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IMMERSION OF WALKING IN A VIRTUAL ENVIRONMENT

Comparative research for physical locomotion techniques

Master's thesis
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ABSTRACT

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Virtual reality (VR) has increased its popularity due to improvements in VR technology and extensive research over 25 years conducted using such technology. Physical locomotion devices have been shown to improve subjective user experience of presence defined as sense of "being there" in the virtual environment (VE) compared to artificial locomotion techniques. This thesis explores how these physical locomotion techniques used for walking interaction affect immersion and presence experienced in a VE. This study examines levels of immersion using three locomotion techniques which are omnidirectional treadmill, omnidirectional slide mill and natural walking. Immersion is examined from both objective and perceptual perspectives, creating a less common multidisciplinary study combining differing perspectives from past research.

This study used a custom-made virtual environment developed during this study using Unity and C# programming language. This environment was designed to represent a realistic Nordic Forest with crossing paths and a set of landmarks with combination of visual, audio and olfactory stimulus. The sample size collected for this thesis was 53 participants in total. The results were received using Kruskal-Wallis non-parametric statistical test combined with post-hoc Dunn's test for pairwise multiple comparisons between the groups.

The results of this study reveal that slide mill as a locomotion technique produces a significantly lower score for presence and perceptual immersion. This finding indicates that natural walk as a locomotion technique produces the highest results for these subjective user experiences which is in line with past research. On the other hand, this study did not find any statistically significant differences on average presence questionnaire results between the groups of natural walk and omnidirectional treadmill. At the same time the omnidirectional treadmill resulted in a higher score for experienced realism subscale despite using older HMD with less performant PC compared to the other two conditions. This discovery indicates that despite this the treadmill managed to produce sufficient user experience comparable to natural walking. These results shine light towards the direction that locomotion techniques influence subjective user-experiences with omnidirectional treadmill being the most immersive after natural walking.

Keywords: virtual reality, virtual environments, immersion, presence, walking locomotion, omnidirectional treadmill, omnidirectional slide mill

TIIVISTELMÄ

Emil Kaskikallio: Virtuaaliympäristössä kävelyn tuottama uppoutuminen
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Virtuaalinen todellisuus on kasvattanut suosiotaan teknologisen kehityksen sekä yli 25 vuoden takaisen kattavan tutkimuksen seurauksena. Aiemmat tutkimukset ovat osoittaneet fyysistä liikettä hyödyntävien liikkumistapojen parantavan käyttäjien kokemaa läsnäoloa ja uppoutumisen tasoa virtuaalisissa ympäristöissä. Tämä diplomityö tutkii, miten erilaiset kävelytekniikat vaikuttavat koettuun uppoutumisen (*perceptual immersion*) ja läsnäolon tunteeseen (*presence*) virtuaalisessa ympäristössä liikuttaessa. Tutkimuksessa on käytössä kolme liikkumistapaa, jotka ovat aktiivinen sekä passiivinen kävelymatto ja luonnollinen kävely. Tässä tutkimuksessa uppoutumista (*immersion*) tutkitaan sekä objektiivisesta teknologian näkökulmasta (*system-level immersion*), että subjektiivisesta käyttäjän kokemuksen (*perceptual immersion*) näkökulmasta. Tutkimuksen teoreettinen viitekehys tutkii immersion tasoa kahdesta näkökulmasta liittäen ne toisiinsa ja yhdistäen aiempien tutkimusten tuloksia.

Tässä tutkimuksessa käytettiin räätälöityä virtuaalista ympäristöä, jonka kehittäminen tapahtui tämän diplomityön rinnalla. Ympäristö rakennettiin Unityllä ja C# ohjelmointikielellä ja sen on tarkoitus esittää realistista pohjoismaista metsää. Tässä ympäristössä hyödynnetään visuaalisia, audio sekä hajuärsykkeitä osana muistin ja tilan hahmottamiseen keskittyvää tutkimusta. Tähän työhön kerätty otoskoko on 53 henkilöä, joilta kerätyt tulokset analysoitiin Kruskal-Wallis merkitsevyystestillä sekä Dunnin post-hoc testillä.

Saadut tulokset paljastavat, että passiivinen kävelymatto (slide mill) tuottaa keskimäärin merkittävästi heikomman läsnäolon ja uppoutumisen tunteen verrattuna luonnolliseen kävelyyn. Luonnollinen kävely tuottaa keskimäärin parhaan tuloksen, mikä on linjassa aiempien tutkimusten kanssa. Merkittäviä eroja luonnollisen kävelyn ja aktiivisen kävelymaton (treadmill) välillä ei tunnistettu, mikä voi kertoa aktiivisen kävelymaton olevan paras tekniikka, mikäli virtuaalisissa ympäristöissä halutaan liikkua pidempiä matkoja. Samaan aikaan aktiivinen kävelymatto tuotti korkeamman tuloksen, vaikka se hyödynsi heikompia virtuaalitodellisuuslaseja kuin kaksi muuta liikkumistapaa. Tämä puolestaan voi kertoa siitä, että kävelytekniikka saattaa vaikuttaa käyttäjäkokemukseen enemmän kuin tässä tutkimuksessa hyödynnettyjen virtuaalilasien kuvanlaatu. Nämä tulokset osoittavat, että liikkumistavat vaikuttavat subjektiivisiin käyttäjäkokemuksiin.

Avainsanat: virtuaalitodellisuus, virtuaaliympäristö, uppoutuminen, läsnäolo, liikkumistapa, monisuuntainen kävelymatto, aktiivinen kävelymatto, passiivinen kävelymatto

Tämän tutkimuksen samankaltaisuus on tarkistettu käyttämällä Turnitin -ohjelmaa.

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I have utilised AI tools in my thesis:

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The AI tools utilised in my thesis and their purposes are described below:

Names and versions of AI tools: ChatGPT-4-turbo

Purpose of using AI tools:
During the research process AI tool was used to examine limitations and past perspectives around the topic when forming the research questions and theoretical framework of this study. AI was also used for developing the Python code for data-analysis used by this quantitative research. AI was also used to give guidance with polishing key points presented in the text.

Sections where AI tools were used: Theoretical framework, Data-analysis, Discussion

I acknowledge that I am fully responsible for the entire content of my thesis, including the parts generated by AI, and accept accountability for any violations of ethical standards in publications.

PREFACE

This paper is a master thesis conducted as part of the NaviNord virtual reality research project conducted at Tampere University. This thesis is submitted for master’s degree in software engineering majoring in software production.

I am thankful for my family and friends who have supported me during my studies and helped me write this thesis and collect data. I am also thankful for my supervisors Elpida Bampouni and Juho Hamari for the guidance and possibility to be part of the NaviNord research project. The experience has taught me a lot about virtual reality, locomotion techniques, software development and data collection and data analysis as well as academic work. This experience has also given me valuable concrete experience for working with a team and progressing systematically with a software project throughout the academic year. I want to also thank Viljami Irri and Niko Väkiparta who were my team members and worked together with me developing the VR application and collecting data.

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TERMS AND ABBREVIATIONS

VE	Virtual environment
IVE	Immersive virtual environment
VR	Virtual reality
IVR	Immersive virtual reality
RDW	Re-directed walking as a locomotion technique
NW	Natural walking as a locomotion technique
OT	Omnidirectional treadmill as a locomotion technique
OS	Omnidirectional slide mill as a locomotion technique
HMD	Head-mounted display
Omnideck	Omnidirectional treadmill device
KatVR	Omnidirectional slide mill device
WIP	Walking in place locomotion method
BIP	Break in presence
IPQ	The Igroup Presence Questionnaire used in this study
FPS	Frames per second
FOV	Field of view
GPU	Graphics processing unit
CPU	Central processing unit
RAM	Random-access memory

Virtual reality: The term virtual reality is defined as the technology allowing to create and interact with three-dimensional digital environments (Lamb, 2023).

System-level immersion: In this study the term system-level immersion is defined as the objective-description of a computer system delivering the virtual environment (Slater et al.,1999). This definition considers various technical parameters of the system describing the ability to produce functionality that is as close as possible to the equivalent real-world. The parameters can be e.g. frame rate (FPS), field of view (FOV), latency and supported modalities.

Perceptual immersion: A subjective user experience of immersion defined as a perceptual response to the degree of system-level immersion (Witmer & Singer, 1998; Slater et al., 1999). In this study measured by using engagement questionnaire.

Immersion: In this study the term immersion is defined as an umbrella term covering both system-level and perceptual perspectives of immersion.

