessels 2009). From a cognitive standpoint, rotation is more difficult to compute and can lead more easily to disorientation than can translation (Presson and Montello 1994; Rieser 1989; Rieser et al. 1995; Williams et al. 2006). Spatial orientation refers to the natural ability of humans to maintain their body orientation and position relative to the surrounding environment (Harris et al. 2014). This sense of spatial orientation relies heavily on visual information and whole-body information when moving within an environment (Wartenberg et al. 1998; Harris et al. 2014). An accurate sense of spatial orientation is necessary to successfully navigate through an environment (Harris et al. 2014). Physical navigation interfaces have been shown to increase usability and spatial orientation (Bowman et al. 1998; Bowman et al. 2004; Riecke et al. 2010; Kitson et al. 2017a). Past studies suggested that adding physical rotational cues can improve spatial orientation performance compared to visual-only simulations for various basic spatial tasks (Bakker et al 1999; Klatzky et al. 1998; Lathrop and Kaiser 2002; Riecke et al. 2010). Bakker and colleagues (1999) reported a significant improvement in accuracy when participants were asked to turn through a prescribed angle (Bakker et al. 1999), while participants responded twice as consistently (measured in terms of angular error) when asked to point from one target to another (Lathrop and Kaiser 2002; Ruddle and Lessels 2009). In addition, Klatzky and colleagues (1998) suggested that accurately performing path integration requires body-based cues associated with rotation (change in orientation) (Klatzky et al. 1998; Cherep et al. 2020).

2.6.3. Locomotion Methods

While humans can navigate with ease when walking in the real world, the realistic simulation of natural locomotion is difficult to achieve in immersive VEs (Steinicke et al. 2013; Bruder et al. 2015). The size of the virtual world often differs from the size of the tracked workspace, meaning that a straightforward implementation of omni-directional, unlimited walking is not possible (Bruder et al. 2015). Thus, many researchers have studied adjustments to standard viewing and walking techniques to overcome real-world limitations, such as limited physical space (Jay and Hubbold 2003; Peck et al. 2009; Razzaque et al. 2001; Terziman et al. 2010; Sargunam et al. 2017).

There has been considerable research on locomotion methods in VEs (Bolte et al. 2011; Bowman et al. 1997; Engel et al. 2008; Hanson et al. 2019; Interrante et al. 2007; Razzaque et al. 2001; Williams et al. 2007; Xie et al. 2010; Paris et al. 2019). However, it is difficult to determine the optimal approach to navigation due to factors (Paris et al. 2019) such as room size and configuration (Azmandian et al. 2017), the performance metric (Peck et al. 2009), judgment of relative direction (Williams et al. 2007), and simulator sickness (Freitag et al. 2014; Grechkin et al. 2016; Habgood et al. 2018; Neth et al. 2011). Thus, identifying an effective method of virtual locomotion for exploring large simulated environments that maximizes presence while mitigating the likelihood of cybersickness remains a major challenge for VR developers (Steinicke et al. 2013; Clifton and Palmisano 2019a).

To date, numerous locomotion methods have been designed for VR navigation, and these directly affect many aspects of the user experience, such as enjoyment, frustration, tiredness, motion sickness, and presence (Hale and Stanney 2014; Cherni et al. 2020; Bozgeyikli et al. 2019). In general, these methods can be categorized (Zanbaka et al. 2005) as either techniques that attempt to replicate the energy and motion of walking (Brooks 1986; Iwata and Yoshida 1999; Iwata and Fujii 1996; Razzaque et al. 2002; Templeman et al. 1999) or as purely virtual travel techniques (Bowman et al. 1997). VR researchers have also designed many embodied locomotion interfaces that require at least some physical motion from the user's body (Hashemian and Riecke 2017). A popular interface design is to navigate based on the direction of the body's center of gravity, which can be achieved by leaning the

entire body (Fairchild et al. 1993; Marchal et al. 2011) or just parts of it (Guy et al. 2015; LaViola et al. 2001) in the desired direction (Zielasko et al. 2016).

Marchal et al. (2011) explored the use of a novel interface for navigating VEs that tended to preserve equilibrioception in place of proprioception. The proposed interface (referred to as Joyman) was based on the metaphor of a human-scale joystick and had a simple mechanical design that allowed the user to indicate their virtual navigation intentions by leaning accordingly. An evaluation of the Joyman system showed that the feeling of immersion in the virtual world was significantly improved in comparison with traditional joystick-based techniques at the cost of some ease of use.

Guy et al. (2015) proposed LazyNav, which used several alternative body motions to control a virtual walk-through and left critical body parts (e.g., the hands, arms, head, and eyes) free to perform other tasks. They evaluated different pairs of body parts, excluding the hands, for translation and rotation in a ground-based scenario. It was found that users performed best when translation and rotation were controlled by uncorrelated body parts and when the movement plane in the VE corresponded to the body plane that was used.

LaViola et al. (2001) presented a cohesive suite of hands-free controls for multiscale navigation through a broad class of floor-constrained VEs. These controls allowed a user to move small and medium distances by leaning in the direction in which they wanted to move independently of their head orientation. They evaluated these techniques in existing projects related to archaeological reconstructions, free-form modeling, and interior design. In each case, their informal observations indicated that motions such as walking and leaning were both appropriate for navigation and were effective in cognitively simplifying complex VE interactions because functionality was more evenly distributed across the body.

2.6.4. Steering and Teleportation

Steering and teleportation are the most commonly available controller-based locomotion methods for navigating VEs. Steering locomotion enables the users to initiate continuous simulated self-motion toward their desired destination (Habgood et al. 2018; Clifton and Palmisano 2019a), which typically generates compelling

vection (Palmisano et al. 2015; Clifton and Palmisano 2019a). Teleportation allows a user to point to where they want to be in a virtual world, and the virtual viewpoint is instantaneously teleported to that position (Boletsis and Cedergren 2019). Typically, teleportation generates less cybersickness than the steering method during VE navigation (Bozgeyikli et al. 2016; Christou and Aristidou 2017; Frommel et al. 2017; Habgood et al. 2018; Ragan et al. 2012; Vlahovic et al. 2018; Clifton and Palmisano 2019a). However, some users using teleportation still report cybersickness (Clifton and Palmisano 2019a). In addition, teleportation has been shown to decrease spatial awareness and spatial cognition (Bowman et al. 1997; Sarupuri et al. 2017). Furthermore, teleportation may be as deficient as steering in terms of not providing proprioceptive and vestibular inputs, and there are also no smooth visual flow cues, which may lead to disorientation in VR (Bowman et al. 1997; Bowman et al. 1998; Christou and Aristidou 2017).

Several studies have identified benefits from steering locomotion in terms of presence (Clifton and Palmisano 2019a; Vlahovic et al. 2018; Keshavarz et al. 2018; Riecke et al. 2006), while others have indicated that teleportation reduces the sense of presence (Bowman et al. 1997; LaViola 2017). The lack of continuous visual motion stimulation during teleportation may weaken presence and remind users that they are in a virtual (as opposed to a real) environment (Slater and Steed 2000; Clifton and Palmisano 2019a). However, previous studies have failed to identify significant differences between steering locomotion and teleportation in their effect on presence (Bozgeyikli et al. 2016; Frommel et al. 2017; Habgood et al. 2018; Clifton and Palmisano 2019a).

Chapter 3. Experiment 1: Third-Person Perspective

3.1. Quantification of the Degree of Freedom in Navigation

This experiment employed two VR games, Bomb Hero and Moss, that offer a different degree of freedom in navigation (DFN). For the quantitative understanding of the DFN, we composed mathematical formulas based on graph theory. Graph theory has long been used in quantitative geography (Phillips et al. 2015) and has been applied to explain the form and structure of geographic space. Common applications of graph theory include the analysis of connectivity, route or transport efficiency, subnetworks, network structure, system behavior and dynamics, and network optimization or engineering (Heckmann et al. 2014). Using a graph framework, Gillner and Mallot (1998) applied a graph structure for space representation and acquired information for a recognized position and movement decisions, while Verma and Mettler (2016) investigated human learning and decision-making in the navigation of unknown environments using a graph layout.

In graph theory, a graph is a collection of points called vertices (V), connected by lines called edges (E). The degree of a vertex (d(V)) is the number of edges incident to the vertex. In this research, it should be noted that we use the term route instead of edge when describing the formulas. In Appendix A, we explain the foundational concepts of the formulas. According to the formulas, when playing Bomb Hero, the number of routes that a player can select from a place (i.e., vertex) is fewer than four, thus the DFN is finite. In contrast, for Moss, the number of routes a player can choose from a place (i.e., vertex) is not limited, meaning that the DFN is infinite. Through the formulas, we clearly understand that the DFN is much higher for Moss than Bomb Hero. Based on the more detailed explanation given in Appendix A, we constructed the two mathematical formulas presented in Table 1.

Table 1. Mathematical Formulas for the Two VR Games

Bomb Hero	**Moss**
$1 \le d(V_i) \le 4$ $1 \le i \le n, \quad i \in N,$ n: finite natural number $d(V_1)d(V_2)d(V_3) \dots d(V_n) \le 4^n$ $\prod_{i=1}^{n} d(V_i) \le 4^n$	$1 \le d(V_i)\ (i \in N, 1 \le i)$ if any $d(V_i)$ is infinite, we can get the formula below ... $\lim_{n\to\infty} d(V_1)d(V_2)d(V_3)d(V_4) \dots d(V_n) = \infty$ $\lim_{n\to\infty} \prod_{i=1}^{n} d(V_i) = \infty$

3.2. Experiment

3.2.1. Experimental Design and Participants

In this experiment, a 3 (body position) x 2 (navigation freedom) between-subjects design was used in a laboratory setting. Sixty-two students (58 male and 4 female) from Seoul National University in South Korea took part in the experiment. All the participants had experience with either computer or video games in the action genre. They were randomly assigned to one of six conditions and asked to play one of the two VR games, resulting in the following group sizes: n=11, 11, and 10 for the finite DFN (Bomb Hero) in a standing, sitting, and half-sitting position, respectively, and n=10, 10, and 10 for the infinite DFN (Moss) in a standing, sitting, and half-sitting position.

In this experiment, we selected the three positions (standing, sitting, and half-sitting) from the practical point of view. Standing and sitting are the most common player modes suggested by VR game developers. In addition, half-sitting was added as a possible position used to play VR games. Some users may play VR games on a bed or sofa with their two legs outstretched, either for comfort or because they are physically unable to stand or sit. As with the sitting position, the participants in a half-sitting position played the VR games with full control of the game space, and this did not degrade their performance in terms of gameplay. Though it might appear that sitting and half-sitting are not substantially different except for the position of legs, the postural control system includes all sensorimotor and musculoskeletal components and is associated with the dynamic interaction among many context-

and task-specific, automatic neural behaviors (Horak and Macpherson 1996). Therefore, we postulate that the cognitive processes related to the sense of presence may differ between the three body positions (standing, sitting, and half-sitting) when playing VR games.

3.2.2. Stimulus Materials

An Oculus Rift HMD, two Oculus Touch controllers, and an ASUS VR ready notebook (ROG GL502VM) were used to play the VR games. The two VR games, Bomb Hero and Moss, were selected because they had similar in-game viewpoints (i.e., they both have a third-person perspective) and gameplay mechanisms (e.g., controlling a character to navigate space and defeating enemies) but distinct navigation structures (finite and infinite). Bomb Hero, a classic arcade game with a finite DFN, was played from Stages 1 to 5. The goal of Bomb Hero is to remove all of the enemies (monsters, in this case) using bombs and to find the portal that leads to the next level. While playing Bomb Hero, a player moves the main character, places the bombs to defeat the enemies, and searches for the portal, which is hidden inside the blocks. Moss, a single-player action-adventure game with an infinite DFN, consists of three chapters; the beginning of "The Mire Temple" chapter was played in this study. In Moss, the player controls the main character Quill in navigating the environment and battling enemies (insects, in this case). During navigation, the player can manipulate or relocate bronze objects to either remove obstacles or open gates, both of which are required for Quill to move forward onto the next stage.

Every VR game offers a unique game playing experience based on its design elements, including its visual features, viewing perspective, goals, game mechanisms and rules, interactions, and problem-solving tasks (Ahmad 2019). Of these characteristics, we selected navigational possibilities as the most important component to be considered when investigating presence in VR game play. The primary goal of this study was to explore the relative effects of body position and spatial cognition on presence when playing VR games. Of the many components of spatial cognition, this research focused on spatial experience (mainly focusing on navigation) relating to the DFN in a VE rather than the small-scale spatial cognitive effects of targeted tasks. We thus used the overall VR game experience to measure

the sense of presence relating to the five factors (control, visual sense, attention, spatial presence, and immersion). With this in mind, we selected two VR games that provided the spatial experience required to meet these research objectives.

3.2.2.1. First- and Third-Person Perspectives in Gameplay

Though the details of the results have varied, past research has revealed that viewpoint can affect the sense of presence and the sense of embodiment. (Gorisse et al. 2017). Player perspective is one of the important design choices made when creating a digital game (Denisova and Cairns 2015). Some games have an egocentric viewpoint (i.e., first-person perspective), in which players see the environment and actions through the eyes of a specific characters or avatars, while some action games have third-person perspectives, in which players view the action from the behind and slightly above the characters or avatars they are controlling or an aerial perspective (i.e., a bird's eye view) (Choi 2013). Several studies have suggested that first- and third-person in-game perspectives offer different cognitive experiences during gameplay (Choi 2013). First-person perspective is believed to provide the most immersive feel for a player (Denisova and Cairns 2015; Ermi and Mäyrä 2003; Voorhees et al. 2012) and generate stronger feelings of spatial presence and cognitive involvement than third-person perspective (Choi 2013; Kallinen et al. 2007). However, video game theorists (Rouse 1999; Taylor 2002) agree that third-person perspective potentially increases the awareness of the virtual space by observing the avatar acting within the environment (Gorisse et al. 2017). Furthermore, research by Salamin et al. (2006, 2010) has shown that perception and navigation can be facilitated by third-person perspective in a VR environment to a greater extent than by first-person perspective. Third-person perspective also makes it easier for the subjects to detect elements located in the periphery of the field of view (Boulic et al. 2009; Debarba et al. 2015; Gorisse et al. 2017). In addition, Schuurink and Toet (2010) found that users experience more control over the avatar and events when they use third-person perspective in a 3D virtual environment (Choi 2013). For these reasons, we selected VR games with third-person perspective to provide better spatial awareness and a wider field of view, enabling the players to observe the spatial relations of the entire VR game space and detect navigation alternatives.

3.2.3. Experimental Setup and Process

After briefly explaining the purpose of the study and the experimental process, we showed the participants a video clip of the game that they would play during the experiment. While watching the clip, we explained the characteristics of the game and how to use the Touch controllers to control the events and navigate the game space. In this way, participants learned about basic gameplay prior to training. After watching the video, the participants practiced the part of the game shown in the clip for about 15 minutes. During this practice stage, the participants used a body position that differed from the condition to which they had been assigned; those in the standing group practiced while sitting, while those in the sitting and half-sitting groups practiced while standing. This was done to eliminate the familiarity effect that would arise from playing the game twice using the same position. After finishing the training, the participants played the practiced section of the game for approximately 10 to 15 minutes in their assigned body position. Upon completion of the game, the participants filled out a questionnaire regarding their feeling of presence. In this experiment, we adjusted the view settings depending on the body position and the height of the participant so that they experienced the same visual perspective. The entire process took approximately 75 minutes for each participant. See Figure 1 for an overview of the experimental process.

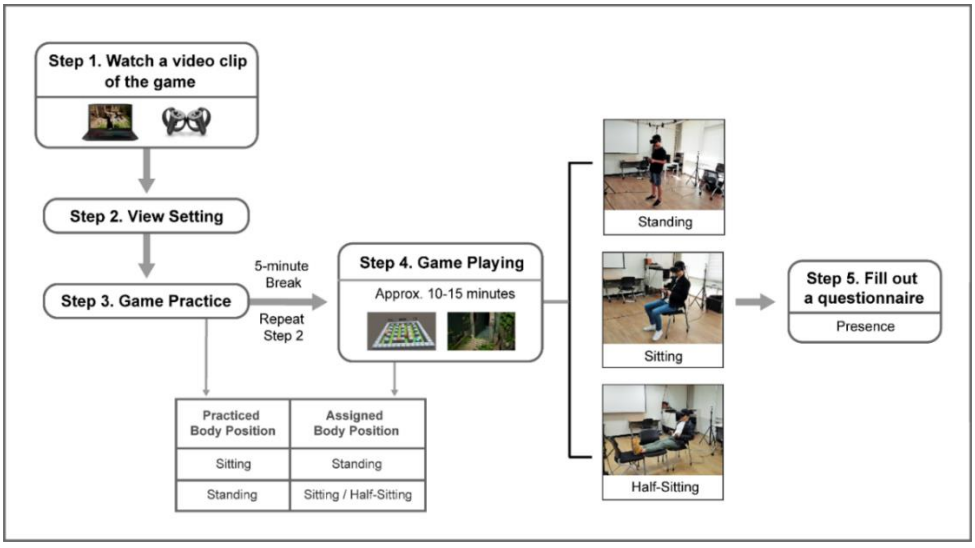


Figure 1. Experimental Process

3.2.4. Measurements

Presence was investigated as the dependent variable in this experiment. Thirty-five items were used to measure the level of presence (Cronbach's alpha for finite DFN = .95; Cronbach's alpha for infinite DFN = .95). The items were categorized into five factors: control (eight items), visual sense (five items), attention (seven items), spatial presence (seven items), and immersion (eight items). The items were selected from the following studies: Baños et al. (2000), Hartmann et al. (2016), Jennett et al. (2008), Weibel and Wissmath (2011), and Witmer and Singer (1998). Responses were scored on a 10-point Likert scale (1 = not at all; 10 = very much).

3.3. Results

A two-way analysis of variance (ANOVA) and a one-way ANOVA were conducted to explore the relative effects of the three body positions and the two types of DFN on presence during VR gameplay. The five factors associated with presence (control, visual sense, attention, spatial presence, and immersion) were also analyzed separately using a one-way ANOVA to understand how their effects differed between the body positions and the navigation types.

3.3.1. Presence: Two-way ANOVA

A two-way ANOVA yielded a main effect for body position, $F(2,56) = 3.70$, $p = 0.031$, with presence significantly higher in the standing position ($M = 7.37$, $SD = 0.97$) than in the half-sitting position ($M = 6.51$, $SD = 1.27$). However, the main effect of the two VR games was nonsignificant, $F(1, 56) = 2.30$, $p = 0.135$. Furthermore, no statistically significant interaction was found between body position and game type in relation to presence, $F(2, 56) = 2.30$, $p = 0.109$ (Table 2). Because the interaction effect was not significant, the two-way ANOVA was re-run without the interaction, i.e., as a main effect only. The results of the analysis yielded a main effect for the three body positions, $F(2,58) = 3.40$, $p = 0.040$ (Table 3), suggesting that at least one of the body positions differs from the other two in terms of the sense of presence.

Table 2. Two-way ANOVA Results for Presence

Source	Sum of squares	df	Mean square	F	*p*-value
Game	2.554	1	2.554	2.303	0.135
Position	8.203	2	4.102	3.700	0.031
Game*Position	5.107	2	2.553	2.303	0.109
Error	62.082	56	1.109		
Total	3032.224	62			

Table 3. Two-way ANOVA Results for Presence (without interaction)

Source	Sum of squares	df	Mean square	F	*p*-value
Game	2.506	1	2.506	2.163	0.147
Position	7.880	2	3.940	3.401	0.040
Error	67.189	58	1.158		
Total	3032.224	62			

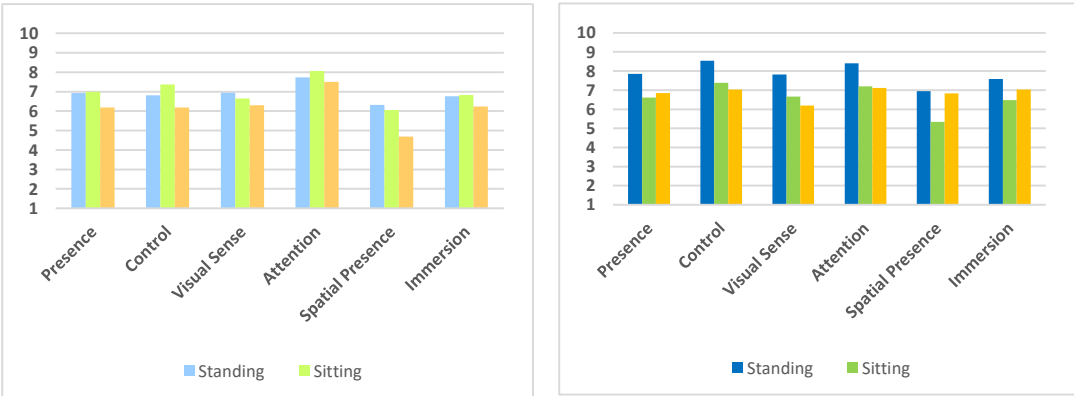


Figure 2. Mean Likert scale score for Presence and its five Associated Factors
(Left: Bomb Hero, Right: Moss)

3.3.2. Presence: One-way ANOVA

3.3.2.1. Finite Navigation Freedom

A one-way ANOVA showed no significant effect of the three body positions in terms of the sense of presence, F [2, 29] = 1.45, p = 0.251 (Table 4), nor for any of the five individual factors (Figure 2). These findings indicate that the cognitive involvement

of a standing position did not positively affect participants under the finite navigation condition, resulting in no effect of body position on presence.