Presence: The term presence is defined as the user's response to the provided level of immersion both system-level and perceptual (Witmer & Singer, 1998; Slater et al., 1999).

Cybersickness: Cybersickness is defined as a term describing symptoms of motion sickness experienced during a VR experience (Chang et al., 2020). The symptoms can include e.g. eye fatigue, nausea, disorientation.

Omnidirectional treadmill: Is defined as a locomotion device which uses active repositioning system such as motorized rollers for constantly countering forces resulted from users walking movement (Nilsson et al., 2018).

Omnidirectional slide mill: Is defined as a locomotion device which uses a passive repositioning system implemented with for example low friction surfaces passively keeping the user in place while they walk (Nilsson et al., 2018).

Natural walking as a locomotion technique: Is defined as a locomotion technique allowing to directly transfer the tracked position and movement of the HMD in 6 degrees of freedom to the corresponding movement of the user's avatar in virtual environment (Lochner & Gain, 2021).

Head-mounted display: Head mounted display (HMD) units represent a wearable display device which allows users to perceive virtual environment through stereoscopic images rendered to both of their eyes.

1. INTRODUCTION

It is commonly known that virtual reality (VR) applications have become increasingly popular for the past 25 years. In fact, the company behind social media platforms Facebook and Instagram, changed their name to Meta in 2021 with an ambitious goal of bringing ‘the Metaverse to life’ (Meta, 2021). With the current understanding, the metaverse would be a VR counterpart for today’s social platforms. Technology around VR has improved significantly, with wearable head-mounted displays (HMDs) becoming progressively lighter and more performant (Angelov et al., 2020; Fuchs, 2017, 3-5). While this technology has not yet reached a level of life-like VR (Cuervo et al., 2018; Al-Jundi & Tanbour, 2022) the cost of HMD technology has decreased drastically making VR more available for consumers and enterprises than ever before (Angelov et al., 2020; Fuchs, 2017, 3-5).

Motivation for studying immersion and presence of virtual reality is grounded in previous research. Concepts of immersion and presence in context of VR have been studied throughout the past 25 years by numerous scholars. Improved VR technology has offered better performance and higher fidelity, leading to increasingly immersive experiences. In contrast, 26 years ago, a resolution of 640 by 480 pixels was considered as excellent with vibrant colours and 30 Hz refresh rate (Usoh et al.,1999). Today’s consumer HMD devices offer a minimum suggestion of 75 Hz refresh rate and over 14 times the number (640x480) of pixels per-eye (Angelov et al., 2020). Yet the landmark studies conducted over two decades ago have shown high relevance to this day by being cited over 402 (Slater et al., 1995) and 526 times (Usoh et al.,1999) in the recent five years alone (Zielasko et al., 2024). Improvements in VR technology has led to discover new ways to explore and interact with virtual environments by various artificial and physical locomotion methods (Slater et al., 1993; Slater et al. 1995; Tan et al., 2022; Diaz et al., 2024).

Research around VR has emerged to create various experimental use cases for this technology. These use cases and innovations include, but are not limited to, multimedia learning (Makransky & Mayer, 2022), collaborative virtual environments (Narayan et al., 2005), procedural training (Sowndararajan et al., 2008), VR-based therapy (Mahalil et al., 2014), simulations, science, sports and games (Slater & Sanchez-Vives, 2016) and spatial understanding of complex underground systems (Schuchardt & Bowman, 2007).

In many of the above use cases, higher level of immersion has shown significant improvement with task performance measured by both time and accuracy. Participants have been mentioned to prefer systems with higher level of immersion (Schuchardt & Bowman, 2007). Results reveal that, as the complexity of the task or training scenario increases, higher level of immersion begins to correlate with increased task performance and decreased error rate (Sowndararajan et al., 2008). The higher the presence and level of immersion is, the more engaged the users tend to become with the virtual environment (VE) leading to better task performance, better results in stress therapy, simulation training and experimental learning (Slater & Sanchez-Vives, 2016; Mahalil et al., 2014; Schuchardt & Bowman, 2007). Achieving higher levels of immersion can have crucial role when VR technology is used for performing more complex tasks around procedural learning or spatial awareness in 3D environments. Studying immersion might therefore be a key factor for developing more effective VR applications in the future. Combination of immersive virtual environments (IVE), with the physical locomotion techniques has the potential to offer more natural ways to explore and interact with these environments.

Literature review around past research reveals that researchers have focused measuring subjective sense of presence when trying to estimate the degree of immersion. Past studies reveal that immersion is often defined either as objective measure of *system-level immersion* (e.g. framerate, latency and modalities) (Slater et al, 2003; Smith et al, 2001) or as subjective response to the virtual environment (*perceptual immersion*) (Witmer & Singer, 1998; Arsenault, 2005; McMahan, 2003; Emmi & Mäyrä, 2005), but rarely considering both perspectives together. This creates a research gap for a multidisciplinary study to combine the two diverged perspectives. It has been stated that the field of VR connects human sciences with engineering in a unique way. This creates new challenges which are still insufficiently researched (Fuchs, 2017, 4-5), one of them being the influence of kinaesthetic modalities in immersive virtual environments.

Systematic review for multisensory VR studies reveals that 84.8% of studies show positive impacts with multisensory VR, while at the same time smell and taste modalities are mentioned to be underexplored (Melo et al., 2022). Including less common olfactory modality with physical locomotion makes this study more interesting and relevant to be researched. The goal of this paper is to bridge the research gap between presence and divergent perspectives of immersion while at the same time introduce less frequent combination of modalities by including smell. This study aims to bridge the gap by examining how physical locomotion techniques influence presence and perceptual immersion while still covering the variations in technological system-level immersion. Studying the physical locomotion techniques and both perspectives of immersion can be crucial when developing more affordable yet more immersive VR environments and systems in the future.

1.1 Research questions and objectives

This research paper examines how locomotion techniques for physical walking interaction in VR may influence user reported sense of *presence* and *perceptual immersion*, in context of a multisensory immersive VR environment. The locomotion techniques examined by this research are natural walking (NW), omnidirectional treadmill (OT) and omnidirectional slide mill (OS). Technical characteristics of locomotion techniques are documented and presented as objective measures of *system-level immersion*. This study uses a three-dimensional immersive virtual environment representing a realistic nordic forest offering visual, audio and olfactory stimuli. The study has been conducted as exploratory comparative research benefitting from both qualitative and quantitative analysis.

The goal of this thesis is to bridge the research gap between objective and subjective definitions of immersion as well as increase understanding of producing VR research with high reproducibility from the co-existence of both measures. The study aims to give answers how the locomotion method and objective *system-level immersion* including performance, hardware, and locomotion affects *perceptual immersion* and *presence*. Based on questionnaire data and extensive literature review, the following research questions are answered.

RQ1: *How walking locomotion techniques influence subjective senses of presence and immersion in an immersive multimodal virtual environment?*

RQ2: *How does system-level immersion, as influenced by locomotion technique, hardware, and performance, impact subjective senses of presence and immersion?*

H1: *Natural walking as locomotion technique will result in a higher user-reported presence and perceptual immersion compared to treadmill or slide mill-based locomotion techniques.*

H2: *Omnidirectional slide mill will result in the lowest user-reported presence and perceptual immersion compared to natural walk or omnidirectional treadmill.*

H3: *The selected locomotion technique will be more critical to the user-reported presence and perceptual immersion than other system-level metrics.*

By answering the formed research questions and hypothesis, additional knowledge considering different types of locomotion techniques and immersion will be achieved. The answers to research questions can bring valuable insights how technical metrics might affect the sense of presence and perceptual immersion in VR applications. The used approach also creates a study with high reproducibility since the equipment and performance will be documented in as much detail as possible.

1.2 Conceptual framework and limitations

This section presents the conceptual framework of this study, formed before starting the extensive literature review and research process. The conceptual framework combines concepts from past research considering an expected relation between two key terms *presence* and *immersion* before forming the final theoretical framework of this study. This conceptual framework describes the core concepts guiding the further literature review presented in theoretical background.

The conceptual framework was also used for forming the research questions of this thesis in advance. In this conceptual framework the term immersion is defined only as the objective system-level immersion. This includes various parts of the system such as the FPS, FOV, and locomotion technique. When the term immersion is defined as objective description of the system, presence is defined as the human response to the "immersiveness" of the system (Slater et al., 2009). This conceptual framework is illustrated below in the figure 1.

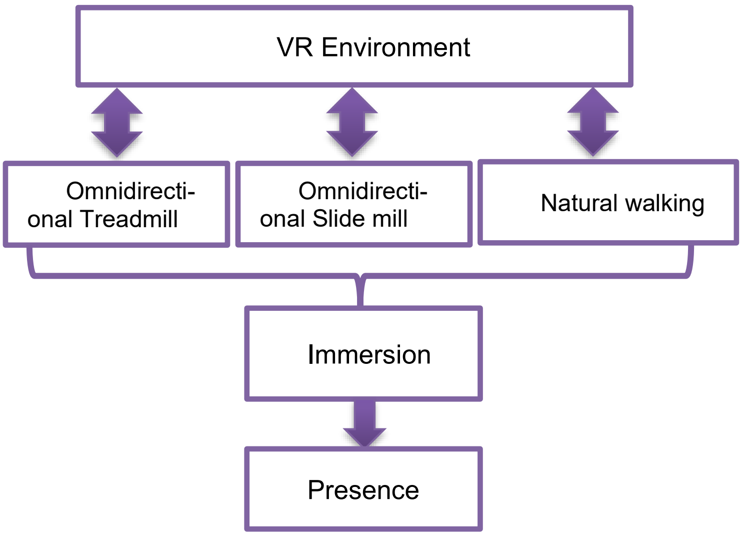


Figure 1. *Conceptual framework*

This conceptual framework describes an assumed relation between technology and user-reported sense of presence illustrated above. In this framework, Omnideck, KatVR and Natural Walk are locomotion techniques used for walking interaction with the same virtual environment. The key assumption of this conceptual framework is that immersion affects subjective user experience of presence and level of immersion is affected by the locomotion technology.

Some of the past research pinpoints that the sense of *presence* might not be affected by the used locomotion technique after the participants gets used to the virtual environment and method for interaction (Soler-Domínguez et al., 2020). This study still expects each locomotion technique to create variance in the reported *presence* and immersion more than previous more constrained locomotion methods such as walking in place or teleportation. Other studies have found out that movement methods which involve natural movement of walking tend to produce higher sense of presence (Zielasko et al., 2024; Slater et al., 1995), however past research comparing the differences of the physical locomotion devices is still limited.

The previous methods such as walking in place and teleportation can be argued to have lesser degree of immersion due to the constrained movement. Therefore, it is expected that the test setup containing the natural walk could reach higher scores for presence and perceptual immersion as it allows the most natural movement inside a VE. This study will also include a combination of visual, audio, and olfactory stimuli. Based on a review done in 2022 this combination of modalities represents approximately 9.5% of the past studies around VR and presence (Melo et al., 2022).

There are also limitations to this study and the approach used for this thesis. Key areas such as the code written or design practices used for the environment, other studies conducted in the same environment, physiological or psychological measures are not considered for the conciseness of this thesis. This thesis is also focused only on comparing physical walking locomotion techniques, therefore does not consider artificial locomotion methods such as teleportation.

The test setup used in this study will change along with one of the locomotion techniques which forms the possibility to research how the user-experience might be affected by different locomotion technique but also the changes in hardware and performance. The differing specifications of the systems used in each experiment will be documented and considered as parts of system-level immersion. The focus is to determine the effects of the locomotion techniques to the user-reported presence while still taking into consideration the system level variances and performance related metrics as part of system-level immersion.

1.3 Research methodology

This study is conducted using a quantitative approach leveraging the use of presence – and engagement questionnaires to explore user experience across different locomotion techniques. Perceptual immersion is measured using engagement questionnaire. An exploratory analysis is used to examine how variations in system-specifications and locomotion methods influence reported *presence* and *perceptual immersion*. Additionally, an extensive literature review is done to provide sufficient background knowledge of the past research around immersion, presence, VR, and locomotion technology and cybersickness. Based on the literature review a theoretical framework is formed to illustrate and clarify relations of variables based on past research.

This study used three locomotion techniques which were natural walk (NW), and omnidirectional treadmill (OT), and omnidirectional slide mill (OS). The participants were voluntary people (N=53) who were divided into three groups which participated in the experiment once by using one of the above locomotion techniques. The final group sizes for this study were the following, NW (N=14), OT (N=20), OS (N=19).

The virtual environment used by this study was developed during autumn 2024 before forming the research questions. Development was continued along this research on spring 2025 before starting with pilot experiments during March 2025 followed by the official data collection conducted between April and May 2025. The environment presents a realistic nordic forest with a set of landmarks and crossing paths. The landmarks are recognizable 3D objects with different combinations of visual, audio, and olfactory stimuli.

More data that this thesis is not exploring were also collected during this research such as cybersickness, spatial cognition and memory. The VR experiment took approximately 2 hours per participant with small breaks between experiments. After the experiment in VR, a Lime survey was given to each participant where the questionnaires of this study were added along with other measures from other studies. The whole procedure took under 3 hours per participant and 20 € gift cards were given as a compensation for participating in this research.

1.4 Structure

This thesis is formed from total of six sections which are introduction, theoretical background, research methodology, results, discussion, and conclusion. After the introduction the theoretical background examines and combines information from the past research considering aspects of VR and locomotion technology, cybersickness, immersion, and presence including various ways for measurement. The theoretical background will critically analyse results from various studies to achieve a clear understanding of similar studies in the past. This section is then followed by the research methodology which will present research methodology and procedure in close detail. The research methodology is followed by the results which are analysed using statistical methods. The received outcomes are discussed in the separate discussion section combining them with provided theoretical background. Lastly, conclusion provides encapsulated answers to the research questions, implications, limitations, and focus for future research.

2. THEORETICAL BACKGROUND

This section introduces the current state of the past research related to VR, VEs, Immersive Virtual Reality (IVR), definitions of immersion and presence, and the concepts of measuring them in the context of virtual environments. This section will also introduce the past research around physical locomotion techniques, head-mounted display (HMD) technology, and cybersickness. The goal of this section is to emphasize the critical terms and concepts used in this study.

2.1 The concept of immersion

Open academic discussion around the term immersion has been ongoing since the 1990s. Studies mention that there is no unified definition for the term and due to this the term has been used in numerous ways and contexts (Smith et al., 2001). A landmark study Measuring Presence in Virtual Environments: A Presence Questionnaire from Witmer & Singer 1998 outlines that *"Immersion is a psychological state characterized by perceiving oneself to be enveloped by, included in, and interacting with an environment that provides a continuous stream of stimuli and experiences"*. Their study disagrees with another landmark study from Slater et al 1995, which defines immersion as an objective technical description of what a particular system can deliver.

Both perspectives have been used across VR studies in the past, however, majority of the studies have focused on immersion as a subjective user experience. Slater et al 1995 on the other hand state that *"Whether or not a system can be classified as immersive depends crucially on the hardware, software, and peripherals (displays and body sensors) of that system. We use "immersion" as a description of a technology, rather than as a psychological characterization of what the system supplies to the human participant".* Their description contains technical details of the system such as display resolution, latency, haptics, framerate and field of view. It is still considered that additionally for having objectively vivid display the information shown must allow the participants to construct their own mental model of reality (Slater et al., 1995). This includes e.g. matching the movement recorded by the locomotion with the display without significantly noticeable lag. The perceptual response to the level of technical level of immersion is then defined as a subjective sense of presence (Slater et al.,1999).

Both perspectives have been noticed by the VR research community as according to a study from the presence questionnaires developed by Witmer & Singer 1998 and Slater et al 1994 have been the most cited according to Google scholar in 2018 and many modified versions of the questionnaires can be assumed to exist by now (Schwind et al 2019). As there is no unified definition for these terms both definitions have been liberally used with varying ways. In some research immersion might have been used to describe both terms (immersion and presence) at once or they might be split to different mental and physical components (Smith et al., 2001). The different definitions for immersion are summarized in a table below. The table shows that most of the definitions around the term immersion focus on the perceptual response while the system-level immersion is still included. Based on the table it could be argued that the term immersion seems to be a factor of both perceptual response but also the technological capabilities of the system.

Table 1. *Definitions of the term immersion*

Authors	A Property of the system	A subjective user experience
(Slater et al., 1999)	Immersion is defined as objective capabilities and fidelity of the technology (display, tracking, modalities) providing the virtual environment.	
Witmer & Singer (1998)		Immersion is defined as a psychological state formed from the user perceiving their self to be enveloped by, included in, and interacting with a virtual environment providing continuous stimuli
McMahan (2003)		Immersion is defined as the experience of being surrounded by the virtual environment, increased by big screens and better sounds.
Ermi & Mäyrä (2005)		Sensory immersion is defined as the feeling of being surrounded by a virtual environment presented by large screens and powerful sounds.