Table 4. One-way ANOVA Results for Finite Navigation

Source	M	SD	F	*p*-value
Standing	6.92	0.87		
Sitting	6.99	1.17	1.452	0.251
Half-Sitting	6.18	1.50		

3.3.2.2. Infinite Navigation Freedom

The effect of body position was found for participants in a standing position, suggesting that presence was higher than those who were sitting or half-sitting, F [2, 27] = 5.79, p = 0.008. However, no statistical difference was found between the sitting and half-sitting positions. Post-hoc comparisons using Tukey HSD tests indicated that the mean score for the standing position (M = 7.86, SD = 0.85) differed significantly from that for the sitting (M = 6.61, SD = 0.81) and half-sitting positions (M = 6.84, SD = 0.95) (Table 5). In addition, all of the individual factors for presence except immersion affected the sense of presence between the three body positions (Table 6). Taken together, these outcomes suggest that additional cognitive resources allocated for the standing position were used effectively, consequently affecting the sense of presence for participants under infinite navigation.

Table 5. One-way ANOVA Results for Infinite Navigation

Source	M	SD	F	*p*-value	Turkey HSD
Standing (a)	7.86	0.85			
Sitting (b)	6.61	0.81	5.787	0.008	c, b < a
Half-Sitting (c)	6.84	0.95			

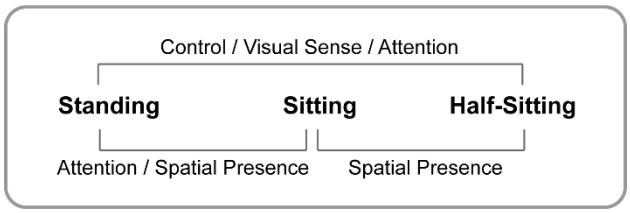


Figure 3. The Relationship Between the Five Presence Factors and the Three Body Positions for Infinite Navigation

Table 6. Means and Standard Deviations for the Five Presence Factors with Infinite Navigation

	Standing	**Sitting**	**Half-Sitting**	**Results**
Control	M = 8.54 SD = 0.65	M = 7.38 SD = 1.43	M = 7.04 SD = 1.28	F [2, 27] = 4.522, *p* = 0.020
Visual Sense	M = 7.82 SD = 1.17	M = 6.67 SD = 1.29	M = 6.20 SD = 1.32	F [2, 27] = 4.384, *p* = 0.022
Attention	M = 8.41 SD = 0.90	M = 7.20 SD = 0.86	M = 7.11 SD = 0.84	F [2, 27] = 7.030, *p* = 0.003
Spatial Presence	M = 6.94 SD = 1.34	M = 5.34 SD = 0.72	M = 6.83 SD = 1.07	F [2, 27] = 6.906, *p* = 0.004
Immersion	M = 7.59 SD = 1.29	M = 6.48 SD = 1.23	M = 7.04 SD = 1.19	F [2, 27] = 2.025, *p* = 0.151

3.3.3. Summary of the Results

In this experiment, we compared three body positions and two types of DFN to explore the cognitive effects of body position on presence in VR. The results of a two-way ANOVA indicated that body position had a significant main effect, with the level of presence greater in the standing than in the half-sitting position. A one-way ANOVA also revealed that standing participants perceived a higher level of presence than those in the sitting or half-sitting positions while playing the game with infinite navigation. In contrast, no noticeable differences were found between the three body positions for the game with finite navigation. An analysis of the five factors associated with presence supported these findings, with four of these (control, visual sense, attention, and spatial presence) involved in the cognitive process of presence for the game with infinite navigation (Table 6). As shown in Figure 3, the effect of the four factors differed between the three positions, with attention in particular more strongly influenced by standing than sitting or half-sitting. This suggests that attention may be a key factor underlying the results of this research. However, it should be noted that none of the presence factors were affected by the three body positions when playing the game with finite navigation.

3.4. Discussion

Previous comparative research on body position has reported the positive influence of a standing position on various cognitive tasks (Britten et al. 2016; Caldwell et al. 2003; Isip 2014; Mehta et al. 2015; Patston et al. 2017; Rosenbaum et al. 2017; Zhou et al. 2017). Based on these studies, we expected that players in a standing position would experience a stronger sense of presence for both the finite and infinite forms of DFN. However, this study revealed that the cognitive effect of a standing position can vary with the DFN. For example, when playing a game with infinite navigation, the decision alternatives may require additional cognitive resources. In this situation, the greater attention generated when standing compared to sitting or half-sitting may have a positive influence on the cognitive processes associated with navigation decisions in the game space, eventually leading to a stronger sense of presence in VR. In contrast, higher attention levels while standing may not have a significant effect when playing a game with finite navigation. Overall, it can be concluded that the cognitive effect of a standing position is related to DFN-related decision alternatives, and we assume that attention directs the interaction between body position, presence, and spatial cognition in a VE.

Two possible explanations for the key findings in this experiment are as follows: (a) the allocation of cognitive resources, such as attention, differs depending on body position, and (b) the utilization of cognitive resources (in this case, heightened attention while standing) is contingent on the decision alternatives dictated by the DFN. We discuss our reasoning for these explanations in more detail below.

3.4.1. Presence and Body Position

Attention must be continuously engaged to maintain a standing position because "quiet standing" does not exist (Rosenbaum et al. 2017). Because "stance postural control [is] attentionally demanding" (Rosenbaum et al. 2017; Woollacott and Shumway-Cook 2002), when the participants played the VR games in a standing position, more attention was required to maintain postural stability compared to the sitting and half-sitting positions. As a result, greater attentional resources were allocated when the player was in a standing position. However, the use of these

attentional resources is affected by task complexity. Challenging tasks (such as the infinite DFN condition in the present study) demand a larger percentage of the available attentional resources, and the greater attention generated while in a standing position has a positive influence on the level of presence. In contrast, relatively easy tasks (as in the finite DFN game) do not require all of the player's attentional resources to make navigation decisions. Thus, the greater levels of attention in a standing position are not used and do not affect the sense of presence when playing a game with finite navigation. In this respect, the present experiment has verified the association between presence and attention in the context of body position when exploring a VE.

3.4.2. Degree of Freedom in Navigation and Decision-Making

Decision-making is a process in which an individual chooses a preferred option or course of action from among a set of alternatives on the basis of given criteria or strategies (Wang and Ruhe 2007; Wang et al. 2004; Wilson and Keil 2001). The requirements of the task that the user must perform will influence the amount of attentional resources that is allocated to the VE (Bystrom et al. 1999). During an engaging task, the user is likely to allocate more attentional resources to the virtual setting, thus creating the conditions for a greater sense of presence (Bystrom et al. 1999; Schultze 2010). The more challenging the task, the greater the required attentional resources (Dault et al. 2001; Palluel et al. 2010).

When a task requires a choice between a given set of options, decision-making is restricted to the options presented (Oliveira et al. 2009). According to the formulas explained in Appendix A, there were fewer than four movement options in the game with finite navigation (Bomb Hero). In this case, the alternatives given to the players did not demand additional cognitive resources, such as attention, in order to successfully play the VR game. Therefore, no cognitive effects of body position on the sense of presence were found, even though standing is known to involve more attentional resources (Donker et al. 2007; Rosenbaum et al. 2017). On the other hand, when the decision alternatives were infinite (Moss), the players may have concentrated more on the game space to determine which direction to move in. In this situation, more cognitive resources might be required because the available routes were infinite in the game space. Indeed, when a task has more decision

alternatives, players might attend to the navigation space differently, which could affect the cognitive process (Witt and Sugovic 2013). Therefore, when playing a game with infinite navigation, it appears that the greater attention generated in standing engages cognitive mechanisms that lead to more thorough item analysis and a more effective selection of task-relevant information (Smith et al. 2019), thus generating a stronger sense of presence. In this case, perception is still being influenced, but the mechanism involves attentional rather than perceptual processes (Witt and Sugovic 2013).

3.4.3. Gender Difference and Gameplay

In the present experiment, we recruited participants who had prior computer or video game experience in the action genre. As a result, most of the participants in this study were male (58 males and 4 females). The findings of past research into gender differences in computer and video games may explain the highly unbalanced gender ratio of this study. According to pervious research, computer and video games are more popular among males than among females (Barnett et al. 1997; Dominick 1984; Greenfield 1994; Lim and Reeves 2009; Sakamoto 1994), although both boys and girls can be equally skilled at using computers and computer games. (Agosto 2004; Cassell and Jenkins 1998a). Furthermore, many studies conducted in the social science field have reported that girls and young women display less interest in digital games, have less game-related knowledge, and play less frequently and for shorter durations than do boys and young men (Brown et al. 1997; Cassell and Jenkins 1998b; Hartmann and Klimmt 2006; Lucas and Sherry 2004; Wright et al. 2001).

In this experiment, we emphasized gameplay ability (intermediate and above) as a key requirement for those who wanted to participate in the experiment. For this reason, the male and female subjects in the present study had sufficient knowledge of gameplay mechanisms and the necessary skills to successfully play the VR games. Consequently, we did not notice any gender differences in terms of gaming performance. The gender effect in VR gameplay was not a focus of the current study, thus we did not attempt to balance the gender ratio of the participants. Overall, despite the asymmetrical gender ratio of the participants, this experiment revealed meaningful relationships between body position, presence, and spatial cognition when playing VR games.

3.5. Limitations

Although this experiment revealed that body position and spatial cognition have an effect on presence in VR, certain limitations should be considered. First, we tested only three body positions and two types of VR game, and the results may vary depending on the number of participants and the playing time. Future research thus needs to investigate a greater variety of body positions and other VR applications that offer different forms of spatial navigation to confirm the results of the present study. Second, though we believe that attention impacted the results of this research, we were not able to confirm the effect of specific cognitive functions because our methodology did not test specific cognitive tasks. In this regard, future research needs to apply a methodology that enables the cognitive functions involved in the association between body position, presence, and spatial cognition in VR to be identified. In addition, the effects of other cognitive functions, such as memory and executive functions, need to be explored to further the understanding of the cognitive mechanisms underlying the role of body position in VR. Third, in conjunction with subjective measures, objective approaches such as physiological (e.g., skin conductance and heart rate) and neuroscientific measures (e.g., EEG) should be pursued in order to further support the results of this research and to be more fully delineate the cognitive functions involved in the relationship between body position, presence, and spatial cognition in a VE.

Chapter 4. Experiment 2: First-Person Perspective

4.1. Experiment

4.1.1. Experimental Design and Participants

In this experiment, a 2 (body position) x 4 (locomotion method) between-subjects design was used in a laboratory setting. Ninety students (54 males and 36 females) from Seoul National University in South Korea took part in the experiment. They were randomly assigned to one of eight conditions, resulting in the following group sizes: n=12, 12, 10, and 11 for a standing position in steering + EC, steering + IC, teleportation + EC, and teleportation + IC, respectively, and n=11, 13, 10, and 11 for a sitting position in steering + EC, steering + IC, teleportation + EC, and teleportation + IC.

In this experiment, we selected two body positions (standing and sitting) and four locomotion methods based on practical considerations. In VR, users are able to choose a number of play modes, such as standing, sitting, or room-scale (i.e., walking), which can lead to different levels of bodily involvement and spatial cognition, thus influencing perceptual responses for presence (Kim et al. 2020) and cybersickness in a VE. The most natural method for moving through both the real world and a VE is physical walking (Freitag et al. 2014). However, real walking is not yet feasible because VEs commonly exceed the size of a tracked walkable space (Cherep et al. 2020), thus standing and sitting are the most common player modes used by VR users.

Most users at home remain relatively stationary and use controllers to navigate VEs due to limits in physical room space and hardware restrictions (Boletsis 2017). Of the myriad locomotion methods in VR, steering and teleportation are the most dominant in many VR applications, and these are typically implemented using a controller for home VR use. Thus, there have been a greater number of empirical studies utilizing and studying these techniques (Boletsis and Cedergren 2019).

In this experiment, we classified the locomotion methods according to the type of translation and rotation involved in the navigation motion. Steering and teleportation were used as the methods for translational movement during VE

navigation. For rotation, the options available for VR users at home when navigating a VE is to utilize their body (i.e., embodied control) or a physical device (i.e., instrumental control) to change directions. In line with this, this study tested four locomotion methods, which were a combination of the two translational approaches (steering and teleportation) and two rotational approaches (embodied and instrumental). In detail, the four locomotion methods were characterized as follows (Figure 1):

Steering + EC: participants steered themselves to change their position (i.e., translation) and turned their body to rotate.

Steering + IC: participants steered themselves to change position (i.e., translation) and used a thumbstick to rotate.

Teleportation + EC: participants teleported themselves to change position (i.e., translation) and turned their body to rotate.

Teleportation + IC: participants teleported themselves to change position (i.e., translation) and used a thumbstick to rotate.

Participants in the EC conditions were able to freely rotate their body when navigating the VE, while those in the IC conditions were given a fixed 45-degree rotation that was preset by the developer of Nature Treks (Figure 2).

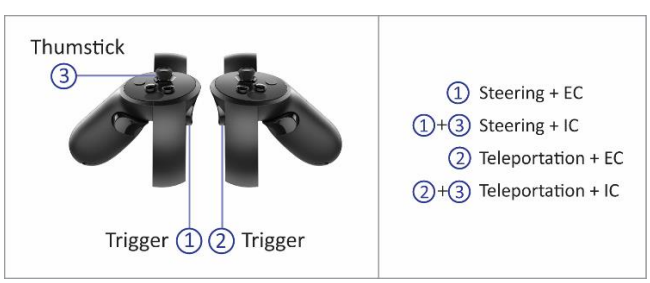


Figure 1. Navigation Mode of the Controller
(Trigger 1 and 2: Translation, Thumbstick: Rotation)

4.1.2. Stimulus Materials

An Oculus Rift HMD, two Oculus Touch controllers, and an ASUS notebook (G531GW) were used to navigate the VE. This experiment focused on the overall navigation experience relating to the locomotion methods within the VE rather than

the small-scale spatial cognitive effects of the targeted tasks. With this in mind, we selected Nature Treks, which provided the navigational experience required to meet the objectives of this research. Nature Treks does not include many visual or auditory distractions, which enabled the participants to remain focused on their navigation tasks. We also turned off the background music except for bird song in order to further eliminate any distractions during navigation. Nature Treks also offers both steering locomotion and teleportation as navigation options, which were investigated in this study. Another benefit of Nature Treks is that it provides an environment with various scales and spatial characteristics. Of the several natural environments in Nature Treks, we selected "Green Bamboo," which includes various landmarks (e.g., a house, gates, and bridges) and geographical characteristics (e.g., hills, flat terrain, and streams). Based on these landmarks and the geographical characteristics, we selected the navigation route for the participants, who would be required to employ different navigation strategies and control techniques to successfully navigate the VE (Figure 3). In particular, two bridge crossings needed more precise navigational control than the open areas.

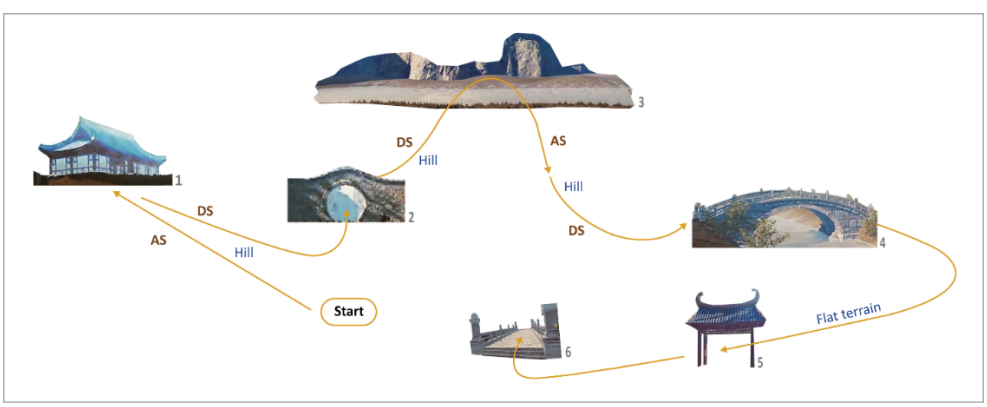


Figure 3. Navigation Route (1. House 2. Round Gate 3. Stream 4. Bridge 5. Gate 6. Bridge) (AC: Ascending, DC: Descending)

4.1.3. Experimental Setup and Process

After briefly explaining the goal of the research and the experimental process, we showed the participants a video clip of the navigation route that they would explore during the experiment. While watching the clip, we explained how to use the Touch controllers to navigate the VE. In this way, participants learned the route and the

control methods for navigation prior to training. After watching the video, the participants practiced the navigation route shown in the clip for about 15 minutes in their assigned body position and locomotion method. During navigation, the participants were only allowed to use forward translational movement using either the steering or teleportation method and the EC or IC for rotation depending on their assigned conditions. After finishing the training, the participants navigated the practiced route for approximately 10 to 15 minutes. Upon completion of the navigation, participants filled out a questionnaire regarding their feeling of presence and cybersickness. In this experiment, we adjusted the view settings depending on the body position and the height of the participant so that they experienced a similar visual perspective. The entire process took approximately 60 minutes for each participant. See Figure 4 for an overview of the experimental process.

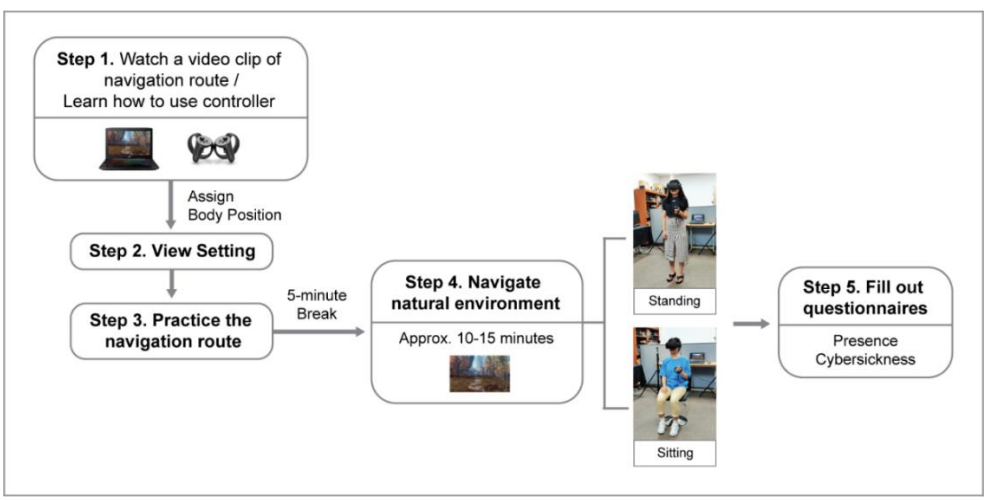


Figure 4. Experimental Process

4.1.4. Measurements

Presence and cybersickness were investigated as the dependent variables in this experiment. Twenty-seven items were used to measure the level of presence (Cronbach's alpha for standing = .94; Cronbach's alpha for sitting = .96). The items were categorized into five factors: control (five items), visual sense (four items), attention (five items), spatial presence (six items), and immersion (seven items). The items were selected from the following studies: Baños et al. (2000), Hartmann et al. (2016), Jennett et al. (2008), Weibel and Wissmath (2011), and Witmer and Singer

(1998). Responses were scored on a 10-point Likert scale (1 = not at all; 10 = very much).

The Simulator Sickness Questionnaire (SSQ) (Kennedy et al., 1993) is the most commonly used measure of cybersickness in a VE (Rebenitsch and Owen, 2016; Saredakis et al. 2020). The questionnaire contains a list of 16 symptoms, which are categorized into three SSQ subscales: nausea (seven items), oculomotor (seven items), and disorientation (seven items). Some items of the SSQ overlap across in the three subscales, thus, twenty-one items were employed to measure the symptoms of cybersickness. Participants rated the symptoms on a 4-point scale (0 = none; 1 = slight; 2 = moderate; and 3 = severe). These ratings were used to compute the scores for each of the three subscales (nausea = [1] x 9.54; oculomotor = [2] x 7.58; and disorientation = [3] x 13.92), while the total score was computed from these three subscales (total score = ([1] + [2] + [3]) x 3.74). The total score reflects the severity of the symptoms for an individual and can be used to assess the likelihood that a VR system will cause cybersickness (Davis et al. 2014; Christou and Aristidou 2017). In this experiment, all three SSQ subscales were used to measure cybersickness when navigating a VE (Cronbach's alpha for standing = .91; Cronbach's alpha for sitting = .96).

4.2. Results

Two-way analysis of variance (ANOVA) and one-way ANOVA were conducted to analyze the relative effects of the two body positions and the four types of locomotion on presence and cybersickness during VE navigation. The five factors associated with presence (control, visual sense, attention, spatial presence, and immersion) and the three SSQ subscales (nausea, oculomotor, and disorientation) connected with cybersickness were also analyzed separately using one-way ANOVA to understand how their effects differed between the body positions and the locomotion methods.

4.2.1. Presence: Two-way ANOVA

The results of the two-way ANOVA showed that there was a significant main effect for the four locomotion methods, F (3,82) = 9.00, *p* = 0.000, indicating that the sense of presence was significantly lower in the steering + IC condition (M = 6.18, SD = 1.20) than were those in the steering + EC (M = 7.00, SD = 1.23), teleportation + EC (M = 7.72, SD = 0.85), and teleportation + IC (M = 7.45, SD = 0.76) conditions. In contrast, the main effect of the two body positions was nonsignificant, F (1, 82) = 0.00, *p* = 0.997. In addition, no statistically significant interaction was found between body position and locomotion method in relation to presence, F (3, 82) = 0.07, *p* = 0.978 (Table 1). Because of the non-significant interaction effect, an additional two-way ANOVA was conducted without the interaction, which revealed a main effect for locomotion method F (3, 85) = 9.357, *p* = 0.000 (Table 2). This indicates that one of the locomotion methods differs from the other three in terms of the sense of presence

Table 1. Two-way ANOVA Results for Presence

Source	Sum of squares	df	Mean square	F	*p*-value
Body Position	1.502E-5	1	1.502E-5	0.000	0.997
Locomotion Method	30.905	3	10.302	9.001	0.000
Body Position*Locomotion Method	0.224	3	0.075	0.065	0.978
Error	93.851	82	1.145		
Total	4586.992	90			

Table 1. Two-way ANOVA Results for Presence (without interaction)

Source	Sum of squares	df	Mean square	F	*p*-value
Body Position	0.001	1	0.001	0.001	0.980
Locomotion Method	31.067	3	10.356	9.357	0.000
Error	94.074	85	1.107		
Total	4586.992	90			

4.2.2. Cybersickness: Two-way ANOVA

The two-way ANOVA yielded a main effect for the four locomotion methods, F (3,82) = 8.65, *p* = 0.000. Participants in the steering + EC (M = 69.43, SD = 52.24) and steering + IC (M = 58.64, SD = 45.08) conditions felt significantly higher cybersickness than did those in the teleportation + EC (M = 19.82, SD = 16.95) and

teleportation + IC (M = 25.33, SD = 25.07) conditions. However, there was no main effect for the two body positions F (1, 82) = 1.53, p = 0.220, nor was there an interaction between body position and locomotion method in relation to cybersickness, F (3, 82) = 0.092, p = 0.964 (Table 3). The two-way ANOVA was thus re-run without the interaction, revealing a main effect for locomotion method, F (3, 85) = 8.940, p = 0.000 (Table 4), and suggesting that the severity of cybersickness during VE navigation varies depending on the locomotion method employed.

Table 3. Two-way ANOVA Results for Cybersickness

Source	**Sum of squares**	**df**	**Mean square**	**F**	***p*-value**
Body Position	2326.520	1	2326.520	1.531	0.220
Locomotion Method	39455.239	3	13151.746	8.654	0.000
Body Position*Locomotion Method	420.173	3	140.058	0.092	0.964
Error	124615.882	82	1519.706		
Total	346305.001	90			

Table 4. Two-way ANOVA Results for Cybersickness (without interaction)

Source	**Sum of squares**	**df**	**Mean square**	**F**	***p*-value**
Body Position	2435.123	1	2435.123	1.655	0.202
Locomotion Method	39451.904	3	13150.635	8.940	0.000
Error	125036.055	85	1471.012		
Total	346305.001	90			

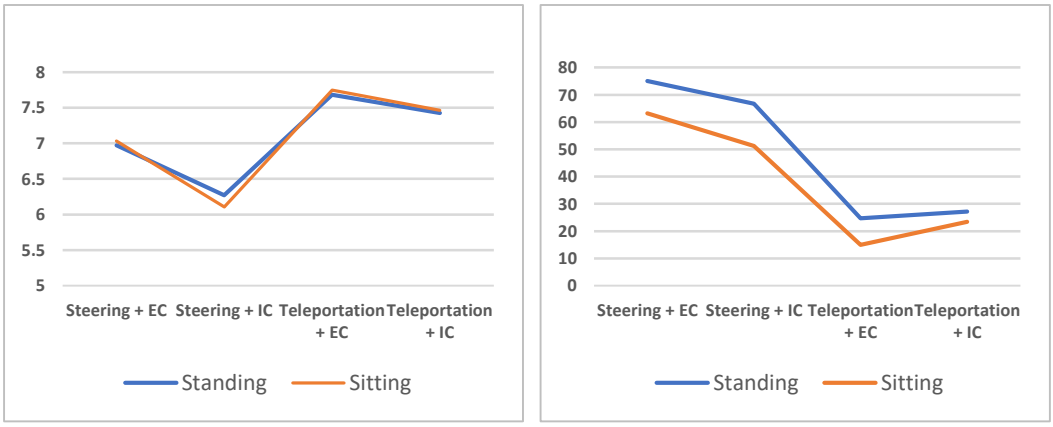


Figure 5. Interaction between body position and locomotion method
(Left: presence; Right: cybersickness)

4.2.3. Presence: One-way ANOVA

4.2.3.1. Standing Position

A one-way ANOVA revealed a meaningful effect of locomotion method on presence, F [3, 41] = 4.43, p = 0.009 (Table 5). Participants in the steering + IC condition reported a weaker sense of presence than those who were in the steering + EC, teleportation + EC, and teleportation + IC conditions. An analysis of the five factors associated with presence indicated that control and immersion affected the level of presence between the four locomotion methods (Table 6). Overall, these results confirmed the importance of translational movement and the effectiveness of physical rotation for successful navigation, suggesting that the type of locomotion method affects the sense of presence when navigating a VE.

Table 5. One-way ANOVA Results for Presence (Standing Position)

Source	M	SD	F	*p*-value
Steering + EC	6.97	1.07	4.428	0.009
Steering + IC	6.27	1.20		
Teleportation + EC	7.68	0.66		
Teleportation + IC	7.42	0.86		

Table 6. Mean and Standard Deviation for the Five Presence Factors (Standing Position)

	Steering + EC	Steering + IC	Teleportation + EC	Teleportation + IC	Results
Control	M = 7.31 SD = 0.70	M = 4.37 SD = 1.36	M = 7.76 SD = 0.85	M = 7.33 SD = 1.37	F [3, 41] = 22.777, p = 0.000
Visual Sense	M = 6.71 SD = 1.03	M = 6.48 SD = 1.67	M = 7.23 SD = 0.69	M = 7.30 SD = 1.40	F [3, 41] = 1.103, p = 0.359
Attention	M = 6.75 SD = 1.52	M = 7.03 SD = 1.48	M = 7.66 SD = 0.86	M = 7.58 SD = 1.14	F [3, 41] = 1.273, p = 0.296
Spatial Presence	M = 6.96 SD = 1.92	M = 6.97 SD = 1.61	M = 7.67 SD = 1.27	M = 7.50 SD = 1.14	F [3, 41] = 0.620, p = 0.606
Immersion	M = 7.12 SD = 1.12	M = 6.50 SD = 1.23	M = 8.10 SD = 0.79	M = 7.42 SD = 1.00	F [3, 41] = 4.284, p =0.010

4.2.3.2. Sitting Position

There was a statistically significant effect of locomotion method on presence, F [3, 41] = 4.65, p = 0.007 (Table 7). The level of presence was lower for the participants in the steering + IC condition than those in the steering + EC, teleportation + EC,

and teleportation + IC conditions. An analysis of presence based on the five factors revealed that control, visual sense, and immersion influenced the sense of presence between the four locomotion methods (Table 8). As with the standing position, these results suggest that presence is related to the locomotion method rather than body position during VE navigation.

Table 7. One-way ANOVA Results for Presence (Sitting Position)

Source	M	SD	F	*p*-value
Steering + EC	7.03	1.44	4.651	0.007
Steering + IC	6.10	1.25		
Teleportation + EC	7.75	1.04		
Teleportation + IC	7.47	0.68		

Table 8. Mean and Standard Deviation for the Five Presence Factors (Sitting Position)

	Steering + EC	Steering + IC	Teleportation + EC	Teleportation + IC	Results
Control	M = 7.45 SD = 1.36	M = 4.71 SD = 1.68	M = 7.66 SD = 1.18	M = 7.38 SD = 1.11	F [3, 41] = 12.737, p = 0.000
Visual Sense	M = 7.14 SD = 1.66	M = 6.06 SD = 1.44	M = 7.60 SD = 1.11	M = 7.25 SD = 1.07	F [3, 41] = 2.907, p = 0.046
Attention	M = 7.16 SD = 1.56	M = 6.78 SD = 1.62	M = 8.04 SD = 1.26	M = 7.56 SD = 0.75	F [3, 41] = 1.774, p = 0.167
Spatial Presence	M = 6.38 SD = 1.99	M = 6.58 SD = 1.63	M = 7.68 SD = 0.92	M = 7.30 SD = 0.69	F [3, 41] = 1.982, p = 0.132
Immersion	M = 7.03 SD = 1.39	M = 6.40 SD = 1.53	M = 7.76 SD = 1.15	M = 7.83 SD = 0.61	F [3, 41] = 3.525, p =0.023

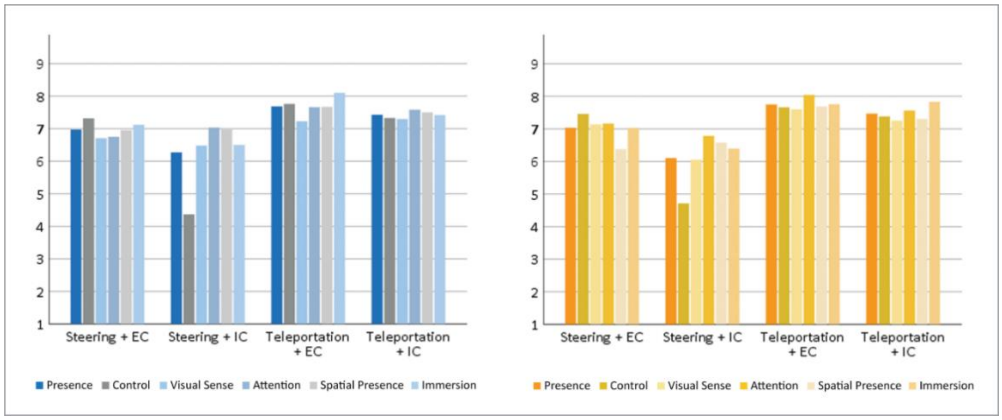


Figure 6. Mean Likert scale score for presence and its five associated factors.
(Left: standing; Right: sitting)

4.2.4. Cybersickness: One-way ANOVA

4.2.4.1. Standing Position

A one-way ANOVA found that locomotion method had a significant effect on cybersickness F [3, 41] = 7.612, p = 0.000 (Table 9). Participants in the steering conditions reported a higher level of cybersickness than those who were in the teleportation conditions. Furthermore, an analysis of the three SSQ subscales associated with cybersickness indicated that all of the subscales (nausea, oculomotor, and disorientation) were associated with cybersickness across the four locomotion methods (Table 9). Overall, these findings illustrate the effects of locomotion method on cybersickness, suggesting that participants in the steering conditions felt stronger cybersickness than those in the teleportation conditions.

Table 9. One-way ANOVA Results for Cybersickness (Standing Position)
(Mean and Standard Deviation for the Total Score and Three SSQ Subscales**)**

	Steering + EC	**Steering + IC**	**Teleportation + EC**	**Teleportation + IC**	**Results**
Nausea	M = 60.42 SD =52.30	M = 40.55 SD = 31.80	M = 9.54 SD = 8.99	M = 16.48 SD = 14.84	F [3, 41] = 5.637, p = 0.002
Oculomotor	M = 49.27 SD = 26.95	M = 49.90 SD = 25.34	M = 23.50 SD = 14.05	M = 22.74 SD = 13.56	F [3, 41] = 5.757, p = 0.002
Disorientation	M = 100.92 SD = 49.70	M = 97.44 SD = 52.08	M = 34.80 SD = 30.25	M = 35.43 SD = 31.96	F [3, 41] = 8.334, p = 0.000
Total Score	M = 75.11 SD = 43.80	M = 66.70 SD = 36.46	M = 24.68 SD =14.98	M = 27.20 SD =19.00	F [3, 41] = 7.612, p = 0.000

4.2.4.2. Sitting Position

The symptoms of cybersickness were stronger in the steering conditions than in the teleportation conditions, F [3, 41] = 2.76, p = 0.054 (Table 10). In addition, analysis of the three SSQ subscales for cybersickness showed that oculomotor and disorientation were related to the level of cybersickness across the four locomotion methods (Table 10). This indicates that cybersickness is associated with the locomotion method, while body positions may not be linked to the symptoms of cybersickness.

Table 10. One-way ANOVA Results for Cybersickness (Sitting Position)
(Mean and Standard Deviation for the Total Score and Three SSQ Subscales)

	Steering + EC	Steering + IC	Teleportation + EC	Teleportation + IC	Results
Nausea	M = 39.89 SD = 47.67	M = 32.29 SD = 41.86	M = 10.49 SD = 18.24	M = 13.00 SD = 17.73	F [3, 41] =1.865, p = 0.151
Oculomotor	M = 48.93 SD = 42.93	M = 39.65 SD = 37.54	M = 11.37 SD = 11.99	M = 19.98 SD = 21.51	F [3, 41] = 3.211, p = 0.033
Disorientation	M = 87.32 SD = 84.46	M = 70.67 SD = 69.94	M = 19.49 SD = 24.73	M = 31.64 SD = 52.49	F [3, 41] = 2.785, p = 0.053
Total Score	M = 63.24 SD = 61.74	M = 51.21 SD = 52.17	M = 14.96 SD = 18.15	M = 23.46 SD = 30.84	F [3, 41] = 2.763, p = 0.054

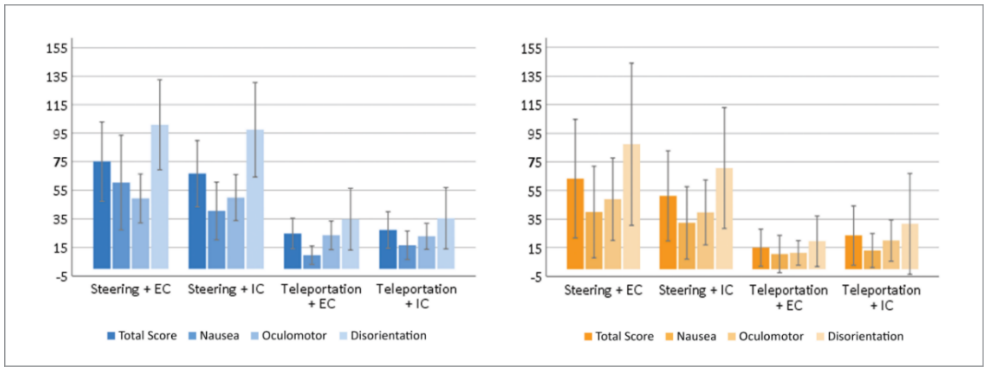


Figure 7. Mean Likert scale score for cybersickness and its three SSQ subscales.
(Left: standing; Right: sitting)
(Error bars represent 95% confidence intervals)

4.2.5. Summary of the Results

In this experiment, we compared two body positions and four locomotion methods to explore the relative effects of body position and locomotion method on presence and cybersickness in VR. The results of two-way ANOVA indicated that the locomotion method had a significant main effect on both presence and cybersickness, with the sense of presence lower in the steering + IC condition than in the other three conditions and cybersickness significantly higher for the steering conditions than for the teleportation conditions. In addition, one-way ANOVA showed that participants in the steering + IC condition reported a weaker sense of presence than those in the steering + EC, teleportation + EC, and teleportation + IC conditions in both the standing and sitting positions. An analysis of the five factors (control, visual sense, attention, spatial presence, and immersion) associated with presence revealed that control and immersion were associated with the cognitive process of presence in the

standing position, while the sense of presence was affected by control, visual sense, and immersion in the sitting position. The total cybersickness score indicated that the participants in the steering conditions felt stronger cybersickness than those in the teleportation conditions in both the standing and sitting positions, which confirmed that teleportation generated fewer symptoms of cybersickness. Analysis of the three subscales of cybersickness (nausea, oculomotor, and disorientation) revealed that all three factors influenced the severity of cybersickness in the standing position, while oculomotor and disorientation were related to the level of cybersickness in the sitting position.

4.3. Discussion

The primary goals of this experiment were to strengthen the understanding of the mechanisms underlying presence and cybersickness in relation to body position and locomotion method when navigating VEs. Overall, the results of this experiment showed that the two body positions (standing and sitting) had no significant effect on presence and cybersickness, while we found a meaningful association between the four locomotion methods (steering + EC, steering + IC, teleportation + EC, and teleportation + IC), presence, and cybersickness.

All behavior involves control (Carver and Scheier 1998; Marken 1988; 2002; McClelland and Fararo 2006; Powers et al. 2011), including navigation in VEs. Control is the process of acting on the world that we perceive to make it the way we want it to be and to keep it that way (Powers 2009). Presence may be diminished by the reliance on inappropriate interactive techniques (Slater et al. 1998), and effective virtual locomotion should promote a strong experience of presence (Bowman et al. 1997; Clifton and Palmisano 2019a). In this study, we speculate that control plays a key role in influencing the perceptual process of presence during VE navigation based on the analysis results for the five factors associated with presence (control, visual sense, attention, spatial presence, and immersion).

Presence was significantly lower for the participants in the steering + IC condition due to the limited DFN, which is related to both translational and rotational movement when navigating VEs. During navigation in the VE, the steering + IC condition showed the difficulties of maneuvering through a narrow space (i.e., the two bridges), which requires more precise control of translational and rotational movement for successful navigation. Participants in the steering + IC condition used the same translational movement (i.e., steering) as the steering + EC condition and the same rotational movement (i.e., instrumental control) as the teleportation + IC condition. However, the rotational method in the steering + EC (i.e., embodied control) and the translational movement in the teleportation + IC (i.e., teleportation) affected the DFN, consequently leading to a different effect on presence when compared to the steering + IC condition. In this respect, we assume that the sense of presence is associated with the translational or rotational degrees of freedom for the locomotion method when navigation a VE. We discuss our reasoning for this in more detail below.

For cybersickness, participants in the steering conditions felt stronger simulation sickness than those in the teleportation conditions when navigating the VE. However, we found no difference in cybersickness between standing and sitting; thus, it can be speculated that cybersickness in this study was related to sensory conflict rather than postural instability. Furthermore, there was a negative correlation between presence and cybersickness during VE navigation, which suggested that participants who reported higher presence felt less cybersickness.

4.3.1. Presence

4.3.1.1. Presence and Locomotion Methods

Presence is a highly activity-dependent and context-dependent process that is both embodied and environmentally and temporally embedded, integrating multimodal sensory data, ongoing actions and intentions, and cognitive and emotional processes (Ijsselsteijn 2002). Presence depends on the suitable integration of elements relevant to the user's movement and perception, to their actions, and to their conception of the overall situation (Carassa et al. 2004). Presence is tied to successfully supported actions within an environment (Zahorik and Jenison 1998). The actions that are represented mentally are bodily actions within the depicted space and are functionally related to navigation, the manipulation of objects, or the interaction with other agents (Schubert et al. 2001).

When navigating through the world, we experience both translation (changes in position) and rotation (changes in orientation) (Sunkara et al. 2016). The motion trajectory through space can be complex; it is typically composed of a combination of translational and rotational components, rather than only one of them (Cheng and Gu 2018). In addition, the type of movement required to move through space depends on the scale of that space (Irish and Ramanan 2019) and the environmental characteristics.

The bodily and cognitive activity of the user – their interaction with the virtual world on various levels – is the true source of presence (Schubert et al. 1999; Steuer 1992). Body-based senses facilitate the acquisition of accurate spatial knowledge about the environment (Campos et al. 2010; Jürgens et al. 1999; Yardley and Higgins 1998; Waller and Hodgson 2013). Indeed, there is some evidence that, especially for

acquiring accurate information about turns and orientation, body-based senses may be necessary (Bakker et al. 1999; Klatzky et al. 1998; Ruddle and Lessels 2009; Waller and Hodgson 2013). Researchers have found using body rotation can lead to an improvement in performance in navigational tasks compared to visual-only rotation (Grechkin and Riecke 2014; Klatzky et al. 1998; Kitson et al. 2015). In addition, physical rotational cues might become more important under high cognitive loads or with higher task difficulty due to the limited availability of visual (re-)orienting cues (Riecke et al. 2010).

Being able to become successfully oriented in VR appears to be essential to completing many tasks (Kitson et al. 2015), and physical turning allows for reflexive orientation to occur (Templeman et al. 1999). Participants in the steering + IC condition employed the same translational movement (i.e., steering) as the participants in the steering + EC condition. The steering in this study was linear and continuous, which only allowed fixed translational movement for navigation resulting in a lower DFN. However, the two rotational methods (i.e., EC and IC) used in the steering conditions affected navigation performance, thus, the effect on presence differed between the steering + EC and steering + IC conditions. Steering + EC applied physical rotation, which enabled participants to set the correct angle and allowed for precise translational movement in the successful navigation of various spatial scales and environmental characteristics. In contrast, participants in the steering + IC condition were not able to execute precise rotation due to the fixed rotational angle (45°), which significantly increased the control errors in selecting the correct direction for effective translational movement via steering during VE navigation. In particular, participants in the steering + IC condition exhibited significantly lower navigation performance when maneuvering through a narrow space (i.e., the two bridges) in the VE. Overall, we confirmed the effectiveness of physical rotation for successful navigation and its relationship with the sense of presence in VR.

While rotational information has been shown to be important for various spatial tasks (Presson and Montello 1994; Rieser 1989; Mou et al. 2004; Ruddle and Lessels 2006), the benefit of the translational component is still unclear, with mixed results reported in previous work (Nguyen-Vo et al. 2019). Participants in the steering + IC and teleportation + IC conditions used the same rotation method (fixed 45° rotation),

which significantly limited the degrees of freedom for rotation when navigating a VE. However, unlike the steering + IC condition, participants in the teleportation + IC condition exhibited similar navigation performance to the steering + EC and teleportation + EC conditions, despite the use of IC rotation; as a result, the level of presence did not decrease. Teleportation is a non-linear and discontinuous motion, which allows the user to freely point in every (or almost every) place in the VE and to instantly change their position to the selected point (Soler-Domínguez et al. 2020). We speculate that the motion type of teleportation allows the participant to select the correct location for the successful translational movement after rotating 45°. On the other hand, participants in the steering + IC condition used restricted translation (i.e., steering: linear and continuous) in addition to fixed 45° rotation when navigating the VE. These constrained translation and rotation methods considerably decreased the degrees of freedom for both translational and rotational movement, which greatly affected navigation performance, consequently, leading to a weaker sense of presence during VE navigation. In this respect, this study highlights the importance of translational movement for successful navigation and presence in VR.