As can be seen from the table 1 above the two different definitions describe similar concept from two different perspectives. While the term system-level immersion is described to increase as the fidelity of the technological properties increases, the perceptual response leaves the technical details ambiguous with words such as “bigger screens and powerful sounds” (Ermi & Mäyrä 2005; McMahan 2003). Still considering that the sensation (of perceptual immersion) is “enveloped by”, “increased” and “presented by” the technological devices which form the virtual environment (Ermi & Mäyrä 2005; McMahan 2003; Witmer & Singer 1998). Combination of these definitions can lead to conclusion that the total degree of immersion could be formed from both the technological properties of the system, but also by the user’s response to the fidelity of the system.

These two objective and subjective perspectives around the field of immersion and virtual reality might be formed due to the unique challenges of the VR field around engineering and human sciences. The field of VR has been mentioned to couple these fields in unique way, which can make it harder to train actors of this field to (Fuchs, 2017, 4-5). User of any virtual reality application is immersed in the virtual environment, and they perceive, decide and act in this environment based on standard “perception, decision, action” loop which is constrained by all technical, physiological, and cognitive constraints (Fuchs, 2017, 4-5). This strengthens the implication that both perspectives should be included in studies around immersion due to the multidisciplinary nature of the VR field.

2.1.1 Immersion as objective property of a system

Degree of immersion was conceptualized to depend on the number of sensor modalities supported by the immersive system (Smith et al., 2001). For example, virtual environment which supports only audio modalities might have lower degree of technological immersion than the same environment with both audio and haptic feedback. As the objective degree of immersion increases, the chances of achieving mental presence tend to increase. (Smith et al. 2001) This approach is in line with the perspective of defining immersion and “immersiveness” as a property of the system. Immersion requires that e.g. the information shown on a display matches the body movements of the user as accurately as possible (Slater et al., 1995). Based on this figure 2 below was adapted from Smith et al. (2001) by adding the locomotion as an additional factor for increasing immersion.

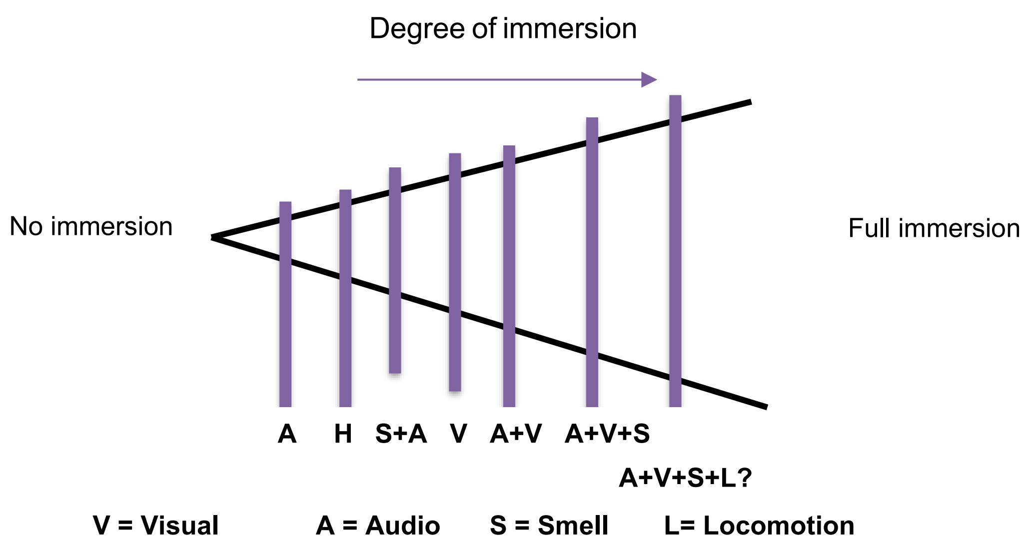


Figure 2. *Degree of immersion. Adapted from (Smith et al.,2001)*

The figure above represents the concept for degree of immersion as objective property of the system, defined in this study as *system-level immersion*. Based on this concept it is expected that the selected locomotion technique would affect the level of immersion and therefore the user-reported presence. This study expects higher user-reported presence for natural walk as locomotion technique (H1) and therefore argues that also the fidelity of the locomotion system should affect user-reported presence.

The differences between the techniques could be related to the level of mapping the users body movements as accurately as possible (Slater et al., 1995). If the presence scores would not be affected by the different locomotives it could be argued that the objective degree of immersion would not be affected by the chosen locomotion technique. The technical details for *system-level immersion* are further discovered in the Barriers section. Next section focuses on measuring the perceptual sensation of immersion followed by the concept of presence.

2.1.2 Immersion as subjective user experience

Many of the past studies around immersion and presence have focused on measuring immersion solely as a perceptual response (Nilsson et al, 2016). Measuring of *perceptual immersion* has been achieved using various questionnaires developed for different VR use cases (Oliveira et al., 2016). Separate questionnaires such as the game engagement questionnaire GEQ were developed to measure level of engagement in video games (Brockmyer et al., 2009). Along with a popular presence questionnaire PQ from Witmer & Singer (1998) they also developed an immersive tendency questionnaire (ITQ) in 1992. This questionnaire measured the user's tendency to become immersed and involved in the virtual environment. They argued that immersion and engagement might be necessary conditions for the existence of presence which will be further explained in the following sections (Witmer & Singer, 1998). The ITQ was originally developed for identifying individual differences affecting experienced sense of presence and showed a significant correlation with the scores of their presence questionnaire (PQ) (Witmer & Singer, 1998).

For this study, it is important to emphasize that immersion as a perceptual response (*perceptual immersion*) is similar, yet not the same as the sense and experience of presence. Based on past research they are separate user-experiences which reflect different aspects of engagement with a virtual environment:

> *"Though the VE equipment configuration is instrumental in enabling immersion, we do not agree with Slater 's view that immersion is an objective description of the VE technology (Slater, Linakis, Usoh, & Cooper, 1996). In our view, immersion, like involvement and presence, is something the individual experiences"*
>
> *- Witmer & Singer, 1998*

Studies have stated that the sense of immersion and presence could be understood as level of continuous engagement. The original presence questionnaire from Witmer & Singer (1998) was revisited again in 2005 when participants (N=325) were placed in an immersive virtual environment. The results of the updated questionnaire revealed that individuals with the ability to easily and rapidly adapt to the virtual environment sensed a greater level of immersion. The original questionnaire was divided into factors of involvement, sensory fidelity, interface quality, and since the new version additional adaptation/immersion (Witmer & Singer, 2005). For this reason, studies argue that engagement might be crucial for immersion and both immersion and engagement would together be crucial for experiencing presence (Witmer & Singer, 2005; Brockmyer et al., 2009; Oliveira et al., 2016).

2.2 The concept of presence

Despite the differences in the definition of the term ‘immersion’ several studies seem to agree that presence can be defined as the user’s propensity to be part of the virtual environment, as if it was real while physically being present in another physical environment. This is defined by past research as the experience or sense of “being there” (Slater et al.,1999; Witmer & Singer, 1998; Smith et al., 2001). Studies outline that the sense of presence would depend on the user’s ability to move their focus towards a VE from their physical environment. The sharper the users focused attention on the VE is, partially determines their level of involvement and reported presence. This leads to a conclusion that both involvement and immersion might be necessary for experiencing presence (Witmer & singer, 1998).

As presence is mentioned to require high level of focus, involvement, and immersion towards a VE, at the same time, both immersion and presence have been shown to have crucial roles sustaining the continuous engagement of users, leading to better results in various use cases (Slater & Sanchez-Vives, 2016; Mahalil et al., 2014). This highlights the impact of immersion and sense of presence as they seem to direct the users focus more on the VE contributing to the sustained engagement. The sustained level of engagement might then strengthen the experienced sense of presence. The table 2 below presents different definitions for the term presence gathered from past research.

Table 2. *Definitions of the term presence*

Author	Definition of presence
(Witmer & Singer, 1998)	“Something the individual experiences and perceives that they interact directly with the virtual environment feeling they are part of the environment.”
(Slater et al., 1999)	“A state of consciousness, the (psychological) sense of being in the virtual environment, and corresponding modes of behaviour”.
(Smith et al., 2001)	“A mental sense of being there in the virtual environment increasingly reinforced by stronger degree of immersion”
(*Presence Defined – ISPR*, n.d.)	“A psychological state or subjective perception in which even though part or all of an 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. Except in the most extreme cases, the individual can indicate correctly that s/he is using the technology, but at *some level* and to *some degree*, her/his perceptions overlook that knowledge and objects, events, entities, and environments are perceived as if the technology was not involved in the experience. Experience is defined as a person’s observation of and/or interaction with objects, entities, and/or events in her/his environment; perception, the result of perceiving, is defined as a meaningful interpretation of experience.”

Since the sense of presence is a subjective user experience it might be hard to achieve for every user of the virtual environment. It is pointed out that even the same immersive system might exhibit different levels of presence with different people, while different immersive systems might be able to produce the same levels of presence for others (Slater et al., 2009). This discovery has led to a theory of whether to achieve the sense of presence there could be two potential ways. The first way would be to construct a system producing such a high-fidelity environment so that it would become indistinguishable from the reality. The other way would be to study key components of our perceptual system to discover what is important for our representation of reality. This could allow to achieve presence even with lower level of system-level immersion (Slater et al., 2009). This subjective nature of the experience of presence represents a paradigm where it is not always clear why some users might reach mental presence while others cannot. The following subsection focuses on the measurement methods of presence and discusses limitations of each approach.

2.2.1 Measuring presence

In general, there are three approaches for measuring presence which are, questionnaires, behavioural methods, and moments of breaking in presence (BIP) (Slater et al. 2009). These are measures which allow to estimate the levels of perceived presence users might be sensing. All the mentioned methods can be combined with each other but will also have their own limitations which will be discussed here in this section.

A common way for measuring the sense of presence is to use presence questionnaires which by now have been developed in various forms. According to Schwind et al. (2019) most common questionnaires cited by previous research have been the developed by Witmer & Singer (1998), Usoh/Slater et al. (1994/2000), and Schubert et al. (2001). Presence questionnaires, however, have shown to be unable to determine a statistical difference between virtual reality and actual reality. In an experiment where participants had to participate in an experiment implemented in both virtual and real office space the participants mean score for 'actually being there' in the actual office space was only four out of seven. This shows that the questionnaire results are doubtful at least when comparing scores of different environments (Usoh et al., 2000). The creators of one of the questionnaires tested states that their presence questionnaires are still internally consistent measures with high reliability when used in the context of virtual environments (Witmer & Singer, 1998). It is then argued that for comparing different environments the questionnaires should pass this so called 'reality test' (Usoh et al., 2000).

The behavioural methods on the other hand require the environment to include specific features which might lead to common real-world behaviour and reflexes (Slater et al. 2009). For example, dodging an object would be a common reaction achieved in real world. Such bodily movement can be seen as an indication of higher presence produced by the virtual environment. Behavioural approach can also be implemented combined with physiological measures such as measuring heart rate. The limitation for these measures is that to estimate the level of presence the participants response for certain situation should be known or truly obvious. Such reactions as fear could be used but this limits the usage of physiological measures to experiments where this is feasible (Slater et al., 2009). Physiological measurements also require additional hardware and analysis which might make them more complex to implement.

The third known method is to use moments of BIP which can be combined with the physiological measurements. The term BIP describes any phenomenon during the VE exposure that might lead the participant into awareness of the real-world e.g. getting tangled with cables (Slater et al., 2009). If the number of reported BIPs is low, it can be an indicator that the immersion and sense of presence was therefore high during the experience.

2.3 Evolution of virtual reality and walking interaction

The first fictional description for the term virtual reality dates to a fictional story of Pygmalion's Spectacles written by American science fiction writer Stanley G, Weinbaum. The story describes a new pair of goggles which enable 'a movie style' experience but with sight, sound, taste smell and touch (Weinbaum, 1935) Despite the fictional characteristic of the story the described characteristics are close to the experience of the VE used in this research. Excluding the sense of taste the VR experiment used in this research offers visual, sound and smell stimulation by using dedicated devices. Additionally, this research examines the additional possibility to interact with the VE using locomotion technology for walking and exploring.

First studies around walking locomotion and virtual reality presented early implementations of walking in place (WIP) methods allowing users to explore virtual environments more naturally for the first time. These methods allowed to transfer physical movements to movement in virtual environment for the first time. The early implementation of the technique used a neural network to detect steps from the participants movement data (Slater et al., 1993; Slater et al., 1995). Early research efforts around walking locomotion derived from a new idea by the time, that subjective sense of presence might be affected by matching the movement of human body with its virtual counterpart. Before walking locomotion, the movement in VR was achieved by using artificial methods such as hand gestures or gaze (Slater et al., 1995).

Natural walking movement resulted in the highest levels of immersion and presence, which was remarkable discovery by the time. This finding with WIP methods from Slater et al. (1995) were later confirmed by Usoh et al (1999) replicating the study with new comparison group from natural walking. This allowed the participants to walk around a tracking area freely rather than only moving their feet in place. It was discovered by the replication effort that WIP approach resulted in higher presence than 'flying' (artificial locomotion) method while the natural walk scored the new highest. VE used by this study was constructed to present two rooms connected with a door. In one of the rooms a deep pothole was placed in the middle of the floor with only narrow ledge going around the room. The participants then had to make their way to the other side of the room with the pothole in the centre. This study showed that the presumably immersed participants refused to get to the other side or otherwise had hard time avoiding this so called ‘virtual pit’ when entering the second room. This finding was a remarkable but unexpected by the time and highlighted the experience of presence and immersion for the first time (Usoh et al., 1999; Slater et al., 1995).

Since the two studies around walking locomotion and the virtual pit were conducted over 25 years ago Zielasko et al., (2024) proposed a replication effort with updated hardware equipment and study design to bring the study to current standards. This was also motivated by the past studies still being cited over 402 (Slater et al., 1995) and 526 times (Usoh et al.,1999) for the past five years (Zielasko et al., 2024). Several walking in place methods have been implemented since the study of virtual pit, in various forms e.g. Head-bob, Arm-swing, Leg-lift, Full body (Tan et al., 2022). Additionally, a treadmill based alternative omnidirectional locomotion techniques have been implemented e.g. Infinadeck, Cyberirt Virtualizer elite 2, EKTO VR, Voyager boots (Diaz et al., 2024) and as we conduct in our research omnidirectional treadmill (Omnideck) and slide mill (KATVR). These technologies will be discussed further in their own sections below.

The replication efforts of the older studies could also be argued to be relevant since the technology around VR has evolved significantly. For example, the modern standard for refresh rates in VR is set to be at least 75 Hz while by the time 30 Hz was achieved with the studies (Angelov et al., 2020). The HMD used in the original studies provided by the time excellent resolution of 640x480 pixels (Usoh et al.,1999). This resolution happens to be at least 14 times less than what the modern Oculus Quest 3 offers per-eye. The drastic development around VR technology creates an additional motivation for studying presence and immersion with modern equipment.

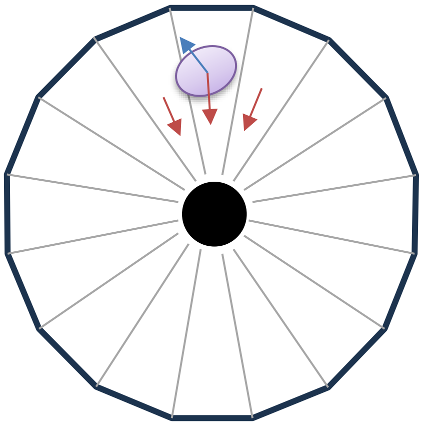
2.3.1 Omnidirectional locomotion devices

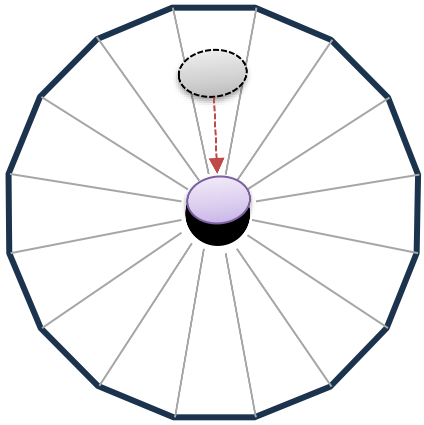
Omnidirectional treadmills are mechanical locomotion devices which allow users to cover large distances in virtual environment while still staying on the treadmill (Diaz et al, 2024). Keeping users within the tracking area while they walk is achieved by using either active or passive repositioning system (Nilsson et al., 2018). Active repositioning systems track the user’s movement and actively adjust the locomotion system to keep the user centred within the tracking area (Nilsson et al., 2018; Diaz et al., 2024). Passive repositioning systems on the other hand may use a separate safety harness to keep the user in the tracking area while they walk in place (Diaz et al., 2024).