4.3.1.2. Presence and Body Position

Successful spatial navigation depends on many cognitive processes including memory, attention, and the perception of direction and distance (Epstein et al., 2017; Irish and Ramanan 2019). Previous research on cognitive functions has suggested that attention is closely associated with the cognitive processes underlying body position and presence (Kim et al. 2020). Postural control is known to recruit attentional resources (Barra et al. 2015; Kerr et al. 1985), and the interaction between posture and cognition is related to the allocation of attention (Barra et al. 2015; Dault et al. 2001; Redfern et al. 2004; Siu et al. 2009; Yardley et al. 2001). Presence may vary depending in part on the allocation of attentional resources, with greater allocation leading to a heightened sense of presence (Witmer and Singer 1998). As a consequence, presence appears to be a matter of focus (Fontaine 1992; Witmer and Singer 1998) and can be achieved by allocating attentional resources (Carassa et al. 2004).

Attention must be continuously engaged when maintaining a standing position because “quiet standing” does not exist (Rosenbaum et al. 2017). Thus, participants

in a standing position likely allocated more attention to maintain their postural stability compared to those in the sitting position. However, the attentional demands of balance control vary depending on the complexity of the task and the type of secondary task being performed (Woollacott and Shumway-Cook 2002). In this study, we did not find significant effects of body position on presence during VE navigation. According to a past study, heightened attention in a standing position was useful for challenging tasks, while no effect of increased attention while standing was found for relatively easy tasks when navigating a VE (Kim et al. 2020). In line with this, we assume that the navigational difficulties in this research were not high, thus the participants did not require more cognitive involvement to successfully navigate the VE. In this respect, additional cognitive resources (e.g., attention) allocated for the standing position were not used and did not affect the sense of presence when navigating the VE.

4.3.2. Cybersickness

4.3.2.1. Cybersickness and Locomotion Method

Steering is the continuous specification of the direction of motion (Bowman et al. 2001), while teleportation allows a user to select a location on the ground plane and be immediately transported to that location without any self-motion cues (Cherep et al. 2020). One major difference between these is that steering locomotion typically induces vection (Palmisano et al. 2015; Clifton and Palmisano 2019a), which may increase the severity of cybersickness. In contrast, teleportation (which does not have accompanying visual motion) is generally less provocative than steering locomotion (which provides continuous, global visual motion stimulation) (Bozgeyikli et al. 2016; Christou and Aristidou 2017; Frommel et al. 2017; Habgood et al. 2018; Ragan et al. 2012; Vlahovic et al. 2018; Clifton and Palmisano 2019a; Clifton and Palmisano 2019b) during VE navigation. In line with these studies, the results of this research confirmed that participants in the steering conditions felt stronger cybersickness than those in the teleportation conditions in both the standing and sitting positions. This outcome clearly establishes the advantage of using teleportation over steering locomotion in terms of reducing cybersickness. Overall

teleportation may provide a more effective way of navigating VEs for users who are more prone to cybersickness (Clifton and Palmisano 2019b).

Sensory conflict (i.e., visual–vestibular) has been identified one of the main causes of cybersickness (Keshavarz et al. 2014b; Reason and Brand 1975; Widdowson et al. 2019), and it has been proposed that illusions of self-motion (vection) produce cybersickness in VR (Reason and Brand 1975). Consistent with the general predictions of most sensory conflict theories, steering locomotion would be expected to generate more visual–vestibular conflict than teleportation (Clifton and Palmisano 2019a). In this study, steering locomotion induced greater self-motion than teleportation, consequently increasing the severity of cybersickness, while no meaningful relationship was found between body position and cybersickness. In this regard, the effects of steering locomotion on cybersickness in this research might be explained by sensory conflict. As a whole, we confirmed the positive correlation between cybersickness and self-motion when navigating a VE.

4.3.2.2. Cybersickness and Body Position

Postural instability occurs when VR can undermine an individual's postural control mechanisms, inducing cybersickness (Riccio and Stoffregen 1991). According to the postural instability theory, sitting appears to be the better position in which to reduce cybersickness symptoms because it would reduce the demands on postural control (LaViola 2000). However, previous studies have indicated that a sitting position does not decrease the severity of cybersickness (Dennison et al. 2016; Kim et al. 2005) or have found that cybersickness occurs in both standing and sitting positions (Merhi et al. 2007; Clifton and Palmisano 2019a). It should be noted that postural instability of the head or torso can contribute to cybersickness in the seated observers (Stoffregen et al. 2013; Villard et al. 2008; Clifton and Palmisano 2019a). Overall, this study found no significant difference in cybersickness between body positions (i.e., standing and sitting), thus postural instability theory may not link to the symptoms of cybersickness in this research.

4.4. Limitations

This experiment revealed the significant effects of locomotion method on presence and cybersickness in VR. However, certain limitations should be considered. First, we examined only four locomotion methods, thus, future research needs to examine more varied locomotion methods to further the understanding of the relationship between locomotion method, presence, and cybersickness in a VE. Second, we used only one type of environment (i.e., a large-scale natural environment). Therefore, future research needs to apply various spatial scales and environmental characteristics, such as small-scale (e.g., rooms) and large-scale environments (e.g., a building or city) to broaden the knowledge of the association between space, navigation, and locomotion method in VR. Third, we were not able to delineate the cognitive functions involved in the relationship between locomotion method, presence, and cybersickness during VE navigation because our methodology did not investigate specific cognitive tasks. In this regard, future research needs to apply a methodology that identifies cognitive functions (e.g., execution, attention, memory, and perception) involved in the association between locomotion method, presence, and cybersickness during VE navigation. Fourth, in conjunction with subjective measures, objective approaches should be pursued in order to further the understanding of the mechanisms underlying the interconnection between locomotion method, presence, and cybersickness in VR. Objective measures of presence include physiological (e.g., skin conductance and heart rate), behavioral, and neuroscientific measures (e.g., Baumgartner et al. 2008 and Clemente et al. 2013 for fMRI and Baumgartner et al. 2006 and Clemente et al. 2014 for EEG) which show potential for identifying neural correlates of presence in VR (Weech et al. 2019). For cybersickness, objective measures may include the analysis of physiological markers (Kim et al. 2005; Weech et al. 2019), such as respiration rate (Kim et al. 2005; Dennison et al. 2016), heart rate (Nalivaiko et al. 2015; Cowings et al.1986), and skin conductance (Hu et al. 1991; Miller et al. 1993; Golding 1992; Gavgani et al., 2017).

Chapter 5. Conclusion

5.1. Summary of Findings

In this dissertation, two separate experiments were conducted based on viewpoint within VR (i.e., third-person and first-person perspectives) to extend the understanding of the effects of body position in relation to spatial cognition, locomotion method, presence, and cybersickness in a VE.

The study results of Experiment 1, which investigated the third-person perspective, suggest that cognitive activity related to attention orchestrates the cognitive processes associated with body position, spatial cognition, and presence, consequently leading to an integrated sense of presence in VR. Specifically, the outcomes of this experiment indicate that the cognitive effect of body position on presence is associated with the DFN within a VE. According to the results of both one- and two-way ANOVAs, standing had the most significant effect on presence of the three body positions that were investigated in this experiment. In this context, the effects of standing reported here add to a growing list of bodily states, postures, and afforded actions that have been shown to provoke changes in vision and cognition (Smith et al. 2019). Overall, this experiment suggests that the cognitive influence of presence is body-dependent in the sense that mental and brain processes rely on or are affected by the physical body (Wilson and Foglia 2011; Zhou et al. 2017).

The overall outcomes of Experiment 2, which assessed the first-person perspective in VR, indicate that presence and cybersickness are associated with the locomotion method employed. This experiment reveals that the DFN for translation and rotation is related to successful navigation and affects the sense of presence when navigating a VE. In accordance with previous studies (Ruddle and Lessels 2009; Riecke et al. 2010; Pausch et al. 1997; Moghadam et al. 2018), this study clearly confirmed the positive effects of body-based rotation (i.e., EC) and the significance of non-continuous translational movement (i.e., teleportation) in the generation of presence during VE navigation. This research also suggests that the use of steering locomotion, which is a form of continuous motion, increases self-motion when

navigating a VE, resulting in stronger cybersickness when compared to the use of teleportation, which is a non-continuous motion.

According to the results, no significant effects of body position on presence were found in experiment 2. It is assumed that this may have been due to the task difficulty for this experiment. Past research has revealed that heightened attention in a standing position is useful for challenging tasks when navigating a VE, while this has no effect for relatively easy tasks (Kim et al. 2020). According to previous studies, maintaining an upright stance may tax cognitive factors, such as attentional processes, when the standing conditions are challenging or when attentional interference between postural control and cognitive processes is high (Huxhold et al. 2006; Wollacott 2000). In addition, the degree of attention or cognitive involvement required to control posture increases with task difficulty (Donker et al. 2007), and the attentional demands of balance control vary depending on the complexity of the task and the type of secondary task being performed (Woollacott and Shumway-Cook 2002). Taken together, it can be speculated that the navigational difficulties in experiment 2 were not high, thus the participants did not require additional cognitive involvement to successfully navigate the VE. Therefore, it appears that additional cognitive resources (e.g., attention) allocated for the standing position were not used because the task difficulty was low; consequently, this position did not affect the sense of presence when navigating the VE.

Taken together, the results of these experiments provide insights into the association between body position, spatial cognition, locomotion method, presence, and cybersickness in a VE. In addition, the present study adds to the understanding of the cognitive influence of navigation in third- and first-person perspectives in VEs.

5.2. Future Research Direction

This dissertation provides a better understanding of the mechanisms underlying the emergence of presence and cybersickness in relation to body position, spatial cognition, and locomotion method in a VE. However, the precise nature of this relationship should continue to be explored, particularly the cognitive effects of VE

navigation from a first-person perspective. Navigating environments using a first-person perspective is the dominant mode in real world, thus, it is important to continue to investigate the association between the body, spatial cognition, and locomotion method for VE navigation from a first-person perspective. A particularly interesting area of future research would be to examine the effects of the vestibular system of self-motion on spatial cognition and cybersickness. Overall, future navigation research into the first-person perspective would further the knowledge of the cognitive process of embodiment when navigating a VE, consequently contributing not only to VR research but also to the development of VR technologies.

References

Ádám G (1980) Perception of the mechanics of body position. Perception, consciousness, memory, Boston, Springer, pp 83-93. https://doi.org/10.1007/978-1-4684-2073-9_4

Agosto D (2004) Girls and gaming: A summary of the research with implications for practice. Teacher Librarian, 31(3):1-8.

Ahmad M (2019) Categorizing game design elements into educational game design fundamentals. IntechOpen. https://doi.org/10.5772/intechopen.89971

Álvarez R, Duarte F (2017) Spatial design and placemaking: Learning from video games. Space and Culture, 21(3), 208–232. https://doi.org/10.1177/1206331217736746

Al Zayer M, MacNeilage P, Folmer E (2020) Virtual locomotion: a survey. IEEE Trans Vis Comput Graph 26(6):2315-2334. https://doi.org/10.1109/TVCG.2018.2887379

Arcioni B, Palmisano S, Apthorp D, Kim J (2018) Postural stability predicts the likelihood of cybersickness in active HMD-based virtual reality. Displays 58:3–11. https://doi.org/10.1016/j.displa.2018.07.001

Arns LL, Cerney MM (2005) The relationship between age and incidence of cybersickness among immersive environment users. In: Proceedings of IEEE VR 2005. Virtual Reality, pp 267-268. https://doi.org/10.1109/VR.2005.1492788

Avraamides MN, Klatzky RL, Loomis JM, Golledge RG (2004) Use of cognitive versus perceptual heading during imagined locomotion depends on the response mode. Psychol Sci 15(6):403–408. https://doi.org/10.1111/j.0956-7976.2004.00692.x

Azmandian M, Grechkin T, Rosenberg ES (2017) An evaluation of strategies for two-user redirected walking in shared physical spaces. In: Proceedings of 2017 IEEE Virtual Reality (VR), pp 91–98. https://doi.org/10.1109/VR.2017.7892235

Bailey J, Bailenson JN, Won AS, Flora JA, Armel KC (2012). Presence and memory: immersive virtual reality effects on cued recall. In: Proceedings of the international society for presence research annual conference, Philadelphia, PA.

Bakker NH, Werkhoven PJ, Passenier PO (1999) The effects of proprioceptive and visual feedback on geographical orientation in virtual environments. Presence Teleoperators Virtual Environ 8(1):36–53. https://doi.org/10.1162/105474699566035

Balakrishnan B, Sundar SS (2011) Where am I? How can I get there? Impact of navigability and narrative transportation on spatial presence. Hum Comput Interact 26(3):161-204.

Baños RM, Botella C, Garcia-Palacios A, Villa H, Perpiña C, Alcañiz M (2000) Presence and reality judgment in virtual environments: A unitary construct? CyberPsychol Behav 3(3):327– 335. https://doi.org/10.1089/10949310050078760

Barnett MA, Vitaglione GD, Harper KG, Quackenbush SW, Steadman LA, Valdez BS (1997) Late adolescents' experiences with and attitudes toward videogames. J Appl Soc Psychol 27(15):1316–1334. https://doi.org/10.1111/j.1559-1816.1997.tb01808.x

Barfield W, Hendrix C (1995) The effect of update rate on the sense of presence within virtual environments. Virtual Real 1(1):3-15. https://doi.org/10.1007/BF02009709

Barfield W, Weghorst S (1993) The sense of presence within virtual environments: a conceptual framework. In: Salvendy G, Smith M (eds) Human-computer interaction: software and hardware interfaces. Elsevier Publisher, pp 699–704.

Barra J, Auclair L, Charvillat A, Vidal M, Pérennou DA (2015) Postural control system influences intrinsic alerting state. Neuropsychology 29(2):226–234. https://doi.org/10.1037/neu0000174

Baumgartner T, Speck D, Wettstein D, Masnari O, Beeli G, Jäncke L (2008) Feeling present in arousing virtual reality worlds: prefrontal brain regions differentially orchestrate presence experience in adults and children. Front Hum Neurosci 2:8. https://doi.org/10.3389/neuro.09.008.2008

Baumgartner T, Valko L, Esslen M, Jäncke L (2006) Neural correlate of spatial presence in an arousing and noninteractive virtual reality: an EEG and psychophysiology study. CyberPsychol Behav 9(1):30–45. https://doi.org/10.1089/cpb.2006.9.30

Bernstein N (1967) The co-ordination and regulation of movements. Pergamon Press, New York.

Berthoz A, Lacour M, Soechting JF, Vidal PP (1979) The role of vision in the control of posture during linear motion. Prog Brain Res 50:197–209. https://doi.org/10.1016/S0079-6123(08)60820-1

Biocca F (1997) The cyborg's dilemma: Progressive embodiment in virtual environments. J Comput Mediat Commun 3(2). https://doi.org/10.1111/j.1083-6101.1997.tb00070.x

Boletsis C (2017) The new era of virtual reality locomotion: a systematic literature review of techniques and a proposed typology. Multimo Technol Interact 1(4):24. https://doi.org/10.3390/mti1040024

Boletsis C, Cedergren JE (2019) VR Locomotion in the new era of virtual reality: An empirical comparison of prevalent techniques. Adv Hum Comput Interact. https://doi.org/10.1155/2019/7420781

Bolte B, Steinicke F, Bruder G (2011) The jumper metaphor: an effective navigation technique for immersive display setups. In Proceedings of virtual reality international conference (VRIC 2011).

Bonato F, Bubka A, Palmisano S, Phillip D, Moreno G (2008) Vection change exacerbates simulator sickness in virtual environments. Presence Teleoperators Virtual Environ 17(3):283–292. https://doi.org/10.1162/pres.17.3.283

Bond D, Nyblom M (2019) Evaluation of four different virtual locomotion techniques in an interactive environment. Thesis.

Bos JE, Bles W, Groen EL (2008) A theory on visually induced motion sickness. Displays, 29(2):47–57. https://doi.org/10.1016/j.displa.2007.09.002

Boulic R, Maupu D, Thalmann D (2009) On scaling strategies for the full-body postural control of virtual mannequins. Interacting with Computers 21:11–25. https://doi.org/10.1016/j.intcom.2008.10.002

Bowman DA, Davis ET, Hodges LF, Badre AN (1999) Maintaining spatial orientation during travel in an immersive virtual environment. Presence Teleoperators Virtual Environ 8(6) 618–631. https://doi.org/10.1162/105474699566521

Bowman DA, Koller D, Hodges, LF (1997) Travel in immersive virtual environments: an evaluation of viewpoint motion control techniques. In: Proceedings of IEEE 1997 virtual reality annual international symposium (VRAIS), pp 45–52. https://doi.org/10.1109/VRAIS.1997.583043

Bowman DA, Koller D, Hodges, LF (1998) A methodology for the evaluation of travel techniques for immersive virtual environments. Virtual Real 3:120-131. https://doi.org/10.1007/BF01417673

Bowman DA, Kruijff E, LaViola JJ, Poupyrev I (2001). An introduction to 3-D user interface design. Presence Teleoperators Virtual Environ 10(1):96-108. https://doi.org/10.1162/105474601750182342

Bowman DA, Kruijff E, LaViola JJ, Poupyrev I (2004) 3D user interfaces: theory and practice. Addison Wesley Longman Publishing, California, Redwood.

Bozgeyikli E, Raij A, Katkoori S, Dubey R (2016) Point & teleport locomotion technique for virtual reality. In: Proceedings of the 2016 annual symposium on computer–human interaction in play (CHI PLAY' 16). ACM, pp 205–216. https://doi.org/10.1145/2967934.2968105

Bozgeyikli E, Raij A, Katkoori S, Dubey R (2019) Locomotion in virtual reality for room scale tracked areas. Int J Hum Comput Stud 122:38-49. https://doi.org/10.1016/j.ijhcs.2018.08.002

Bridgeman B, Hoover M (2008) Processing spatial layout by perception and sensorimotor interaction. J of Exp Psychol 61(6):851–859. https://doi.org/10.1080/17470210701623712

Britten L, Shire KA, Coats RO, Astill S (2016) The effect of standing desks on manual control in children and young adults. Gait Posture 48:42-46. https://doi.org/10.1016/j.gaitpost.2016.04.027

Brooks FP (1986) Walkthrough—a dynamic graphics system for simulating virtual buildings. In: Proceedings of the 1986 workshop on interactive 3D graphics (I3D' 86). ACM, pp 9–21. https://doi.org/10.1145/319120.319122

Brown RM, Hall LR, Holtzer R, Brown SL, Brown NL (1997) Gender and video game performance. Sex Roles, 36, 793–812. https://doi.org/10.1023/A:1025631307585

Bruder G, Lubos P, Steinicke F (2015) Cognitive resource demands of redirected walking. IEEE Trans Vis Comput Graph 21(4): 539–544. https://doi.org/10.1109/TVCG.2015.2391864

Bystrom K, Barfield W, Hendrix CM (1999) A conceptual model of the sense of presence in virtual environments. Presence Teleoperators Virtual Environ 8(2): 241-244. https://doi.org/10.1162/105474699566107

Caldwell JA, Prazinko B, Caldwell JL (2003) Body posture affects electrocenphalographic activity and psychomotor vigilance task performance in sleep-deprived subjects. Clin Neurophysiol 114(1):23–31. https://doi.org/10.1016/S1388-2457(02)00283-3

Calvert G, Spence C, Stein BE (eds) (2004) The handbook of multisensory processes. MIT Press, Massachusetts, Cambridge.

Campos JL, Siegle JH, Mohler BJ, Bülthoff HH, Loomis JM (2009) Imagined self-motion differs from perceived self-motion: evidence from a novel continuous pointing method. PLOS ONE 4(11): e7793. https://doi.org/10.1371/journal.pone.0007793

Campos JL, Byrne P, Sun HJ (2010) The brain weights body-based cues higher than vision when estimating walked distances. Eur J Neurosci 31(10):1889–1898. https://doi.org/10.1111/j.1460-9568.2010.07212.x

Carassa A, Morganti F, Tirassa M (2004) Movement, action, and situation: presence in virtual environments. In: Proceedings of the international workshop on presence (Presence 2004), pp 7-12.

Carver CS, Scheier MF (1998) On the self-regulation of behavior. Cambridge University Press, Cambridge, United Kingdom.

Cassell J, Jenkins H (1998a) Chess for girls? Feminism and computer games. In: J. Cassell & H. Jenkins (eds) From barbie to mortal kombat: Gender and computer games (pp. 2–45). Cambridge, MA: The MIT Press.

Cassell J, Jenkins H (eds) (1998b) From barbie to mortal kombat: Gender and computer games. Cambridge, MA: MIT Press.