Early implementations of omnidirectional treadmills used a pedal-based approach (Darken et al., 1997). Since then, devices such as wheel and belted treadmills have been implemented to offer increased speed, acceleration, and natural feel by improving the power transmission (Diaz et al., 2024). While allowing more natural movement these devices have still shown to come with drawbacks of increased cyber sickness, ingress, and egress and restricted movement (Darken et al, 1997). Yet these devices have presented potential to replace software-based traditional locomotion techniques such as teleport or early artificial walking in place methods. This is due to their ability to still offer better user experience, less breaks in presence while reducing the requirement of large, tracked spaces (Diaz et al, 2024).

Active repositioning system could be implemented for example by using motor-controlled rollers which counter users' movements (Nilsson et al., 2018). One example of a roller based omnidirectional treadmill is the Omnideck used in this study. This device introduces a treadmill shaped as a hexadecagon with 16 sectors of rollers guiding the user towards the centre (*The Omnideck - Omnifinity*, 2022). When the user walks on actively repositioning treadmill the device adjusts constantly to counter users' movements guiding the user back towards the centre. In case of the Omnideck for example the speed of the rollers is controlled according to players distance from the centre point. This creates a treadmill where the user can walk freely while staying in the tracking area, but unlike regular treadmills the user can walk towards any direction.

Actively repositioning omnidirectional treadmills have their own drawbacks which can affect overall user experience, adaptation, and number of breaks in presence (Diaz et al., 2024). For example, when the user stops walking this type of treadmill might keep moving until the user is returned to the centre of the device. This results the user moving backwards in real world while their avatar continues to move forward in the virtual environment for a short period of time. This could be argued to increase the chances of cybersickness as this phenomenon might cause a sensory conflict (Chang et al., 2020). The sensory conflict could be argued to make it harder for people to adapt to the environment compared to other locomotion methods where sensory conflict would be less noticeable. The figure 3 below illustrates this behaviour in section B.





A) User walks and turns at the same time and experiences a sideways force

B) User stops walking and the treadmill moves them back to the centre.

Figure 3. *Free-body diagram of walking on actively repositioning treadmill.*

These systems might require additional adaptation due to the active repositioning mechanism. Constantly moving rollers counter users walk when they walk in a straight line, however, if the user wants to turn simultaneously while they walk, they will shift their direction to be closer to perpendicular against the force of the rollers potentially challenging their balance. This is due to a force from the rollers still pushing the user sideways towards the centre rather than parallel to the direction of their feet. This is also demonstrated in the above figure 3 section A. This phenomenon is highlighted in the case of Omnideck, but the issues of sensory conflict and balance also apply to other actively repositioning systems which try to keep the user in place while they walk.

Omnidirectional slide mills such as the KATVR represent a different sliding-based approach implemented with a slippery surface and special tracking shoes. This device has a separate safety harness which can rotate 360 degrees and move up and down freely while keeping the user in the centre. Unlike the Omnideck the KatVR can be defined as passively repositioning system which often rely on friction-free platforms (Nilsson et al., 2018). The shoes track users' steps when they are glided against the slippery surface. According to the manufacturers website this device allows natural walking and levels up immersion of virtual reality (*KAT Walk C 2 - Second-Generation Personal VR Treadmill*, 2025). The slide mill replaces some of the drawbacks from treadmill with its own challenges. The gliding approach and the safety harness allow the user to turn and stop anytime without sensory conflict. Below is a free-body figure 4 demonstrating the movement and forces affecting users' feet while walking on the device.

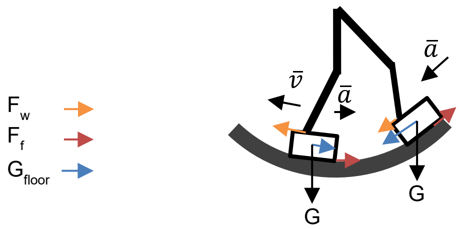


Figure 4. *Free-body diagram of walking on passively repositioning slide mill.*

The figure 4 represents forces affecting user's feet while walking on a passively repositioning system. When taking a step, they produce a small walking force F_w towards the direction of the floor together with the component force G_{floor}. A small sliding frictional force F_f resists the movement through the entire sliding motion. When their foot starts to move it has acceleration and therefore increasing velocity towards the centre of the pit. The acceleration occurs when the user overcomes static critical friction, resulting their foot to start sliding. When an object moves the frictional force becomes sliding friction which is weaker force than static friction. (Persson, 2013) Due to this user must provide more force to get their foot sliding, but once the movement is achieved the resisting force is reduced resulting increase in acceleration towards the centre. This physical phenomenon can make it difficult to control movement of objects smoothly (Persson, 2013) and could result in less natural movement.

The experience could be compared to taking steps towards a slippery uphill. This figure will not consider in a further detail the dynamics of human walking but rather demonstrate how these locomotion techniques work and how they might affect overall user-experience. Additionally, to keep the user in the centre separate harness could be used to attach the user to the device. The harness can also help with balance when walking on a slippery surface. The detailed description gives better perspective how walking on this device differs from standard walking and how does a passively repositioning system differ from actively repositioning.

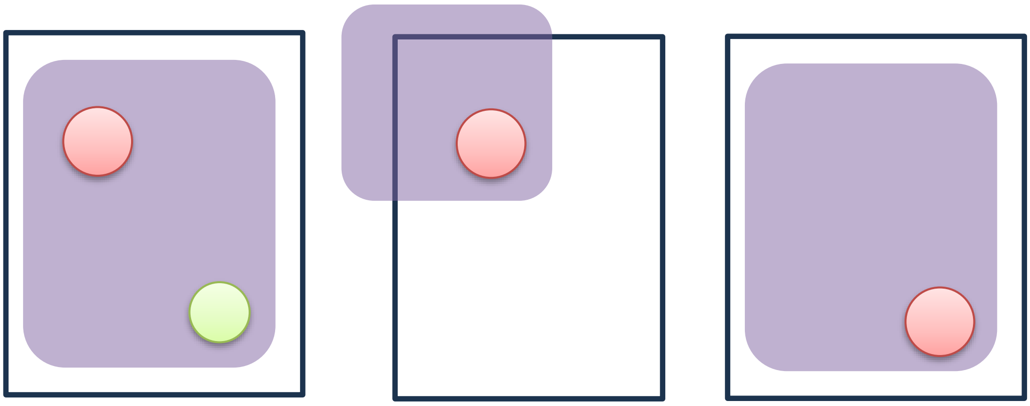
Drawbacks of the slide mill approach could be seen to be the additional safety harness which might create additional breaks in presence and the sliding-based movement which might require additional adaptation. Also, the separate tracking shoes require a fitting pair for every user to get a good experience with the device. Sliding of the feet might also cause a virtual avatar to accelerate unnaturally which might require additional adaptation but also cause cybersickness (Chang et al., 2020).

2.3.2 Natural walking in VR

Natural walk as a locomotion technique transfers tracked position of the user directly to the virtual world requiring a physical space as large as the virtual world would be. This offers the possibility for realistic exploration of virtual worlds while facing the limitation of available physical space. This on the other hand requires that the headset has support for six degrees of freedom allowing to track the HMDs position accurately (Lochner & Gain, 2021). The largest limitation of this locomotion method must therefore be the requirement of large tracking area which also introduces a so called spatial-conflict problem. This problem presents the challenge of mapping natural movement/position in smaller space for covering larger distances in a virtual world (De Back et al., 2024; Sun et al., 2020). Natural Walk may also introduce other challenges for implementation which were also faced in this study. For example, wireless implementations tend to be constrained by limited computing power or bandwidth. While wired solutions might introduce other physical problems with large tracking areas. Limitations of this study will be further discussed in the research methodology section.