Chance SS, Gaunet F, Beall AC, Loomis JM (1998) Locomotion mode affects the updating of objects encountered during travel: The contribution of vestibular and proprioceptive inputs to path integration. Presence Teleoperators Virtual Environ 7(2):168–178. https://doi.org/10.1162/105474698565659

Chang CH, Pan WW, Tseng LY, Stoffregen TA (2012) Postural activity and motion sickness during video game play in children and adults. Exp Brain Res 217:299–309. https://doi.org/10.1007/s00221-011-2993-4

Chang CH, Pan WW, Chen FC, Stoffregen TA (2013) Console video games, postural activity, and motion sickness during passive restraint. Exp Brain Res 229:235–242. https://doi.org/10.1007/s00221-013-3609-y

Chardonnet JR, Mirzaei MA, Mérienne F (2017) Features of the postural sway signal as indicators to estimate and predict visually induced motion sickness in virtual reality. Int J Hum Comput Interact 33(10):771–785. https://doi.org/10.1080/10447318.2017.1286767

Chen Y, Yu Y, Niu R, Liu Y (2018) Selective effects of postural control on spatial vs. nonspatial working memory: a functional near infrared spectral imaging study. Front Hum Neurosci 12:243. https://doi.org/10.3389/fnhum.2018.00243

Cheng Z, Gu Y (2018) Vestibular system and self-motion. Front Cell Neurosci 12:456. https://doi.org/10.3389/fncel.2018.00456

Cherep LA, Lim AF., Kelly JW, Acharya D, Velasco A, Bustamante E, Ostrander AG, Gilbert SB (2020) Spatial cognitive implications of teleporting through virtual environments. J Exp Psychol Appl 26(3):480–492. https://doi.org/10.1037/xap0000263

Cherni H, Métayer N, Nicolas S (2020) Literature review of locomotion techniques in virtual reality. Int J Virtu Reali 20:1-20. https://doi.org/10.20870/IJVR.2020.20.1.3183

Choi H (2013). The impact of visuospatial characteristics of video games on improvements in cognitive abilities. Unpublished Master Dissertation, North Carolina State University.

Chrastil ER, Warren WH (2012) Active and passive contributions to spatial learning. Psychon Bull Rev 19(1):1–23. https://doi.org/10.3758/s13423-011-0182-x

Christou CG, Aristidou P. (2017) Steering versus teleport locomotion for head mounted displays. In: De Paolis L, Bourdot P, Mongelli A (eds) Augmented reality, virtual reality, and computer graphics. AVR 2017. Lecture notes in computer science, vol 10325. Springer, Cham. https://doi.org/10.1007/978-3-319-60928-7_37

Clemente M, Rey B, Rodríguez-Pujadas A, Barros-Loscertales A, Baños RM, Botella C, Alcañiz M, Á vila C (2013). An fMRI study to analyze neural correlates of presence

during virtual reality experiences. Interact Comput 26(3):269–284. https://doi.org/10.1093/iwc/iwt037

Clemente M, Rodríguez A, Rey B, Alcañiz M (2014) Assessment of the influence of navigation control and screen size on the sense of presence in virtual reality using EEG. Expert Syst Appl 41(4):1584–1592. https://doi.org/10.1016/j.eswa.2013.08.055

Clifton J, Palmisano S (2019a) Effects of steering locomotion and teleporting on cybersickness and presence in HMD-based virtual reality. Virtual Real 24:453–468. https://doi.org/10.1007/s10055-019-00407-8

Clifton J, Palmisano S (2019b) Comfortable locomotion in VR: teleportation is not a complete solution. In: 25th ACM symposium on virtual reality software and technology (VRST'19). ACM, pp 1–2. https://doi.org/10.1145/3359996.3364722

Cobb SVG (1999) Measurement of postural stability before and after immersion in a virtual environment. Appl Ergon 30(1):47-57. https://doi.org/10.1016/s0003-6870(98)00038-6

Coomer N, Bullard S, Clinton W, Sanders B (2018) Evaluating the effects of four VR locomotion methods: joystick, arm-cycling, point-tugging, and teleporting. In: Proceedings of the 15th ACM symposium on applied perception. ACM, pp 1–8. https://doi.org/10.1145/3225153.3225175

Cowings PS, Suter S, Toscano WB, Kamiya J, Naifeh K (1986) General autonomic components of motion sickness. Psychophysiology 23(5):542-51. https://doi.org/10.1111/j.1469-8986.1986.tb00671.x

Dault MC, Geurts ACH, Mulder TW, Duysens J (2001) Postural control and cognitive task performance in healthy participants while balancing on different support-surface configurations. Gait Posture 14(3):248–255. https://doi.org/10.1016/S0966-6362(01)00130-8

Davis ET, Graham N (1981) Spatial frequency uncertainty effects in the detection of sinusoidal gratings. Vision Research 21:705–712. https://doi.org/10.1016/0042-6989(81)90079-1

Davis S, Nesbitt K, Nalivaiko E (2014) A systematic review of cybersickness. In: Proceedings of the 2014 conference on interactive entertainment (IE2014). ACM, pp 1–9. https://doi.org/10.1145/2677758.2677780

Davis S, Nesbitt K, Nalivaiko E (2015) Comparing the onset of cybersickness using the Oculus Rift and two virtual roller coasters. In: Proceedings of the 11th Australasian conference on interactive entertainment (IE 2015), pp 3–14.

Debarba HG, Molla E, Herbelin B, Boulic R (2015) Characterizing embodied interaction in first and third person perspective viewpoints. In: IEEE Symposium on 3D User Interfaces (3DUI), pp 67–72. Arles, France. https://doi.org/10.1109/3DUI.2015.7131728

Denisova A, Cairns P (2015) First person vs. third person perspective in digital games: Do player preferences affect immersion? In: Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI'15), pp 145–148. https://doi.org/10.1145/2702123.2702256

Dennison MS, D'Zmura M (2017) Cybersickness without the wobble: experimental results speak against postural instability theory. Appl Ergon 58:215–223. https://doi.org/10.1016/j.apergo.2016.06.014

Dennison M, D'Zmura M (2018) Effects of unexpected visual motion on postural sway and motion sickness. Appl Ergon 71: 9 –16. https://doi.org/10.1016/j.apergo.2018.03.015

Dennison MS, Wisti AZ, D'Zmura M (2016) Use of physiological signals to predict cybersickness. Displays 44:42–52. https://doi.org/10.1016/j.displa.2016.07.002

Dichgans J, Brandt T (1973) Optokinetic motion sickness and pseudo-coriolis effects induced by moving visual stimuli. Acta Oto-Laryngologica 76(1-6):339-348. https://doi.org/10.3109/00016487309121519

Dichgans J, Brandt T (1978) Visual-vestibular interaction: effects on self-motion perception and postural control. In: Held R, Leibowitz HW, Teuber HL (eds) Perception. Handbook of sensory physiology, 8. Springer, Berlin, Heidelberg, pp 755– 804. https://doi.org/10.1007/978-3-642-46354-9_25

Dijkerman H, De Haan E (2007) Somatosensory processes subserving perception and action. Behav Brain Sci 30(2):189-201.https://doi.org/10.1017/S0140525X07001392

Dolezal L (2009) The remote body: The phenomenology of telepresence and re-embodiment. In Human Technology: An Interdisciplinary Journal on Humanities in ICT Environments, 5(2):208-226. https://doi.org/10.17011/ht/urn.200911234471

Dominick JR (1984) Videogames, television violence, and aggression in teenagers. J Commun, 34, 136–147. https://doi.org/10.1111/j.1460-2466.1984.tb02165.x

Donker SF, Roerdink M, Greven AJ, Beek PJ (2007) Regularity of center-of-pressure trajectories depends on the amount of attention invested in postural control. Exp Brain Res 181:1–11. https://doi.org/10.1007/s00221-007- 0905-4

Dorado JL, Figueroa PA (2014) Ramps are better than stairs to reduce cybersickness in applications based on a HMD and a Gamepad. In: Proceedings of 2014 IEEE symposium on 3D user interfaces (3DUI), pp 47–50. https://doi.org/10.1109/3DUI.2014.6798841

Draper JV, Kaber DB, Usher JM (1998) Telepresence. Human Factors 40(3):354-375. https://doi.org/10.1518/001872098779591386

Dreyfus HL (2008) On the internet (2nd ed.). Routledge.

Dużmańska N, Strojny P, Strojny A (2018) Can simulator sickness be avoided? A review on temporal aspects of simulator sickness. Front Psychol 9:2132. https://doi.org/10.3389/fpsyg.2018.02132

Ellis SR (1991) Nature and origin of virtual environments: A bibliographic essay. Computing Systems in Engineering 2(4):321-347.https://doi.org/10.1016/0956-0521(91)90001-L

Engel D, Curio C, Tcheang L, Mohler B, Bülthoff HH (2008) A psychophysically calibrated controller for navigating through large environments in a limited free-walking space. In: Proceedings of the 2008 ACM symposium on virtual reality software and technology. ACM, pp 157–164. https://doi.org/10.1145/1450579.1450612

Epstein RA, Patai EZ, Julian JB, Spiers HJ (2017) The cognitive map in humans: spatial navigation and beyond. Nat Neurosci 20(11):1504-1513. https://doi.org/10.1038/nn.4656

Eriksen CW, Hoffman JE (1972) Temporal and spatial characteristics of selective encoding from visual displays. Percept Psychophys 12:201–204. https://doi.org/10.3758/BF03212870

Ermi L, Mäyrä F (2003) Power and control of games: Children as the actors of game cultures. In Proceedings of the 2003 DiGRA International Conference: Level Up, Utrecht, The Netherlands.

Fabricatore C (2007) Gameplay and game mechanics: A key to quality in videogames. OECD Expert Meeting on Videogames and Education, Santiago de Chile, Chile. https://doi.org/10.13140/RG.2.1.1125.4167

Fairchild KM, Lee BH, Loo J, Ng H, Serra L (1993) The heaven and earth virtual reality: designing applications for novice users. In: Proceedings of IEEE virtual reality annual international symposium, pp 47-53. https://doi.org/10.1109/VRAIS.1993.380799

Farmani Y, Teather RJ (2018) Viewpoint snapping to reduce cybersickness in virtual reality. In: Proceedings of the 44th graphics interface conference (GI'18). Canadian Human-Computer Communications Society, pp 168–175. https://doi.org/10.20380/GI2018.23

Farmani Y, Teather RJ (2020) Evaluating discrete viewpoint control to reduce cybersickness in virtual reality. Virtual Reality 24:645–664. https://doi.org/10.1007/s10055-020-00425-x

Fernandes AS, Feiner SK (2016) Combating VR sickness through subtle dynamic field-of-view modification. In: Proceedings of 2016 IEEE symposium on 3D user interfaces (3DUI), pp 201-210. https://doi.org/10.1109/3DUI.2016.7460053

Ferracani A, Pezzatini D, Bianchini J, Biscini G, Del Bimbo A (2016) Locomotion by natural gestures for immersive virtual environments. In: Proceedings of the 1st international workshop on multimedia alternate realities (AltMM'16). ACM, pp 21–24. https://doi.org/10.1145/2983298.2983307

Flach JM, Holden JG (1998) The reality of experience: Gibson's way. Presence Teleoperators Virtual Environ 7(1), 90–95. https://doi.org/10.1162/105474698565550

Fontaine G (1992) The experience of a sense of presence in intercultural and international encounters. Presence Teleoperators Virtual Environ 1(4):482–490. https://doi.org/10.1162/pres.1992.1.4.482

Freitag S, Rausch D, Kuhlen T (2014) Reorientation in virtual environments using interactive portals. In: Proceedings of 2014 IEEE symposium on 3D user interfaces (3DUI), pp 119–122. https://doi.org/10.1109/3DUI.2014.6798852

Frommel J, Sonntag S, Weber M (2017) Effects of controller-based locomotion on player experience in a virtual reality exploration game. In: Proceedings of the 12th international conference on the foundations of digital games (FDG'17). ACM, pp 1–6. https://doi.org/10.1145/3102071.3102082

Fuchs P, Moreau G, Papin JP (2001) Le trait´e de la r´ealit´e virtuelle, Paris: Les Presses de l'Ecole des Mines.

Gallagher S (2005) How the body shapes the mind. New York: Oxford University Press.

Gavgani AM, Nesbitt KV, Blackmore KL, Nalivaiko E (2017) Profiling subjective symptoms and autonomic changes associated with cybersickness. Auton Neurosci 203:41–50. https://doi.org/10.1016/j.autneu.2016.12.004

Golding JF (1992) Phasic skin conductance activity and motion sickness. Aviat Space Environ Med 63(3):165–171.

Grechkin TY, Riecke BE (2014) Re-evaluating benefits of body-based rotational cues for maintaining orientation in virtual environments: men benefit from real rotations, women don't. In: Proceedings of the ACM symposium on applied perception (SAP'14). ACM, pp 99–102. http://doi.org/10.1145/2628257.2628275

Grechkin T, Thomas J, Azmandian M, Bolas M, Suma E (2016) Revisiting detection thresholds for redirected walking: combining translation and curvature gains. In: Proceedings of the ACM symposium on applied perception (SAP'16). ACM, pp 113–120. https://doi.org/10.1145/2931002.2931018

Greenfield PM (1994) Video games as cultural artifacts. Special issue: Effects of interactive entertainment technologies on development. Journal of Applied Developmental Psychology, 15, 3–12. https://doi.org/10.1016/0193-3973(94)90003-5

Gillner S, Mallot H (1998) Navigation and acquisition of spatial knowledge in a virtual maze. J Cogn Neurosci 10:445-463. https://doi.org/10.1162/089892998562861

Gorisse G, Christmann O, Amato EA, Richir S (2017). First- and third-person perspectives in immersive virtual environments: presence and performance analysis of embodied users. Front Robot AI 4(33) https://doi.org/10.3389/frobt.2017.00033

Guna J, Geršak G, Humar I, Song J, Drnovšek J, Pogačnik M (2019) Influence of video content type on users' virtual reality sickness perception and physiological response. Future Gener Comput Syst 91:263–276. https://doi.org/10.1016/j.future.2018.08.049

Guy E, Punpongsanon P, Iwai D, Sato K, Boubekeur T (2015) LazyNav: 3D ground navigation with non-critical body parts. In: Proceedings of 2015 IEEE symposium on 3D user interfaces (3DUI), pp 43-50. https://doi.org/10.1109/3DUI.2015.7131725

Habgood MPJ, Moore D, Wilson D, Alapont S (2018) Rapid, continuous movement between nodes as an accessible virtual reality locomotion technique. In: Proceedings of 2018 IEEE conference on virtual reality and 3D user interfaces (VR), pp 371–378. https://doi.org/10.1109/VR.2018.8446130

Hale KS, Stanney KM (2014) Handbook of virtual environments: design, implementation, and applications. CRC Press, Florida, Boca Raton. https://doi.org/10.1201/b17360

Hanson S, Paris RA, Adams HA, Bodenheimer B (2019) Improving walking in place methods with individualization and deep networks. In: Proceedings of 2019 IEEE conference on virtual reality and 3D user interfaces (VR), pp 367-376. https://doi.org/10.1109/VR.2019.8797751

Harrington J, Williams B, Headleand C (2019) A somatic approach to combating cybersickness utilising airflow feedback. In: Proceedings of computer graphics & visual computing (CGVC 2019), pp 35-43. https://doi.org/10.2312/cgvc.20191256

Harris A, Nguyen K, Wilson PT, Jackoski M, Williams B (2014) Human joystick: Wii-leaning to translate in large virtual environments. In: Proceedings of the 13th ACM SIGGRAPH international conference on virtual-reality continuum and its applications in industry (VRCAI'14). ACM, pp 231–234. https://doi.org/10.1145/2670473.2670512

Harris LR, Carnevale MJ, D'Amour S, Fraser LE, Harrar V, Hoover AE, Mander C, Pritchett LM (2015). How our body influences our perception of the world. Frontiers in Psychology, 6. https://doi.org/10.3389/fpsyg.2015.00819

Harris LR, Jenkin MR, Zikovitz D, Redlick F, Jaekl P, Jasiobedzka UT, Jenkin HL, Allison RS (2002) Simulating self-motion I: cues for the perception of motion. Virtual Real 6:75-85. https://doi.org/10.1007/s100550200008

Harris R (1998) Introduction to decision making, VirtualSalt. Retrieved from http://www.virtualsalt.com/crebook5.htm

Hartmann T, Klimmt C (2006) Gender and computer games: Exploring females' dislikes. J Comput Mediat Commun 11:910-931. https://doi.org/10.1111/j.1083-6101.2006.00301.x

Hartmann T, Wirth W, Schramm H, Klimmt C, Vorderer P, Gysbers A, Böcking S, Ravaja N, Laarni J, Saari T, Gouveia F, Sacau AM (2016) The spatial presence experience scale (SPES): a short self-report measure for diverse media settings. J of Media Psychol: theories, methods, and applications 28(1):1–15. https://doi.org/10.1027/1864-1105/a000137

Hashemian AM, Riecke BE (2017). Leaning-based 360° interfaces: investigating virtual reality navigation interfaces with leaning-based-translation and full-rotation. In: Lackey S., Chen J. (eds) Virtual, augmented and mixed reality. VAMR 2017. Lecture notes in computer science, vol 10280. Springer, Cham, pp 15-32. https://doi.org/10.1007/978-3-319-57987-0_2

Heckmann T, Schwanghart W, Phillips J (2014) Graph theory - Recent developments of its application in geomorphology. Geomorphology, 243. https://doi.org/10.1016/j.geomorph.2014.12.024

Heekeren HR, Marrett S, Ungerleider LG (2008) The neural systems that mediate human perceptual decision making. Nature Reviews: Neuroscience 9(6):467–479. https://doi.org/10.1038/nrn2374

Heeter C (1992) Being there: The subjective experience of presence. Presence Teleoperators Virtual Environ 1(2):262-271. https://doi.org/10.1162/pres.1992.1.2.262

Held RM, Durlach NI (1992) Telepresence. Presence Teleoperators Virtual Environ 1(1):109-112. https://doi.org/10.1162/pres.1992.1.1.109

Hettinger LJ, Berbaum KS, Kennedy RS, Dunlap WP, Nolan MD (1990) Vection and simulator sickness. Mil Psychol 2(3):171–181. https://doi.org/10.1207/s15327876mp0203_4

Hettinger LJ, Riccio GE (1992) Visually induced motion sickness in virtual environments. Presence Teleoperators Virtual Environ 1(3):306-310. https://doi.org/10.1162/pres.1992.1.3.306

Hettinger LJ, Schmidt-Daly TN, Jones DL, Keshavarz B (2014) Illusory self-motion in virtual environments. In: Hale KS, Stanney KM (eds) Handbook of virtual environments: design, implementation, and applications. CRC Press, Florida, Boca Raton, pp 435–467. https://doi.org/10.1201/b17360

Hill KJ, Howarth PA (2000) Habituation to the side effects of immersion in a virtual environment. Displays 21:25–30. https://doi.org/10.1016/S0141-9382(00)00029-9

Horak FB (2006) Postural orientation and equilibrium: what do we need to know about neural control of balance to prevent falls? Age and Ageing 35(2): ii7–ii11. https://doi.org/10.1093/ageing/afl077

Horak FB, Macpherson JM (1996) Postural orientation and equilibrium. In: Rowell LB, Shepard JT (eds) Handbook of physiology: exercise regulation and integration of multiple systems. Oxford University Press, New York pp 255–292. https://doi.org/10.1002/cphy.cp120107

Hu S, Grant WF, Stern RM, Koch KL (1991) Motion sickness severity and physiological correlates during repeated exposures to a rotating optokineic drum. Aviat Space Environ Med 62(4):308-314.

Hu S, McChesney KA, Player KA, Bahl AM, Buchanan JB, Scozzafava JE (1999) Systematic investigation of physiological correlates of motion sickness induced by viewing an optokinetic rotating drum. Aviat Space Environ Med 70(8):759–765.

Hüttermann S, Helsen WF, Put K, Memmert D (2018) Does visual attention impact on decision making in complex dynamic events? J Sport Exerc Psychol 40(3):163-166. https://doi.org/10.1123/jsep.2017-0169

Huxhold O, Li SC, Schmiedek F, Lindenberger U (2006) Dual-tasking postural control: Aging and the effects of cognitive demand in conjunction with focus of attention. Brain Res Bull 69: 294-305. https://doi.org/10.1016/j.brainresbull.2006.01.002

Ihde D (2002) Bodies in technology. University of Minnesota Press, Minneapolis.

Ijsselsteijn WA (2002) Elements of a multi-level theory of presence: phenomenology, mental processing, and neural correlates. In: Proceedings of presence 2002, pp 245–259.

International Society for Presence Research (2000) The concept of presence: explication statement. http://ispr.info/ Accessed 15 Jan 2009

Interrante V, Ries B, Anderson L (2007) Seven league boots: a new metaphor for augmented locomotion through moderately large scale immersive virtual environments. In: Proceedings of 2007 IEEE symposium on 3D user interfaces, pp 167–170. https://doi.org/10.1109/3DUI.2007.340791

Irish M, Ramanan S (2019) Spatial navigation: a question of scale. eLife 2019; 8: e50890. https://doi.org/10.7554/eLife.50890

Isip MIG (2014) Effect of a standing body position during college students' exam: implications on cognitive test performance. Ind Eng Manag Syst 13(2):185–192. https://doi.org/10.7232/iems.2014.13.2.185

Iwata H, Fujii T (1996) Virtual perambulator: a novel interface device for locomotion in virtual environment. In: Proceedings of the IEEE 1996 virtual reality annual international symposium, pp 60-65. https://doi.org/10.1109/VRAIS.1996.490511

Iwata H, Yoshida Y (1999) Path reproduction tests using a torus treadmill. Presence Teleoperators Virtual Environ 8(6):587–597. https://doi.org/10.1162/105474699566503

Johnson DM (2005) Introduction to and review of simulator sickness research. Research Report. United States Army Research Institute for the Behavioral and Social Sciences.