Solutions to the spatial-conflict problem have been found from a method called redirected walking (RDW). This method allows the participant to think they are walking in a straight line while in the real world they walk in a slight curve. The curve creates a large but circular path allowing them to travel larger distances in virtual world. This method is based on the idea of slightly rotating the virtual world, so that the participant would not notice their path is circular in real world (De Back et al., 2024; Sun et al., 2020). There are various methods for implementing this technique, but as it is not used in this study the details are not discussed further. The past research however suggests that natural walking as a locomotion technique tends to still offer the highest task performance and user experience when a space for implementing it is available. This is then followed by redirected walking as a second option (De Back et al., 2024).

The spatial-conflict problem also presents another sub-problem considering the utilization of physical space. While the spatial conflict limits the distance a user can cover in virtual environment while walking inside a restricted physical space, the subproblem of this is utilization of the restricted space. The figure below demonstrates how the virtual environment (purple) must be positioned in a way that the user can access it from the restricted physical space (black). In case of natural walk if we would want to move the player to another location in this virtual environment the virtual environment would either be designed in a way that the user can reach it even when only moved artificially inside the virtual environment or the user would have to be guided physically to a new position in this environment.



When moving the user from red position to green in the virtual environment.

A) Not moving the user physically in the room

B) Physically moving the player to the new location in the room

Figure 5*. Spatial repositioning problem with limited available physical space*

The figure above represents the paradigm that the virtual environment (purple) must always fit inside the physical space to be accessible by the user. This means that the environments must be synced despite changes of the user position in virtual environment. If the environment stays the same and user is only wanted to move to another position inside the virtual environment it requires physically moving the user to a new location. This can occur if for example inside one environment multiple experiments are conducted which alter the user's position in this environment. This creates a problem that you will have to know the matching locations in the physical space to keep the environments in sync. Additionally, it might cause breaks in presence since the user will become aware of the physical space (Slater et al., 2009).

The challenges around natural walking as a locomotion technique have sparked interest to create innovative solutions for moving between environments while physically staying inside a small tracking area. One of these solutions is a locomotion technique called natural walking in impossible spaces. This approach moves the player between environments using a portal-based approach. For example, an apartment where the user wants to move between the rooms. When the user walks through a portal the next room or environment is rendered so that the user can walk around the new environment while staying in the same tracking area. This has resulted in higher immersion, but immersion might be reduced if the users realize that the environment is physically impossible (Lochner & Gain, 2021).

2.3.3 Virtual reality and head-mounted displays

The development of head-mounted displays also called HMDs have introduced various approaches for implementation but also developed discussion around a term called Life-like VR. Life-Like VR describes a concept of high-fidelity HMD system where the technology becomes indistinguishable from reality (Cuervo et al., 2018). Studies around this term try to determine what are the key specifications the technology would have to match to reach life-like experience. Other studies have focused on identifying the key specifications of our current modern HMD devices and their effects on presence, immersion and cybersickness (Angelov et al., 2020).

There are two categories for modern HMD devices which are standalone and tethered. Standalone means that the head mounted device can run the virtual environment on its own computational hardware natively. Tethered headsets on the other hand require a separate computer along with the headset for rendering the virtual environment and streaming the image to the headset. Tethered headsets are often wired to the computer allowing better performance due to increased computational power and larger bandwidth (Angelov et al., 2020). Tethering requires transmitting the rendered frames to the device either using cable or wireless transmission, although for life like VR the required data rates will likely be too high even for modern wireless standards (Cuervo et al., 2018). Typically, tethered devices tend to offer better performance and lighter devices while standalone headsets have offered better mobility and ergonomics due to less physical restrictions from the wires. Standalone headsets on the other hand must contain computational units along with a battery and tracking technology, resulting them being heavier than tethered devices. Latest headsets such as the Oculus Quest series have highlighted a hybrid approach where the headset can be used in both ways standalone and tethered offering more flexibility with the cost of added weight compared to other tethered headsets (Angelov et al., 2020).

Under the terms standalone and tethered there are two subtypes for tracking the headset movement, which are outside-in and inside-out tracking. Most of the modern headsets today use the inside- out approach where the headset tracks its movements internally. Outside in on the other hand uses separate cameras outside the headset for constantly tracking the headset movements based on markers on the headset. This leads to tracking approaches which can be implemented with either marker-based or markerless approaches. The marker-based approach uses separate markers outside the tracking device to determine the position of the tracked device while the markerless approach uses only cameras and algorithms to track the movements of the headset internally. This potentially completely removes the need for any external hardware used for tracking (Angelov et al., 2020).

The effects of different hardware specifications used in HMDs have also been studied previously and it has been shown that they have affected the degree of immersion, sense of presence but also the level of cybersickness. For Life -like VR experience the field of view FOV should ideally match the human eye which is 210° horizontally and 135° vertically (Cuervo et al., 2018). Devices with larger field of view FOV combined with large pixel density have shown to produce the highest levels of immersion while lower pixel density has shown to produce an irritating screen-door artifact reducing immersion. The screen-door artifact means that the user is be able to see a contour around the individual pixels of the display reducing the quality of their experience. Tracking and refresh rate has also been shown to be crucial for immersion and the minimum recommendation typically is at least 75 Hz (Angelov et al., 2020).

2.3.4 Cybersickness

In the context of VR and virtual environments it was discovered early on that some users might experience various symptoms during their experience. This phenomenon is called cybersickness or VR sickness and it could negatively affect the user experience in VR. Cybersickness contains some of the same symptoms that motion sickness has. These can be e.g. eye fatigue, disorientation, and nausea (Chang et al., 2020). It has been mentioned by previous studies that cybersickness can also negatively affect presence and this is why it was added to this study to be discussed briefly (Kim et al., 2024). Some probable causes for cybersickness have been mentioned to be field of view, low refresh rate, stereoscopic rendering, latency, flickering display, and weight of HMDs (Angelov et al., 2020; Chang et al., 2020).

Though earlier it was believed that improving the performance and increasing fidelity of the systems could completely remove cybersickness but that has not happened (Chang et al., 2020). The symptoms of motion sickness are caused by sensory conflict of visual information with dynamic vestibular input (Chang et al., 2020; Kim et al., 2024) or by postural instability (Kim et al., 2024). Outside VR this can happen for example in transportation where user might feel their body is moving but not receive matching visual information. In VR on the other hand this could happen the other way around, so that the visual stimuli can cause a conflict as user does not receive expected corresponding vestibular input; the expected feeling of moving their body. This form of motion sickness is defined as visually induced motion sickness (VIMS) also referred cybersickness (Chang et al., 2020). It has been studied that the symptoms of cybersickness might be increased in a standing position compared to sitting (Kim et al., 2024).

The symptoms of cybersickness have since been studied thoroughly and it has been discovered that a noticeable lag between the user's movement and the corresponding movement of their virtual avatar can increase the sensory conflict and therefore decrease sense of presence and increase the likelihood of cybersickness (Chang et al., 2020; Slater et al., 2009). However, studies have also shown that the absolute value of the lag does not seem to correlate with users' discomfort directly if the latency is constant. Based on the findings user discomfort significantly increases when the latency has large variances making it harder for users to get used to. Another discovery is that the sensory conflict might also increase as the degree of details increase making the experience more immersive (Chang et al., 2020). Due to the discomfort caused by cybersickness, higher degree of immersion might not always result in better presence if the sensory conflict is dominant (e.g. sitting in place while the virtual world moves).

2.4 Barriers for achieving immersion and presence in VR

This section covers technological, perceptual and environmental barriers, which might negatively affect the degree of immersion (perceptual and system-level) and achieved sense of presence. Based on the theory above, it is known that immersion as an umbrella term contains two perspectives. These perspectives are the system-level and the perceptual perspective which might now always go hand in hand with each other since some people might achieve presence and feel immersed in the same VE while others do not (Slater et al., 2009). By now it is also known that increasing the fidelity of the system could increase the likelihood of achieving presence by increasing the degree of system-level immersion. This section determines what might be the detailed barriers for achieving both immersion and presence which will be crucial to cross when designing immersive virtual environments and using them for various use cases effectively. For example, if we wanted to make technically immersive system, it could be argued that it should have for example framerate and refresh rate of 75 Hz or higher to increase chances of presence and immersion. This section focuses on the barriers in structured way dividing them into own sub sections for system-level, perceptual, and environmental. The different barriers are also presented in a picture below.