Jennett C, Cox A, Cairns P, Dhoparee S, Epps A, Tijs T, Walton A (2008) Measuring and defining the experience of immersion in games. Int J Hum Comput Stud 66(9):641–661. https://doi.org/10.1016/j.ijhcs.2008.04.004

Jürgens R, Boß T, Becker W (1999) Estimation of self-turning during active and passive rotation in the dark. Exp Brain Res 128:491–504. https://doi.org/10.1007/s002210050872

Kallinen K, Salminen M, Ravaja N, Kedzior R, Sääksjärvi M (2007) Presence and emotion in computer game players during 1st person vs. 3rd person playing view: Evidence from self-report, eye-tracking, and facial muscle activity data. In: Proceedings of the PRESENCE 2007 (pp. 187-190). Barcelona, Spain.

Kearns MJ, Warren WH, Duchon AP, Tarr MJ (2002) Path integration from optic flow and body senses in a homing task. Perception 31(3):349–374. https://doi.org/10.1068/p3311

Kemeny A, George P, Mérienne F, Colombet F (2017) New VR navigation techniques to reduce cybersickness. In: The engineering reality of virtual reality 2017. Electric Imaging, pp 48-53(6). https://doi.org/10.2352/ISSN.2470-1173.2017.3.ERVR-097

Kennedy RS, Drexler JM, Compton DE, Stanney KM, Harm DL (2001) Configural scoring of simulator sickness, cybersickness and space adaptation syndrome: similarities and differences. In: Hettinger LJ, Haas M W (eds.) Virtual and adaptive environments: applications, implications, and human performance issues. Lawrence Erlbaum, New Jersey, Mahwah, pp 247–278.

Kennedy RS, Fowlkes JE (1992) Simulator sickness is polygenic and polysymptomatic: implications for research. Int J Aviat Psychol 2(1):23–38. https://doi.org/10.1207/s15327108ijap0201_2

Kennedy RS, Lane NE, Berbaum KS, Lilienthal MG, (1993) Simulator sickness questionnaire: an enhanced method for quantifying simulator sickness. Int J Aviat Psychol 3(3):203-220, https://doi.org/10.1207/s15327108ijap0303_3

Kerr B, Condon SM, McDonald LA (1985) Cognitive spatial processing and the regulation of posture. J of Exp Psychol 11(5):617–622. https://doi.org/10.1037//0096-1523.11.5.617

Keshavarz B, Hecht H, Lawson BD (2014a) Visually induced motion sickness: causes, characteristics, and countermeasures. In: Hale KS, Stanney KM (eds) Handbook of virtual environments: design, implementation, and applications. CRC Press, Florida, Boca Raton, pp 647–698. https://doi.org/10.1201/b17360

Keshavarz B, Hettinger LJ, Kennedy RS, Campos JL (2014b) Demonstrating the potential for dynamic auditory stimulation to contribute to motion sickness. PLOS ONE 9(7): e101016. https://doi.org/10.1371/journal.pone.0101016

Keshavarz B, Phillip-Muller AE, Hemmerich W, Riecke BE, Campos JL (2018) The effect of visual motion stimulus characteristics on vection and visually induced motion sickness. Displays 58:71– 81. https://doi.org/10.1016/j.displa.2018.07.005

Keshavarz B, Riecke BE, Hettinger LJ, Campos JL (2015) Vection and visually induced motion sickness: how are they related? Front Psychol 6:472. https://doi.org/10.3389/fpsyg.2015.00472

Kim T, Biocca F (1997) Telepresence via television: Two dimensions of telepresence may have different connections to memory and persuasion, Journal of Computer-Mediated Communication, 3(2). https://doi.org/10.1111/j.1083-6101.1997.tb00073.x

Kim JS, Gračanin D, Matković K, Quek F (2010) The effects of finger-walking in place (FWIP) for spatial knowledge acquisition in virtual environments. In: Taylor R, Boulanger P, Krüger A, Olivier P (eds) Smart graphics. SG 2010. Lecture notes in computer science, 6133. Springer, Berlin, Heidelberg, pp 56–67. https://doi.org/10.1007/978-3-642-13544-6_6

Kim YY, Kim HJ, Kim EN, Ko HD, Kim HT (2005) Characteristic changes in the physiological components of cybersickness. Psychophysiology 42:616–625. https://doi.org/10.1111/j.1469-8986.2005.00349.x

Kim J, Palmisano S, Bonato F (2012) Simulated angular head oscillation enhances vection in depth. Perception 41(4):402–414. https://doi.org/10.1068/p6919

Kim A, Kim MW, Bae H, Lee KM (2020) Exploring the relative effects of body position and spatial cognition on presence when playing virtual reality games. Int J Hum Comput Interact 36(18):1683-1698. https://doi.org/10.1080/10447318.2020.1775373

Kitson A, Hashemian AM, Stepanova ER, Kruijff E, Riecke BE (2017a) Comparing leaning-based motion cueing interfaces for virtual reality locomotion. In: Proceedings of 2017 IEEE symposium on 3D user interfaces (3DUI), pp 73-82. https://doi.org/10.1109/3DUI.2017.7893320

Kitson A, Hashemian AM, Stepanova ER, Kruijff E, Riecke BE (2017b) Lean into it: exploring leaning-based motion cueing interfaces for virtual reality movement. In: Proceedings of 2017 IEEE Virtual Reality (VR), pp 215-216. https://doi.org/10.1109/VR.2017.7892253

Kitson A, Riecke BE, Abraham H, Carman N (2015) NaviChair: evaluating an embodied interface using a pointing task to navigate virtual reality. In: Proceedings of the 3rd ACM symposium on spatial user interaction (SUI'15). ACM, pp 123–126. https://doi.org/10.1145/2788940.2788956

Klatzky RL, Loomis JM, Beall AC, Chance SS, Golledge RG (1998) Spatial updating of self-position and orientation during real, imagined, and virtual locomotion. Psychol Sci 9(4):293–298. http://doi.org/10.1111/1467-9280.00058

Kohn J, Rank S (2016) You're the Camera!: physical movements for transitioning between environments in VR. In: Proceedings of the 13th international conference on advances in computer entertainment technology (ACE'16). ACM, pp 1–9. https://doi.org/10.1145/3001773.3001824

Kolasinski EM (1995) Simulator sickness in virtual environments. Technical Report 1027. U.S. Army Research Institute for the Behavioral and Social Sciences.

Kolasinski EM, Gilson RD (1998) Simulator sickness and related findings in a virtual reality. In: Proceedings of human factors and ergonomics society annual meeting 42(21):1511-1515. https://doi.org/10.1177/154193129804202110

Kruijff E, Marquardt A, Trepkowski C, Lindeman RW, Hinkenjann A, Maiero J, Riecke BE (2016) On your feet!: enhancing vection in leaning-based interfaces through multisensory stimuli. In: Proceedings of the 2016 symposium on spatial user interaction (SUI '16). ACM, pp 149–158. https://doi.org/10.1145/2983310.2985759

Langbehn E, Eichler T, Ghose S, von Luck K, Bruder G, Steinicke F (2015) Evaluation of an omnidirectional walking-in-place user interface with virtual locomotion speed scaled by forward leaning angle. In: Proceedings of the GI workshop on virtual and augmented reality (GI VR/AR), pp 149–160.

Langbehn E, Lubos P, Steinicke F (2018) Evaluation of locomotion techniques for room-scale VR: joystick, teleportation, and redirected walking. In: Proceedings of the virtual reality international conference (VRIC'18). ACM, pp 1–9. https://doi.org/10.1145/3234253.3234291

Lathrop WB, Kaiser MK (2002) Perceived orientation in physical and virtual environments: changes in perceived orientation as a function of idiothetic information available. Presence Teleoperators Virtual Environ 11(1):19–32. https://doi.org/10.1162/105474602317343631

LaViola JJ (2000) A discussion of cybersickness in virtual environments. ACM SIGCHI Bulletin 32(1):47–56. https://doi.org/10.1145/333329.333344

LaViola JJ, Kruijff E, McMahan RP, Bowman D, Poupyrev IP (2017) 3D user interfaces: theory and practice. Addison-Wesley, Massachusetts, Boston.

LaViola JJ, Feliz DA, Keefe DF, Zeleznik RC (2001) Hands-free multi-scale navigation in virtual environments. In: Proceedings of the 2001 symposium on interactive 3D graphics (I3D' 01). ACM, pp 9–15. https://doi.org/10.1145/364338.364339

Lawson BD (2014) Motion sickness symptomatology and origins. In: Hale KS, K. M. Stanney KM (eds) Handbook of virtual environments: design, implementation, and applications. CRC Press, Florida, Boca Raton, pp 531-600. https://doi.org/10.1201/b17360

Lee KM (2004) Presence, Explicated. Commun Theory 14(1):27–50. https://doi.org/10.1111/j.1468-2885.2004.tb00302.x

Lim SH, Reeves B (2009) Being in the game: Effects of avatar choice and point of view on psychophysiological responses during play. Media Psychol 12:348-370. https://doi.org/10.1080/15213260903287242

Litleskare S, Calogiuri G (2019) Camera stabilization in 360° videos and its impact on cyber sickness, environmental perceptions, and psychophysiological responses to a simulated nature walk: a single-blinded randomized trial. Front Psychol 10:2436. https://doi.org/10.3389/fpsyg.2019.02436

Lombard M, Ditton T (1997) At the heart of it all: the concept of presence. J of Comput Mediat Commun 3(2). https://doi.org/10.1111/j.1083-6101.1997.tb00072.x

Longo MR, Azañón E, Haggard P (2010). More than skin deep: body representation beyond primary somatosensory cortex. Neuropsychologia 48(3):655–668. https://doi.org/10.1016/j.neuropsychologia.2009.08.022

Loomis JM (1992) Presence and distal attribution: phenomenology, determinants, and assessment. In: Proceedings of SPIE 1666, Human vision, visual processing, and digital display III. https://doi.org/10.1117/12.136005

Lucas K, Sherry JL (2004) Sex differences in video game play: A communication-based explanation. Commun Res 31(5):499–523. https://doi.org/10.1177/0093650204267930

Mania K, Chalmers A (2001) The effects of levels of immersion on memory and presence in virtual environments: a reality centered approach. CyberPsychol Behav 4(2):247–264. https://doi.org/10.1089/109493101300117938

Marchal M, Pettré J, Lécuyer A (2011) Joyman: a human-scale joystick for navigating in virtual worlds. In: Proceedings of 2011 IEEE symposium on 3D user interfaces (3DUI), pp 19-26. https://doi.org/10.1109/3DUI.2011.5759212

Marken RS (1988) The nature of behavior: control as fact and theory. Behav Sci 33(3):196-206. https://doi.org/10.1002/bs.3830330304

Marken RS (2002) Looking at behavior through control theory glasses. Rev of Gen Psychol 6(3):260–270. https://doi.org/10.1037/1089-2680.6.3.260

Marsh WE, Kelly JW, Dark VJ, Oliver JH (2013) Cognitive demands of semi-natural virtual locomotion. Presence Teleoperators Virtual Environ 22(3):216–234. https://doi.org/10.1162/PRES_a_00152

Maylor EA, Allison S, Wing AM (2001) Effects of spatial and nonspatial cognitive activity on postural stability. Br J of Psychol 92(2):319–338. https://doi.org/10.1348/000712601162211

Maylor EA, Wing AM (1996) Age differences in postural stability are increased by additional cognitive demands. J of Gerontol 51B (3):143–154. https://doi.org/10.1093/geronb/51B.3.P143

McCauley ME, Sharkey TJ (1992) Cybersickness: perception of self-motion in virtual environments. Presence Teleoperators Virtual Environ 1(3):311-318. https://doi.org/10.1162/pres.1992.1.3.311

McClelland KA, Fararo TJ (2006) Purpose, meaning, and action: control systems theories in sociology. Palgrave Macmillan, New York. https://doi.org/10.1007/978-1-137-10809-8

Meehan M, Insko B, Whitton M, Brooks FP (2002) Physiological measures of presence in stressful virtual environments. ACM Trans Graph 21(30):645-652. https://doi.org/10.1145/566654.566630

Mehta RK, Shortz AE, Benden ME (2015) Standing up for learning: a pilot investigation on the neurocognitive benefits of stand-biased school desks. Int J Environ Res Public Health 13(1):59. https://doi.org/10.3390/ijerph13010059

Merhi O, Faugloire E, Flanagan MB, Stofregen TA (2007) Motion sickness, console video games, and head-mounted displays. Hum Factors 49(5):920–934. https://doi.org/10.1518/001872007X230262

Miller, J. C., Sharkey, T. J., Graham, G. A., & McCauley, M. E. (1993). Autonomic physiological data associated with simulator discomfort. Aviat Space Environ Med 64(9 Pt 1):813-819.

Moghadam K, Banigan C, Ragan E (2018) Scene transitions and teleportation in virtual reality and the implications for spatial awareness and sickness. In: IEEE Trans Vis Comput Graph 26(6):2273-2287. https://doi.org/10.1109/TVCG.2018.2884468

Money KE (1990) Motion sickness and evolution. In G. H. Crampton (Ed.), Motion and space sickness. CRC Press, Florida, Boca Raton, pp 1-7.

Mou W, McNamara TP, Valiquette CM, Rump B (2004) Allocentric and egocentric updating of spatial memories. J Exp Psychol Learn Mem Cogn 30(1):142–157. https://doi.org/10.1037/0278-7393.30.1.142

Mousavi M, Jen YH, Musa SNB (2013) A review on cybersickness and usability in virtual environments. Adv Electron Forum 10:34-39. https://doi.org/10.4028/www.scientific.net/aef.10.34

Munafo J, Diedrick M, Stofregen TA (2017) The virtual reality head-mounted display Oculus Rift induces motion sickness and is sexist in its effects. Exp Brain Res 235:889–901. https://doi.org/10.1007/s00221-016-4846-7

Nalivaiko E, Davis SL, Blackmore KL, Vakulin A, Nesbitt KV (2015) Cybersickness provoked by head-mounted display affects cutaneous vascular tone, heart rate and reaction time. Physiol Behav 151:583–590. https://doi.org/10.1016/j.physbeh.2015.08.043

Neth CT, Souman JL, Engel D, Kloos U, Bülthoff HH, Mohler BJ (2012) Velocity-dependent dynamic curvature gain for redirected walking. In: IEEE Trans Vis Comput Graph 18(7):1041-1052. https://doi.org/10.1109/TVCG.2011.275

Nescher T, Huang YY, Kunz A (2014) Planning redirection techniques for optimal free walking experience using model predictive control. In: Proceedings of 2014 IEEE symposium on 3D user interfaces (3DUI), pp 111-118. https://doi.org/10.1109/3DUI.2014.6798851

Nguyen-Vo T, Riecke BE, Stuerzlinger W, Pham DM, Kruijff E (2019) NaviBoard and NaviChair: limited translation combined with full rotation for efficient virtual locomotion. In: IEEE Trans Vis Comput Graph 27(1):165-177. https://doi.org/10.1109/TVCG.2019.2935730

Nowak KL, Biocca F (2003) The effect of agency and anthropomorphism on users' sense of telepresence, copresence, and social presence in virtual environments. Presence Teleoperators Virtual Environ 12(5):481-494. https://doi.org/10.1162/105474603322761289

Nunez MD, Vandekerckhove J, Srinivasan R (2017). How attention influences perceptual decision making: Single-trial EEG correlates of drift-diffusion model parameters. J Math Psychol 76(B):117-130. https://doi.org/10.1016/j.jmp.2016.03.003

Nutt C (2014) After 20 years working with VR, Jesse Schell speaks his mind. Gamasutra.com.

Oliveira RF, Damisch L, Hossner EJ, Oudejans RR, Raab M, Volz KG, Williams AM (2009) The bidirectional links between decision making, perception, and action. Progress in brain research 174:85-93. https://doi.org/10.1016/S0079-6123(09)01308-9

Oman CM (1990) Motion sickness: a synthesis and evaluation of the sensory conflict theory. Can J Physiol Pharmacol 68(2):294-303. https://doi.org/10.1139/y90-044.

Orquin JL, Loose SM (2013). Attention and choice: A review on eye movements in decision making. Acta Psychologica, 144, 190–206. https://doi.org/10.1016/j.actpsy.2013

Owen N, Leadbetter AG, Yardley L (1998) Relationship between postural control and motion sickness in healthy subjects. Brain Res Bull 47(5):471-474. https://doi.org/10.1016/s0361-9230(98)00101-4

Palluel E, Nougier V, Olivier ID (2010) Postural control and attentional demand during adolescence. Brain Res 1358:151-159. https://doi.org/10.1016/j.brainres.2010.08.051

Palmisano S, Allison RS, Kim J, Bonato F (2011) Simulated viewpoint jitter shakes sensory conflict accounts of vection. Seeing and Perceiving 24(2):173-200. https://doi.org/10.1163/187847511X570817

Palmisano S, Allison RS, Schira MM, Barry RJ (2015) Future challenges for vection research: definitions, functional significance, measures, and neural bases. Front Psycho 6:193. https://doi.org/10.3389/fpsyg.2015.00193

Palmisano S, Apthorp D, Seno T, Stapley PJ (2014) Spontaneous postural sway predicts the strength of smooth vection. Exp Brain Res 232:1185–1191. https://doi.org/10.1007/s00221-014-3835-y

Palmisano S, Arcioni B, Stapley PJ (2017a) Predicting vection and visually induced motion sickness based on spontaneous postural activity. Exp Brain Res 236:315–329. https://doi.org/10.1007/s00221-017-5130-1

Palmisano S, Mursic R, Kim J (2017b) Vection and cybersickness generated by head-and-display motion in the Oculus Rift. Displays 46: 1–8. https://doi.org/10.1016/j.displa.2016.11.001

Park GD, Allen RW, Fiorentino D, Rosenthal TJ, Cook ML (2006) Simulator sickness scores according to symptom susceptibility, age, and gender for an older driver assessment study. In: Proceedings of the human factors and ergonomics society annual meeting, 50(26):2702–2706. https://doi.org/10.1177/154193120605002607

Paris R, Klag J, Rajan P, Buck L, McNamara TP. Bodenheimer B (2019) How video game locomotion methods affect navigation in virtual environments. In: ACM symposium on applied perception (SAP'19). ACM, pp 1–7. https://doi.org/10.1145/3343036.3343131

Patston L, Henry A, Mcewen M, Mannion J, Ewens L (2017) Thinking while standing: an exploratory study on the effect of standing on cognitive performance. Occasional and Discussion Paper Series 2017(3). Unitec ePress.

Pausch R, Crea T, Conway M (1992) A literature survey for virtual environments: military flight simulators visual systems and simulator sickness. Presence Teleoperators Virtual Environ 1(3): 344-363. https://doi.org/10.1162/pres.1992.1.3.344

Pausch R, Proffitt D, Williams G (1997) Quantifying immersion in virtual reality. In Proceedings of the 24th annual conference on computer graphics and interactive techniques (SIGGRAPH'97). ACM, pp 13–18. https://doi.org/10.1145/258734.258744

Peck TC, Fuchs H, Whitton MC (2009) Evaluation of reorientation techniques and distractors for walking in large virtual environments. IEEE Trans Vis Comput Graph 15(3):383–394. https://doi.org/10.1109/TVCG.2008.191

Phillips J, Schwanghart W, Heckmann T (2015). Graph theory in the geosciences. Earth-Science Reviews 143. https://doi.org/10.1016/j.earscirev.2015.02.002

Powers WT (2009) PCT in 11 Steps. In: Forssell D (eds) Perceptual control theory 2016. Living Control Systems, California, Menlo Park, pp 20-25.

Powers WT, Abbott B, Carey TA, Goldstein DM, Mansell W, Marken RS, Nevin B, Robertson R, Taylor M (2011) A model for understanding the mechanisms and phenomena of control. In: Forssell D (eds) Perceptual control theory 2016. Living Control Systems, California, Menlo Park, pp 30-46.

Presson CC, Montello DR (1994) Updating after rotational and translational body movements: coordinate structure of perspective space. Perception 23(12):1447–1455. https://doi.org/10.1068/p231447

Previc FH (1998) The neuropsychology of 3-D space. Psychol Bull 124(2):123–164. https://doi.org/10.1037/0033-2909.124.2.123

Ragan ED, Huber KJ, Laha B, Bowman DA (2012a) The effects of navigational control and environmental detail on learning in 3D virtual environments. IEEE Virtual Reality Workshops (VRW), pp 11-14. https://doi.org/10.1109/VR.2012.6180868

Ragan ED, Kopper R, Schuchardt P, Bowman DA (2013) Studying the effects of stereo, head tracking, and field of regard on a small-scale spatial judgment task. IEEE Transact on Visual and Comput Graph 19(5):886–896. https://doi.org/10.1109/TVCG.2012.163

Ragan ED, Wood A, McMahan RP, Bowman DA (2012b) Trade-offs related to travel techniques and level of display fidelity in virtual data-analysis environments. In: Proceedings of joint virtual reality conference of ICAT/EGVE/EuroVR, pp 81–84. http://dx.doi.org/10.2312/EGVE/JVRC12/081-084

Razzaque S, Swapp D, Slater M, Whitten M, Steed A (2002) Redirected walking in place. In: Proceedings of the workshop on virtual environments 2002 (EGVE'02). Eurographics Association, pp 123–130.

Razzaque S, Kohn Z, Whitton MC (2001) Redirected Walking. In: Proceedings of Eurographics 2001, Eurographics Association. http://dx.doi.org/10.2312/egs.20011036

Reason J T (1978) Motion sickness adaptation: a neural mismatch model. J R Soc Med 71(11):819–829. https://doi.org/10.1177/014107687807101109

Reason JT, Brand JJ (1975) Motion sickness. Academic Press, New York, New York.

Rebenitsch L, Owen C (2016) Review on cybersickness in applications and visual displays. Virtual Reality 20:101–125. https://doi.org/10.1007/s10055-016-0285-9

Redfern MS, Talkowski ME, Jennings JR, Furman JM (2004) Cognitive influences in postural control of patients with unilateral vestibular loss. Gait Posture 19(2):105–114. https://doi.org/10.1016/S0966-6362(03)00032-8

Regenbrecht H, Schubert T, Friedmann F (1998) Measuring the sense of presence and its relations to fear of heights in virtual environments. International Journal of Human-Computer Interaction, 10(3), 233–249. https://doi.org/10.1207/s15327590ijhc1003_2

Riccio GE, Stoffregen TA (1991) An ecological theory of motion sickness and postural instability. Ecol Psychol 3(3):195–240. https://doi.org/10.1207/s15326969eco0303_2

Riecke BE (2008) Consistent left-right reversals for visual path integration in virtual reality: more than a failure to update one's heading? Presence Teleoperators Virtual Environ 17(2):143-175. https://doi.org/10.1162/pres.17.2.143

Riecke BE, Bodenheimer B, McNamara TP, Williams B, Peng P, Feuereissen D (2010) Do we need to walk for effective virtual reality navigation? Physical rotations alone may suffice. In: Hölscher C, Shipley TF, Olivetti Belardinelli M, Bateman JA, Newcombe NS (eds) Spatial Cognition 2010. Lecture notes in computer science, 6222. Springer. Berlin, Heidelberg, pp 234–247. https://doi.org/10.1007/978-3-642-14749-4_21

Riecke BE, Cunningham DW, Bülthoff HH (2007) Spatial updating in virtual reality: the sufficiency of visual information. Psychol Res 71(3):298–313. https://doi.org/10.1007/s00426-006-0085-z

Riecke BE, Feuereissen D (2012) To move or not to move: can active control and user-driven motion cueing enhance self-motion perception ("vection") in virtual reality? In: Proceedings of the ACM symposium on applied perception (SAP'12). ACM, pp 17–24. https://doi.org/10.1145/2338676.2338680

Riecke BE, Heyde MVD, Bülthoff HH (2005) Visual cues can be sufficient for triggering automatic, reflexlike spatial updating. ACM Trans Appl Percept 2(3):183–215. https://doi.org/10.1145/1077399.1077401

Riecke BE, Schulte-Pelkum J, Avraamides MN, Heyde MVD, Bülthof HH (2006) Cognitive factors can influence self-motion perception (vection) in virtual reality. ACM Trans Appl Percept 3(3):194–216. https://doi.org/10.1145/1166087.1166091

Riecke BE, Schulte-Pelkum J, Caniard F (2006) Visually induced linear vection is enhanced by small physical accelerations. In: 7th international multisensory research forum (IMRF), pp 18-21.

Riecke BE, van Veen HAHC, Bülthoff HH (2002) Visual homing is possible without landmarks: A path integration study in virtual reality. Presence Teleoperators Virtual Environ 11(5):443–473. https://doi.org/10.1162/105474602320935810

Rieser JJ (1989) Access to knowledge of spatial structure at novel points of observation. J Exp Psychol Learn Mem Cogn 15(6):1157-1165. https://doi.org/10.1037//0278-7393.15.6.1157

Rieser JJ, Pick HL Jr, Ashmead DH, Garing AE (1995) Calibration of human locomotion and models of perceptual-motor organization. J Exp Psychol Hum Percept Perform 21(3):480-497. https://doi.org/10.1037//0096-1523.21.3.480

Riva G (2007) Virtual reality and telepresence. Science 318(5854):1240-1242. https://doi.org/10.1126/science.318.5854.1240d

Riva G (2009) Is presence a technology issue? Some insights from cognitive sciences. Virtual Reality 13(3):159–167. https://doi.org/10.1007/s10055-009-0121-6

Riva G, Mantovani F (2012) From the body to the tools and back: a general framework for presence in mediated interactions. Interact Comput 24(4):203-210. https://doi.org/10.1016/j.intcom.2012.04.007

Riva G, Waterworth J, Murray D (eds) (2014) Interacting with presence: HCI and the sense of presence in computer-mediated environments. De Gruyter, Berlin/Boston. https://doi.org/10.2478/9783110409697

Rosenbaum D, Mama Y, Algom D (2017) Stand by your stroop: standing up enhances selective attention and cognitive control. Psychol Sci 28(12):1864–1867. https://doi.org/10.1177/0956797617721270

Rouse R (1999) What's your perspective? ACM SIGGRAPH Computer Graphics, 33, pp 9–12. https://doi.org/10.1145/330572.330575

Ruddle RA (2013) The effect of translational and rotational body-based information on navigation. In: Steinicke F, Visell Y, Campos J, Lécuyer A (eds) Human walking in

virtual environments. Springer, New York, pp. 99–112. https://doi.org/10.1007/978-1-4419-8432-6_5

Ruddle RA, Lessels S (2006) For efficient navigational search, humans require full physical movement, but not a rich visual scene. Psychol Sci 17(6):460-465. https://doi.org/10.1111/j.1467-9280.2006.01728.x

Ruddle RA, Lessels S (2009) The benefits of using a walking interface to navigate virtual environments. ACM Trans Comput-Hum Interact 16(1):1–18. https://doi.org/10.1145/1502800.1502805

Sadiq O, McIlroy R, Izadi SS, Chung W, Wise A, Basharat A, Varghese JP, Barnett-Cowan M (2017) Balance control and motion sickness in real and virtual environments. Southern Ontario Neuroscience Association 37th Annual Meeting.

Sadowski W, Stanney K (2002) Presence in virtual environments. In: Hale KS, Stanney KM (eds) Handbook of virtual environments: design, implementation, and applications. CRC Press, Florida, Boca Raton, pp 791–806. https://doi.org/10.1201/b17360

Salamin P, Thalmann D, Vexo F (2006) The benefits of third-person perspective in virtual and augmented reality? In Proceedings of the ACM Symposium on Virtual Reality Software and Technology, pp 27–30. https://doi.org/10.1145/1180495.1180502

Sakamoto A (1994) Video game use and the development of sociocognitive abilities in children: Three surveys of elementary school students. J Appl Soc Psychol 24:21–42. https://doi.org/10.1111/j.1559-1816.1994.tb00551.x

Sanchez-Vives MV, Slater M (2005) From presence to consciousness through virtual reality. Nat Rev Neurosci 6:332–339. https://doi.org/10.1038/nrn1651

Saredakis D, Szpak A, Birckhead B, Keage H, Rizzo A, Loetscher T (2020) Factors associated with virtual reality sickness in head-mounted displays: a systematic review and meta-analysis. Front Hum Neurosci 14:96. https://doi.org/10.3389/fnhum.2020.00096

Sargunam SP, Moghadam KR, Suhail M, Ragan ED (2017) Guided head rotation and amplified head rotation: evaluating semi-natural travel and viewing techniques in virtual reality. In: Proceedings of 2017 IEEE Virtual Reality (VR), pp 19-28. https://doi.org/10.1109/VR.2017.7892227

Sarupuri, B, Hoermann S, Steinicke F, Lindeman RW (2017). Triggerwalking: a biomechanically-inspired locomotion user interface for efficient realistic virtual walking. In: Proceedings of the 5th symposium on spatial user interaction (SUI'17). ACM, pp 138–147. https://doi.org/10.1145/3131277.3132177

Schubert T, Friedmann F, Regenbrecht H (1999) Embodied presence in virtual environments. In: Paton R, Neilson I (eds) Visual representations and interpretations. Springer, London, pp 269–278. https://doi.org/10.1007/978-1-4471-0563-3_30

Schubert T, Friedmann F, Regenbrecht H (2001) The experience of presence: factor analytic insights. Presence Teleoperators Virtual Environ 10(3):266–281. https://doi.org/10.1162/105474601300343603

Schulman D, Shontz FC (1971) Body posture and thinking. Percept Mot Skills 32(1):27–33. https://doi.org/10.2466/pms.1971.32.1.27

Schuemie MJ, Abel B, van der Mast CAPG, Krijn M, Emmelkamp PMG (2005) The effect of locomotion technique on presence, fear and usability in a virtual environment. In: Proceedings Euromedia 2005. Al-Akaidi M, Rothkrantz L (eds) Eurosis publication, p.129–135.

Schultze U (2010) Embodiment and presence in virtual worlds: A review. J Inf Technol 25(4):434–449. https://doi.org/10.1057/jit.2010.25

Seay AF, Krum DM, Hodges L, Ribarsky W (2002) Simulator sickness and presence in a high field-of-view virtual environment. In: CHI'02 extended abstracts on human factors in computing systems (CHI EA'02). ACM, pp 784–785. https://doi.org/10.1145/506443.506596

Seegelke C, Schack T (2016) Cognitive representation of human action: theory, applications, and perspectives. Front Public Health 4:24. https://doi.org/10.3389/fpubh.2016.00024

Serino A, Haggard P (2010) Touch and the body. Neuroscience and biobehavioral reviews, 34. 224-36. https://doi.org/10.1016/j.neubiorev.2009.04.004

Shadlen MN, Kiani R (2013) Decision making as a window on cognition. Neuron, 80, 791-806. https://doi.org/10.1016/j.neuron.2013.10.047

Shaw M L, Shaw P (1977) Optimal allocation of cognitive resources to spatial locations. Journal of Experimental Psychology: Human Perception and Performance, 3(2), 201-211. https://doi.org/10.1037/0096-1523.3.2.201

Sheridan TB (1992) Musings on telepresence and virtual presence. Presence Teleoperators Virtual Environ 1(1): 120-126. https://doi.org/10.1162/pres.1992.1.1.120

Siu KC, Chou LS, Mayr U, van Donkelaar P, Woollacott MH (2009) Attentional mechanisms contributing to balance constraints during gait: the effects of balance impairments. Brain Res 1248:59–67. https://doi.org/10.1016/j.brainres.2008.10.078

Skopp NA, Smolenski DJ, Metzger-Abamukong MJ, Rizzo AA, Reger GM (2014) A pilot study of the VirtuSphere as a virtual reality enhancement. Int J Hum Comput Interact 30(1):24–31. https://doi.org/10.1080/10447318.2013.796441

Slater M (2009) Place illusion and plausibility can lead to realistic behaviour in immersive virtual environments. Philos Trans R Soc Lond B Biol Sci 364(1535):3549-3557. https://doi.org/10.1098/rstb.2009.0138

Slater M, Linakis V, Usoh M, Kooper R (1996) Immersion, presence, and performance in virtual environments: an experiment with tridimensional chess. In: Proceedings of the ACM symposium on virtual reality software and technology (VRST' 96) ACM, pp 163-172. https://doi.org/10.1145/3304181.3304216

Slater M, Lotto B, Arnold MM, Sanchez-Vives MV (2009) How we experience immersive virtual environments: the concept of presence and its measurement. Anuario de Psicología 40(2):193–210.

Slater M, McCarthy J, Maringelli F (1998) The influence of body movement on subjective presence in virtual environments. Hum Factors 40(3):469-477. https://doi.org/10.1518/001872098779591368

Slater M, Steed A (2000) A virtual presence counter. Presence Teleoperators Virtual Environ 9(5):413–434. https://doi.org/10.1162/105474600566925

Slater M, Steed A, McCarthy J, Maringelli F (1998) The influence of body movement on subjective presence in virtual environments. Human Factors, 40, 469-477. https://doi.org/10.1518/001872098779591368

Slater M, Usoh M (1993) Presence in immersive virtual environments, In: Proceedings of IEEE Virtual Reality Annual International Symposium (pp. 90-96). Seattle, WA. https://doi.org/10.1109/VRAIS.1993.380793

Slater M, Usoh M (1994) Body centred interaction in immersive virtual environments. In: Thalmann NM, Thalmann D (eds) Artificial life and virtual reality. John Wiley and Sons, New York, pp. 125–148

Slater M, Usoh M, Steed A (1994) Depth of Presence in Virtual Environments. Presence Teleoperators Virtual Environ 3(2):130-144. https://doi.org/10.1162/pres.1994.3.2.130

Slater M, Usoh M, Steed A (1995) Taking steps: the influence of a walking metaphor on presence in virtual reality. ACM Trans Comput-Hum Interact 2(3):201–219. https://doi.org/10.1145/210079.210084

Slater M, Wilbur S (1997) A framework for immersive virtual environments (FIVE): Speculations on the role of presence in virtual environments. Presence Teleoperators Virtual Environ 6(6):603-616. https://doi.org/10.1162/pres.1997.6.6.603

Smith K, Davoli C, Knapp W, Abrams R (2019) Standing enhances cognitive control and alters visual search. Atten Percept Psychophys 81(7):2320–2329. https://doi.org/10.3758/s13414-019-01723-6

Smith PL, Ratcliff R (2009) An integrated theory of attention and decision making in visual signal detection. Psychol Rev 116(2):283-317. https://doi.org/10.1037/a0015156

So RHY (1999) The search for a cybersickness dose value. In: Proceedings of the international conference on human-computer interaction: ergonomics and user interfaces, pp 152–156.

Soler-Domínguez JL, de Juan C, Contero M, Alcañiz M (2020) I walk, therefore I am: a multidimensional study on the influence of the locomotion method upon presence in virtual reality. J Comput Des Eng 7(5):577–590. https://doi.org/10.1093/jcde/qwaa040

Spagnolli A, Gamberini L (2005) A place for presence. Understanding the human involvement in mediated interactive environments. PsychNology 3(1):6–15.

Spence I, Feng J (2010) Video games and spatial cognition. Review of General Psychology 14(2):92-104. https://doi.org/10.1037/a0019491

Stanney KM, Hale KS, Nahmens I, Kennedy RS (2003) What to expect from immersive virtual environment exposure: influences of gender, body mass index, and past experience. Hum Factors 45(3):504-520. https://doi.org/10.1518/hfes.45.3.504.27254

Stanney KM, Hash P (1998) Locus of user-initiated control in virtual environments: Influences on cybersickness. Presence Teleoperators Virtual Environ 7(5):447-459. https://doi.org/10.1162/105474698565848

Stanney KM, Kennedy RS (1997) The psychometrics of cybersickness. Commun ACM 40(8):67–68. https://doi.org/10.1145/257874.257889

Stanney KM, Mourant RR, Kennedy RS (1998) Human factors issues in virtual environments: a review of the literature. Presence Teleoperators Virtual Environ 7(4): 327–351. https://doi.org/10.1162/105474698565767

Stanney KM, Kennedy RS, Drexler JM (1997) Cybersickness is not simulator sickness. In: Proceedings of the human factors and ergonomics society annual meeting, 41(2):1138–1142. https://doi.org/10.1177/107118139704100292

Stanney KM, Kingdon KS, Graeber D, Kennedy RS (2002) Human performance in immersive virtual environments: effects of exposure duration, user control, and scene complexity. Hum Perform 15(4):339–366. https://doi.org/10.1207/S15327043HUP1504_03

Steinicke F, Visell Y, Campos JL, Lécuyer A (eds) (2013) Human walking in virtual environments: perception, technology, and applications. Springer, New York. https://doi.org/10.1007/978-1-4419-8432-6

Steuer J (1992) Defining virtual reality: dimensions determining telepresence. J Commun 42(4):73–93. https://doi.org/10.1111/j.1460-2466.1992.tb00812.x

Stoffregen TA, Chen FC, Varlet M, Alcantara C, Bardy BG (2013) Getting your sea legs. PLOS ONE 8(6): e66949. https://doi.org/10.1371/journal.pone.0066949

Stoffregen TA, Chen YC, Koslucher FC (2014) Motion control, motion sickness, and the postural dynamics of mobile devices. Exp Brain Res 232(4):1389-1397. https://doi.org/10.1007/s00221-014-3859-3

Stoffregen TA, Faugloire E, Yoshida K, Flanagan MB, Merhi O (2008) Motion sickness and postural sway in console video games. Hum Factors 50(2):322-331. https://doi.org/10.1518/001872008X250755

Stoffregen TA, Smart LJ Jr (1998) Postural instability precedes motion sickness. Brain Res Bull 47(5):437-448. https://doi.org/10.1016/s0361-9230(98)00102-6

Suma EA, Bruder G, Steinicke F, Krum DM, Bolas M (2012) A taxonomy for deploying redirection techniques in immersive virtual environments. In: 2012 IEEE virtual reality workshops (VRW), pp 43-46. https://doi.org/10.1109/VR.2012.6180877

Suma EA, Babu S, Hodges LF (2007) Comparison of travel techniques in a complex, multi-level 3d environment. In: Proceedings of 2007 IEEE symposium on 3D user interfaces (3DUI), pp147-153. https://doi.org/10.1109/3DUI.2007.340788

Sun HJ, Campos JL, Chan GSW (2004) Multisensory integration in the estimation of relative path length.Exp Brain Res 154(2):246-54.https://doi.org/10.1007/s00221-003-1652-9

Sunkara A, DeAngelis GC, Angelaki DE (2016) Joint representation of translational and rotational components of optic flow in parietal cortex. In: Proceedings of the national academy of sciences, 113(18):5077-5082. https://doi.org/10.1073/pnas.1604818113

Tamborini R, Skalski P (2006) The role of presence in the experience of electronic games. Playing video games: Motives, responses, and consequences pp. 225-240. New Jersey: Lawrence Erlbaum Associates Publishers.

Taylor LN (2002) Video games: Perspective, point-of-view, and immersion. Master's thesis, University of Florida.

Teasdale N, Simoneau M (2001) Attentional demands for postural control: the effects of aging and sensory reintegration. Gait Posture 14(3):203–210. https://doi.org/10.1016/S0966-6362(01)00134-5

Telford L, Howard IP, Ohmi M (1995) Heading judgments during active and passive self-motion. Exp Brain Res 104(3):502-510. https://doi.org/10.1007/BF00231984

Templeman JN, Denbrook PS, Sibert LE (1999) Virtual locomotion: walking in place through virtual environments. Presence Teleoperators Virtual Environ 8(6):598-617. https://doi.org/10.1162/105474699566512

Teramoto W, Riecke BE (2010) Dynamic visual information facilitates object recognition from novel viewpoints. J Vis 10(13):11. https://doi.org/10.1167/10.13.11

Toet A, de Vries SC, van Emmerik ML, Bos JE (2008) Cybersickness and desktop simulations: field of view effects and user experience. In: Proceedings of SPIE 6957, Enhanced and synthetic vision 2008. https://doi.org/10.1117/12.771992

Tsotsos JK, Kotseruba I, Rasouli A, Solbach MD (2018) Visual attention and its intimate links to spatial cognition. Cognitive Processing 19(1). https://doi.org/10.1007/s10339-018-0881-6

Usoh M, Arthur K, Whitton MC, Bastos R, Steed A, Slater M, Brooks FP (1999) Walking> walking-in-place> flying, in virtual environments. In: Proceedings of the 26th annual conference on computer graphics and interactive techniques (SIGGRAPH'99). ACM, pp 359–364. https://doi.org/10.1145/311535.311589

Usoh M, Catena E, Arman S, Slater M (2000) Using presence questionnaires in reality. Presence Teleoperators Virtual Environ 9(5):497–503. https://doi.org/10.1162/105474600566989

Verma A, Mettler B (2016) Investigating human learning and decision-making in navigation of unknown environments. In 1st IFAC Conference on Cyber-Physical & Human-Systems (pp. 113-118), 49 (32). Florianopolis, Brazil. https://doi.org/10.1016/j.ifacol.2016.12.199

Villard SJ, Flanagan MB, Albanese GM, Stofregen TA (2008) Postural instability and motion sickness in a virtual moving room. Hum Factors 50(2):332–345. https://doi.org/10.1518/001872008X250728

Vlahović S, Suznjevic M, Skorin-Kapov L (2018) Subjective assessment of different locomotion techniques in virtual reality environments. In: Proceedings of 2018 tenth international conference on quality of multimedia experience (QoMEX), pp 1–3. https://doi.org/10.1109/QoMEX.2018.8463433

Voorhees GA, Call J, Whitlock K (eds) (2012) Guns, grenades, and grunts: First-person shooter games. New York: Bloomsbury Publishing.

Wade MG, Jones G (1997) The role of vision and spatial orientation in the maintenance of posture. Physical therapy 77(6):619-628. https://doi.org/10.1093/ptj/77.6.619

Waller D, Loomis JM, Haun DBM (2004) Body-based senses enhance knowledge of directions in large-scale environments. Psychon Bull Rev 11:157–163 https://doi.org/10.3758/BF03206476

Waller D, Hodgson E (2013) Sensory contributions to spatial knowledge of real and virtual environments. In: Steinicke F, Visell Y, Campos J, Lécuyer A (eds) Human walking in virtual environments. Springer, New York, pp 3–26. https://doi.org/10.1007/978-1-4419-8432-6_1

Wang RF (2004) Between reality and imagination: when is spatial updating automatic? Percept Psychophys 66(1):68-76. https://doi.org/10.3758/bf03194862

Wang Y, Ruhe G (2007) The cognitive process of decision making. Int J Cogn Inform Nat Intell 1(2):73-85. https://doi.org/10.4018/jcini.2007040105

Wang Y, Wang Y, Patel S, Patel D (2004) A layered reference model of the brain (LRMB). IEEE Transactions on Systems, Man, and Cybernetics 36(2):124-133. https://doi.org/10.1109/TSMCC.2006.871126

Warren LE (2018) The effect of interaction fidelity on user experience in virtual reality locomotion. Master Thesis.

Wartenberg F, May M, Péruch P (1998) Spatial orientation in virtual environments: background considerations and experiments. In: Freksa C, Habel C, Wender KF (eds) Spatial cognition. Lecture notes in computer science, vol 1404. Springer, Berlin, Heidelberg, pp 469–489. https://doi.org/10.1007/3-540-69342-4_22

Waterworth JA, Waterworth E L (2003) The meaning of presence. Presence-Connect 3(2). https://www8.informatik.umu.se/~jwworth/PRESENCE-meaning.htm

Waterworth JA, Waterworth EL (2006) Presence as a dimension of communication: context of use and the person. In: Riva G, Anguera MT, Wiederhold B.K, Mantovani F (eds) From communication to presence: cognition, emotions, and culture toward the ultimate communicative experience. IOS Press, Amsterdam, pp 80–95.

Watson MJ (1999) Neurophysiological basis of movement [review of the book: neurophysiological basis of movement by Latash, M.]. Physiotherapy 85(10):575. https://doi.org/10.1016/s0031-9406(05)61260-6

Weech S, Kenny S, Barnett-Cowan M (2019) Presence and cybersickness in virtual reality are negatively related: a review. Front Psychol 10:158. https://doi.org/10.3389/fpsyg.2019.00158

Weech S, Kenny S, Lenizky M, Barnett-Cowan M (2020) Narrative and gaming experience interact to affect presence and cybersickness in virtual reality. Int J Hum Comput Stud 138 (2020):102398. https://doi.org/10.1016/j.ijhcs.2020.102398

Weech S, Moon J, Troje NF (2018a) Influence of bone-conducted vibration on simulator sickness in virtual reality. PLOS ONE 13(3):e01941. https://doi.org/10.1371/journal.pone.0194137

Weech S, Troje NF (2017) Vection latency is reduced by bone-conducted vibration and noisy galvanic vestibular stimulation. Multisens Res 30(1):65–90. https://doi.org/10.1163/22134808-00002545

Weech S, Varghese JP, Barnett-Cowan M (2018b) Estimating the sensorimotor components of cybersickness. J Neurophysiol 120(5):2201-2217. https://doi.org/10.1152/jn.00477.2018

Weibel D, Wissmath B (2011) Immersion in computer games: the role of spatial presence and flow. Int J Comput Games Technol 2011. https://doi.org/10.1155/2011/282345

Welch RB, Blackmon TT, Liu A, Mellers BA, Stark LW (1996) The effects of pictorial realism, delay of visual feedback, and observer interactivity on the subjective sense of presence. Presence Teleoperators Virtual Environ 5(3)263–273. https://doi.org/10.1162/pres.1996.5.3.263

Whitton MC, Cohn JV, Feasel J, Zimmons P, Razzaque S, Poulton SJ, McLeod B, Brooks FP (2005) Comparing VE locomotion interfaces. In: Proceedings of IEEE virtual reality 2005, pp 123–130. https://doi.org/10.1109/VR.2005.1492762

Widdowson C, Becerra I, Merrill C, Wang RF, LaValle S (2019) Assessing postural instability and cybersickness through linear and angular displacement. Hum Factors. https://doi.org/10.1177/0018720819881254

Williams B, Narasimham G, McNamara TP, Carr TH, Rieser JJ, Bodenheimer B (2006) Updating orientation in large virtual environments using scaled translational gain. In: Proceedings of the 3rd symposium on applied perception in graphics and visualization (APGV'06). ACM, pp 21–28. https://doi.org/10.1145/1140491.1140495

Williams B, Narasimham G, Rump B, McNamara TP, Carr TH, Rieser JJ, Bodenheimer B (2007) Exploring large virtual environments with an HMD when physical space is limited. In: Proceedings of the 4th symposium on applied perception in graphics and visualization (APGV'07). ACM, pp 41–48. https://doi.org/10.1145/1272582.1272590

Williams B, Narasimham G, Westerman C, Rieser JJ, Bodenheimer B (2007) Functional similarities in spatial representations between real and virtual environments. ACM Trans Appl Percept 4(2). https://doi.org/10.1145/1265957.1265961

Wilson RA, Foglia L (2011) Embodied cognition. In: Zalta EN (eds) The Stanford encyclopedia of philosophy. Stanford University. https://plato.stanford.edu/archives/spr2017/entries/embodied-cognition

Wilson A, Golonka S (2013) Embodied cognition is not what you think it is. Frontiers in psychology, 4, 58. https://doi.org/10.3389/fpsyg.2013.00058.

Wilson R A, Keil FC (eds) (2001) The MIT encyclopedia of the cognitive sciences. Cambridge, Massachusetts: The MIT Press.

Wilson JR (1997) Virtual environments and ergonomics: needs and opportunities, Ergonomics 40(10):1057-1077. https://doi.org/10.1080/001401397187603

Wilson JR, Nichols S, Haldane C (1997) Presence and side effects: complementary or contradictory? In: Smith MJ, Salvendy G, Koubek RJ (eds) Design of computing systems: social and ergonomic considerations. Elsevier, Amsterdam, pp 889–892.

Wilson PT, Kalescky W, MacLaughlin A, Williams B (2016) VR locomotion: walking > walking in place > arm swinging. In: Proceedings of the 15th ACM SIGGRAPH conference on virtual-reality continuum and its applications in industry (VRCAI'16). ACM, pp 243–249. https://doi.org/10.1145/3013971.3014010

Wirth W, Hartmann T, Blocking S, Vorderer P, Klimmt C, Schramm H, Saari T, Laarni J, Ravaja N, Gouveia F, Biocca F, Sacau A, Jäncke L, Baumgartner T, Jäncke P (2007) A process model of the formation of spatial presence experiences. Media Psychology, 9(3), 493–525. https://doi.org/10.1080/15213260701283079

Witmer BG, Singer MJ (1998) Measuring presence in virtual environments: a presence questionnaire. Presence Teleoperators Virtual Environ 7(3):225–240. https://doi.org/10.1162/105474698565686

Witt J, Sugovic M (2013) Catching ease influences perceived speed: evidence for action-specific effects from action-based measures. Psychon Bull Rev 20(6):1364–1370. https://doi.org/10.3758/s13423-013-0448-6

Wong SCP, Frost BJ (1981) The effect of visual-vestibular conflict on the latency of steady-state visually induced subjective rotation. Percept Psychophys 30(3):228–236. https://doi.org/10.3758/bf03214278

Woollacott MH (2000). Systems contributing to balance disorders in older adults. J Gerontol Series A, 55(8):M424-M428. https://doi.org/10.1093/gerona/55.8.M424

Woollacott M, Shumway-Cook A (2002) Attention and the control of posture and gait: A review of an emerging area of research. GAIT POSTURE 16(1):1–14. https://doi.org/10.1016/S0966-6362(01)00156-4

Wraga M, Creem-Regehr SH, Proffitt DR (2004) Spatial updating of virtual displays during self- and display rotation. Mem Cognit 32(3):399-415. https://doi.org/10.3758/bf03195834

Wright JC, Huston AC, Vandewater EA, Bickham DS, Scantlin RM, Kotler JA, Caplovitz AG, Lee J (2001) American children's use of electronic media in 1997: A national survey. J Appl Dev Psychol 22(1):31–47. https://doi.org/10.1016/S0193-3973(00)00064-2

Xie X, Lin Q, Wu H, Narasimham G, McNamara TP, Rieser JJ, Bodenheimer B (2010) A system for exploring large virtual environments that combines scaled translational gain and interventions. In: Proceedings of the 7th symposium on applied perception

in graphics and visualization (APGV'10). ACM, pp 65–72. https://doi.org/10.1145/1836248.1836260

Yardley L, Gardner M, Bronstein A, Davies R, Buckwell D, Luxon L (2001) Interference between postural control and mental task performance in patients with vestibular disorder and healthy controls. J Neurol Neurosurg Psychiatry 71:48–52. https://doi.org/10.1136/jnnp.71.1.48

Yardley L, Higgins M (1998) Spatial updating during rotation: the role of vestibular information and mental activity. J Vestib Res 8(6):435-442.

Yogev-Seligmann G, Hausdorff JM, Giladi N (2008) The role of executive function and attention in gait. Mov Disord 23(3):329–342. https://doi.org/10.1002/mds.21720

Zacharias GL, Young LR (1981) Influence of combined visual and vestibular cues on human perception and control of horizontal rotation. Exp Brain Res 41:159–171. https://doi.org/10.1007/BF00236605

Zahorik P, Jenison RL (1998) Presence as being-in-the-world. Presence Teleoperators Virtual Environ 7(1):78–89. https://doi.org/10.1162/105474698565541

Zanbaka CA, Lok BC, Babu SV, Ulinski AC, Hodges LF (2005) Comparison of path visualizations and cognitive measures relative to travel technique in a virtual environment. IEEE Trans Vis Comput Graph 11(6):694-705. https://doi.org/10.1109/TVCG.2005.92

Zanbaka CA, Babu SV, Xiao D, Ulinski AC, Hodges LF, Lok BC (2004) Effects of travel technique on cognition in virtual environments. In: Proceedings of IEEE virtual reality 2004, pp 149-286. https://doi.org/10.1109/VR.2004.1310068

Zank M, Kunz A (2016) Where are you going? Using human locomotion models for target estimation. Vis Comput 32:1323–1335. https://doi.org/10.1007/s00371-016-1229-9

Zeltzer D (1992) Autonomy, interaction, and presence. Presence Teleoperators Virtual Environ 1(1):127-132. https://doi.org/10.1162/pres.1992.1.1.127

Zhou Y, Zhang Y, Hommel B, Zhang H (2017) The impact of bodily states on divergent thinking: evidence for a control-depletion account. Front Psychol 8:1546. https://doi.org/10.3389/fpsyg.2017.01546

Zielasko D, Horn S, Freitag S, Weyers B, Kuhlen TW (2016) Evaluation of hands-free HMD-based navigation techniques for immersive data analysis. In: Proceedings of 2016 IEEE symposium on 3D user interfaces (3DUI), pp 113-119. https://doi.org/10.1109/3DUI.2016.7460040

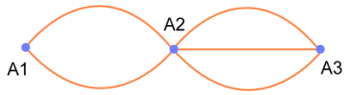
APPENDIX A.

The foundational concepts for the quantification of the degree of freedom in navigation are listed below:

1. V_i = a specific place where a character is located and from which they select a route at t_i. V = vertex

   t_i = a specific time where a character is located at V_i. t = time
2. E_i = the available set of routes from V_i
3. d (V_i)= degree of V_i , the number of available routes at a specific V_i
4. ($i \in N,\ 1 \leq i$)

1) During gameplay, the total number of routes available for a character can be expressed as the product of the routes available at each V_i.
2) For example, in the figure below, if a character follows the sequence of $A_1 \rightarrow A_2 \rightarrow A_1 \rightarrow A_2 \rightarrow ??$ (the ending vertex is not included in this case), the total number of available routes can be expressed as $2 \times 5 \times 2 \times 5$.



3) The available routes from A1 are 2, and the available routes from A2 are 5.
4) Because of the fact in Point 3 above, we may conclude that "When a character follows the sequence of $A_1 \rightarrow A_2 \rightarrow A_1 \rightarrow A_2 \rightarrow ??$, the total number of routes can be expressed as $2 \times 2 \times 2 \times 5$".
5) However, we should pay attention to the fact that, when navigating the game space, a character needs to decide which direction to move in at every moment (time) and every place (vertex) along the available route.
6) Thus, the formula should not derive from the precondition that the character knows the moving sequence. The formula should instead derive from the available routes at a specific place (V_i). This can be expressed using the following formula:

$$d(V_1)d(V_2)d(V_3)d(V_4) = \prod_{i=1}^{4} d(V_i) = 2 \times 5 \times 2 \times 5 = 100$$

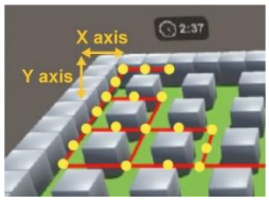


Figure 1. Bomb Hero

Figure 2. Moss

Bomb Hero

1) For Bomb Hero, the range of available routes at a specific place (V_i) can be expressed as $1 \leq d(V_i) \leq 4$
2) The yellow dots shown in Figure A1 represent a specific place (V_i) where a character could be located at a specific time (t_i)
3) At each yellow dot (V_i), we can clearly see there are fewer than four available routes.
4) In other words, the maximum number of available routes a character can select at a specific place (V_i) are fewer than 4.
5) For corners, the maximum number of available routes d (V_i) is 2, i.e., fewer than 4. Therefore, this does not contradict the assumption explained in Point 4.
6) In the game space of Bomb Hero, the navigational direction a character can select is limited to either the x-axis or y-axis. In this case, the available V_i is finite, thus it can be expressed as $1 \leq i \leq n,\ i \in N,$ where n is a finite natural number.
7) While playing Bomb Hero, the specific places where a character is located can be expressed as $V_1 \sim V_n$
8) Based on the explanation above, the formula for the degree of freedom in navigation for Bomb Hero can be expressed as follows:

$$d(V_1)d(V_2)d(V_3)d(V_4)\ldots d(V_n) = \prod_{i=1}^{n} d(V_i) \leq \underbrace{4 \times 4 \times 4 \times \ldots \times 4}_{n} = 4^n$$

$$1 \leq d(V_i) \leq 4$$

$$1 \leq i \leq n,\ i \in N,\ n\text{: finite natural number}$$

$$d(V_1)d(V_2)d(V_3)\ldots d(V_n) \leq 4^n$$

$$\prod_{i=1}^{n} d(V_i) \leq 4^n$$

Moss

1) For Moss, the range of available routes at a specific place (V_i) can be expressed as $1 \leq d(V_i)$ $(i \in N, 1 \leq i)$
2) The spatial structure of Moss is such that the available routes a character can select at a specific place (V_i) can be infinite, unlike Bomb Hero (d (V_i): finite).
3) In the left panel of Figure A2, a specific place (V_i) could be any of the dots along the red line. In other words, the connection of the red dots produces a red line, thus each dot in the line could be a specific place (V_i). Therefore, the available V_i can be considered infinite.
4) Shown in the right panel of Figure A2, the number of available routes from the small yellow dot can be considered infinite because there is no restriction in the moving direction. If the degree of freedom in navigation is infinite at each dot, the total number of available routes is also infinite.
5) Based on the explanation above, the formula for the degree of freedom in navigation for Moss can be expressed as follows:

$$1 \leq d(V_i) \ (i \in N, 1 \leq i)$$

$$\text{if any } d(V_i) \text{ is infinite, we can get the formula below...}$$

$$\lim_{n \to \infty} d(V_1)d(V_2)d(V_3)d(V_4) \ldots d(V_n) = \infty$$

$$\lim_{n \to \infty} \prod_{i=1}^{n} d(V_i) = \infty$$

APPENDIX B.

Examples of navigation routes in the tested VR games
(Left: Bomb Hero, Right: Moss)

국문초록

가상현실은 몸과 마음이 공간에 함께 존재한다는 일상적 경험에 대해 새로운 관점을 제시한다. 컴퓨터로 매개된 커뮤니케이션에서 많은 경우 사용자들은 몸은 배제되며 마음의 존재가 중요하다고 느끼게 된다. 이와 관련하여 가상현실은 사용자들에게 커뮤니케이션에 있어 물리적 몸의 역할과 비체화된 상호작용의 중요성에 대해 연구할 수 있는 기회를 제공한다.

기존 연구에 의하면 실행, 주의집중, 기억, 지각과 같은 인지기능들이 몸의 자세에 따라 다르게 작용한다고 한다. 하지만 이와 같은 인지기능들과 몸 자세의 상호연관성은 여전히 명확히 밝혀지고 있지 않다. 특히 가상현실에서 몸의 자세가 지각반응에 대한 인지과정에 어떤 작용을 하는지에 대한 이해는 매우 부족한 상황이다.

가상현실 연구자들은 존재감을 가상현실의 핵심 개념으로 정의하였으며 효율적인 가상현실 시스템 구성과 밀접한 관계가 있다고 한다. 존재감은 가상공간에 있다고 느끼는 의식상태를 말한다. 구체적으로 가상현실 속 경험을 실재 존재한다고 느끼는 의식상태를 말한다. 이런 존재감이 높을 수록 현실처럼 인지하기에 존재감은 가상현실 경험을 측정하는 중요한 지표이다. 따라서 가상공간에 존재하고 있다는 의식적 경험 ((거기에 있다(being there)), 즉 존재감은 매개된 가상경험들의 인지 연구에 중요한 개념이다.

가상현실은 사이버멀미를 유발하는 것으로 알려져 있다. 이 증상은 가상현실의 사용성을 제약하는 주요 요인으로 효과적인 가상현실 경험을 위해 사이버멀미에 대한 다양한 연구가 필요하다. 사이버멀미는 가상현실 시스템을 사용할때 나타나며 어지러움, 방향상실, 두통, 땀흘림, 눈피로도등의 증상을 포함한다. 이런 사이버멀미에는 개인차, 사용된 기술, 공간디자인, 수행된 업무등 매우 다양 요인들이 관여하고 있어 명확한 원인을 규정할 수 없다. 이런 배경으로 인해 사이버멀미 저감과 관련한 다양한 연구들이 필요하며 이는 가상현실 발전에 중요한 의미를 갖는다.

공간인지는 3 차원 공간에서 신체 움직임과 대상과의 상호작용에 중요한 역할을 하는 인지시스템이다. 가상공간에서 신체 움직임은 네비게이션, 사물조작,

다른 에이전트들과 상호작용에 관여한다. 특히 가상공간에서 네비게이션은 자주 사용되는 중요한 상호작용 방식이다. 이에 가상공간을 네비게이션 할때 존재감에 영향을 주지 않고 멀미증상을 유발하지 않는 효과적인 공간이동 방법에 대한 다양한 연구들이 이루어지고 있다.

이전 연구들에 의하면 시점이 존재감과 체화감에 영향을 준다고 한다. 이는 시점에 따라 사용자의 행동과 대상들과의 상호작용 방식에 달라지기 때문이다. 따라서 가상공간에서 경험 또한 시점에 따라 달라진다. 이런 배경으로 몸의 자세, 공간인지, 이동방법, 존재감, 사이버멀미의 상호 연관성에 대한 연구를 시점에 따라 분류해서 연구할 필요가 있다. 이를 통해 가상현실 속 공간 네비게이션에 대한 인지과정을 보다 다각적으로 이해 할 수 있을 것이다.

그동안 존재감과 사이버 멀미에 내재된 매커니즘을 이해하기 위해 다양한 연구들이 진행되어 왔다. 하지만 몸의 자세에 따른 인지작용이 존재감과 사이버멀미에 어떤 영향을 주는지에 대한 연구는 거의 이루어지지 않았다. 이에 본 학위논문에서는 1 인칭과 3 인칭 시점으로 분류된 별도의 실험과 연구를 진행하여 가상현실에서 몸의 자세와 공간인지, 공간이동방법, 존재감, 사이버멀미의 상호연관성을 보다 심층적으로 이해하고자 한다.

제 3 장에서는 3 인칭시점의 실험과 결과에 대한 내용을 기술했다. 3 인칭시점 실험에서는 가상공간에서 몸의 자세와 존재감의 상호연관성 연구를 위해 세가지 몸의 자세 (서있는 자세, 앉은 자세, 다리를 펴고 앉은 자세)와 2 가지 타입의 공간이동 자유도 (무한, 유한)를 상호 비교했다. 실험결과에 의하면 공간이동 자유도가 무한한 경우 서있는 자세에서 존재감이 높게 나타났다. 추가적으로 가상공간에서 몸의 자세와 존재감은 공간이동자유도와 관련이 있는 것으로 나타났으며 여러 인지기능 중 주의집중이 몸의 자세, 존재감, 공간인지의 통합적 상호작용을 이끌어 낸 것으로 파악되었다. 3 인칭시점의 결과들을 종합해 보면 몸 자세의 인지적 영향은 공간이동자유도와 상관관계가 있는 것으로 추측할 수 있다.

제 4 장에서는 1 인칭시점의 실험과 결과에 대한 내용을 기술했다. 1 인칭시점 실험에서는 가상공간에서 몸의 자세, 공간이동방법, 존재감, 사이버멀미의 상호연관성 연구를 위해 두 조건의 몸의 자세 (서있는 자세, 앉아 있는 자세)와 네가지 타입의 이동방법 (스티어링 + 몸을 활용한 회전, 스티어링 + 도구를 활용한 회전, 텔레포테이션 + 몸을 이용한 회전, 텔레포테이션 + 도구를 활용한 회전)의

상호 비교가 이루어 졌다. 실험결과에 의하면 위치이동방식과 회전방식에 따른 공간이동자유도는 성공적인 네비게이션과 관련이 있으며 존재감에 영향을 주는 것으로 나타났다. 추가적으로 연속적으로 시각정보가 입력되는 스티어링 방법은 자가운동을 높여 비연속적 방법인 텔레포테이션보다 사이버멀미를 더 유발하는 것으로 나타났다. 1 인칭시점의 결과들을 종합해 보면 가상공간에서 네비게이션을 할때 존재감과 사이버멀미는 공간이동방법과 관련이 있는 것으로 가정할 수 있다.

제 3 장의 3 인칭 시점 실험결과에 의하면 몸의 자세와 존재감은 상관관계가 있는 것으로 제시되었다. 반면 제 4 장의 실험결과에 의하면 1 인칭시점으로 가상공간을 네비게이션 할 때는 공간이동방법이 존재감과 사이버멀미에 영향을 주는 것으로 나타났다. 이 두 실험에 대한 연구 결과를 통해 가상현실에서 몸의 자세와 공간인지 (네비게이션)의 상호연관성에 대한 이해를 확대하고 존재감 및 사이버멀미와 공간이동방법의 관련성을 밝힐 수 있을 것으로 기대한다.

주요어: 몸의 자세, 공간인지, 이동방법, 존재감, 사이버 멀미, 가상현실
학번: 2015-30940