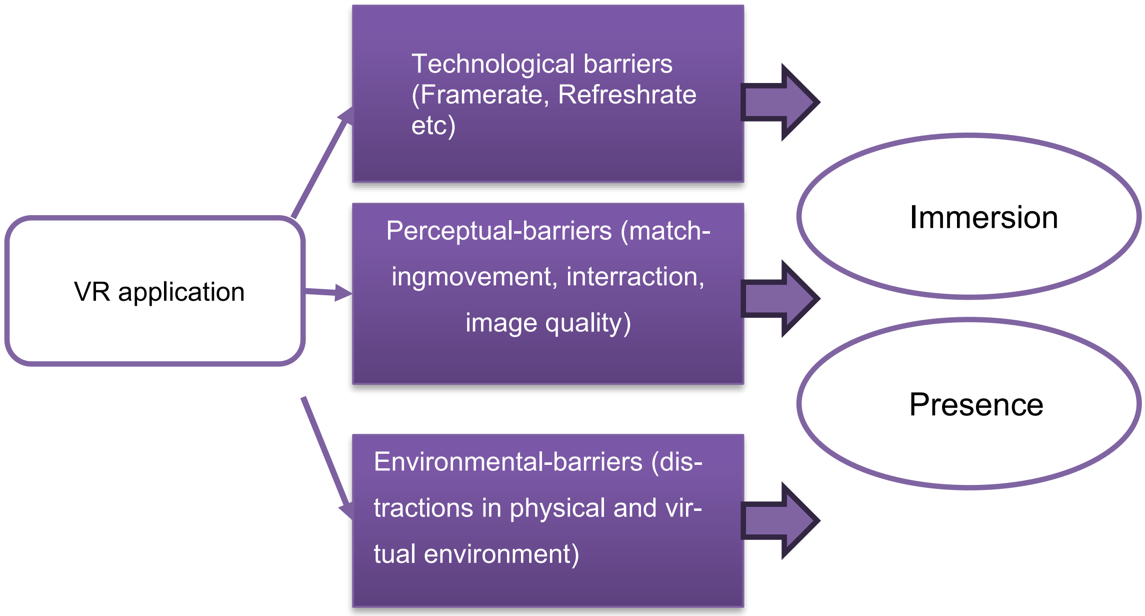


Figure 6. *Barriers for achieving perceptual immersion and sense of presence*

2.4.1 Technological barriers

The objective *system-level immersion* has mentioned to contain various technical characteristics of VR equipment; however, the technical details and barriers have not yet been discussed in detail. These metrics will be in crucial role when it comes to evaluating the degree of immersion achieved by the equipment used. As earlier was mentioned immersion and presence can sometimes be achieved even in lower level of *system-level immersion* yet it is stated that higher technical degree of immersion might increase the chances of achieving presence and experiencing *perceptual immersion*.

It was also pointed out that many of the system specifications might have a link to increased chances of experiencing cybersickness which has been reported to decrease sense of presence. (Al-Jundi & Tanbour, 2022) Based on this, the technology might introduce barriers which affect the perceptual immersion and presence. Additional to barriers it is important to distinguish a clear boundary between high and low fidelity systems. Table 3 presented below covers different system metrics categorized in low, medium, and high-fidelity categories. The table contains authors for resources where the metrics were extracted from. The low medium and high scales for variables were introduced by high-fidelity framework developed by Al-Jundi & Tanbour (2022).

Table 3. *Definition of categories (Low, Medium & High) for attributes of system-level immersion*

Metric	Low	Medium	High	Authors
Field of view (degrees)	30-60	60-110	110-210	Al-Jundi & Tanbour, 2022; Angelov et al, 2020
Frame rate (FPS)	30-45	60	90-120	Al-Jundi & Tanbour, 2022
Latency (ms)	< 20	< 10	< 5	Al-Jundi & Tanbour, 2022
Pixel density (PPD)	< 10	>11	>20	Al-Jundi & Tanbour, 2022; Angelov et al, 2020
Tracking degrees of freedom	3	6	6	Al-Jundi & Tanbour, 2022; Angelov et al, 2020
Audio Resolution	Monophonic Playback	Stereo audio	3D audio	Al-Jundi & Tanbour, 2022
Number of tracked bodyparts	Head tracking	Head, hand, other body parts	Full body	Al-Jundi & Tanbour, 2022; Slater et al, 2009
Refresh rate (Hz)	< 75	>75	>120	Angelov et al, 2020

From the table above it can be seen that most of the variables consider the visual components of VR systems. This is not a surprise, since studies mention that the quality of the display components tends to have a strong impact on user experience (Angelov et al., 2020). The metrics of the table were picked based on previous studies mentioning a clear relation with *immersion* or *presence*. Additionally, tracking and audio resolution were found to be important for higher fidelity systems. The low medium and high categories allow to evaluate not only the fidelity of the system, but also possible minimum requirements for immersion and presence to occur. The scale also puts into perspective what might be considered as “high-fidelity displays” or “large screens and powerful sounds” which were used previously to describe the factors of *perceptual immersion* (Witimer & Singer, 1998; Arsenault, 2005; McMahan, 2003; Emmi & Mäyrä, 2005)

2.4.2 Perceptual barriers

Scientists discovered around early implementations of immersive virtual environments, that *presence* would have at least three necessities to be formed and maintained during VR experience. The three things were matching the sensorimotor loop, *system-level immersion* and both perceptual and cognitive responses to the users’ actions. The sensorimotor loop represents a concept, which expects the virtual body also called avatar to immediately and consistently match the users’ movements in the real world (Slater et al., 2009). For example, moving their hand in real world should move their avatars hand in the virtual environment without significantly noticeable latency to avoid breaking the sensorimotor loop. Previous studies have discovered that a mismatch between movement and the virtual environment might be one reason for cybersickness and increased breaks of presence (Daşdemir, 2023; Chang et al., 2020; Slater et al., 2009). This is in line with experimental studies around locomotion techniques which have revealed that locomotion linked to more natural movement of feet might result in higher reported *presence*, *immersion,* and decreased cybersickness (Lee et al., 2017; Daşdemir, 2023).

The degree of system-level immersion should be on a level, that the images shown to the participant would be plausible and realistic enough to allow the user to respond as if the environment was real (Slater et al., 2009). Artifacts such as the screen-door effect and other technical measures can affect how the environment and level of immersion is perceived (Angelov et al., 2020). Thirdly the *presence* of users in virtual environment can be decreased even from high initial levels if other actors of the environment e.g. do not respond to their questions or other interactions appropriately (Slater et al., 2009).

2.4.3 Environmental barriers

Environmental barriers cover factors from both physical and virtual environments, which might affect the user experience negatively. Environmental barriers for both *perceptual immersion* and *presence* can be e.g. lack of physical space (Lee et al., 2017), breaking in presence due to distractions such as cables or noise and lack of embodiment in the virtual environment (Slater et al., 2009). Studies have tried to resolve whether higher detail in 3D graphics in virtual environments would directly increase the achieved sense of presence and level of immersion, but the results have been conflicting. Studies have reported that increasing the details might increase the likelihood of cybersickness since the users tend to become more immersed in their experience but lack the vestibular stimulus causing a stronger sensory conflict (Chang et al., 2020). This could lead to a conclusion that in immersive virtual environments it would be crucial to minimize the sensory conflict to reduce cybersickness and maintain higher sense of presence with the increased degree of immersion.

There have been efforts for modifying virtual environments so that this conflict could be decreased. Methods such as reference frame have shown significantly decreasing cybersickness and increasing time enjoying VR. The concept of reference frame means that the environment renders a constantly visible fixed visual stimuli in the displayed VR scene such as a grid, 3D objects or a virtual nose which will stay in place despite the otherwise moving VR content (Chang et al., 2020). This leads to conclusion that highly immersive virtual reality applications might benefit from locomotion techniques which minimize the sensory conflict. Also designing the environments in a way that chances of cybersickness would be decreased can have the potential to maintain higher levels of presence.

In the section measuring of perceptual immersion, it was stated that Witmer & Singer discovered in 2005 that immersion is also greater on those individuals who can adapt to the virtual environment the most (Witmer & Singer, 2005). This leads to think whether adaptation might be a key barrier of the technology to be not only technically immersive but also implement high usability. Perhaps the easier it is to adapt to the virtual environment the higher could the chances of achieving presence.

2.5 Theoretical Framework

Based on past research around immersive virtual environments, locomotion, immersion and presence, a theoretical framework was formed. The theoretical framework presented in this section differs from the conceptual framework as it contains more detailed variables and relations supported by previous research.

This framework suggests that objective *system-level immersion* (e.g. frame rate, resolution, locomotion) might affect subjective user experiences of *presence* and *perceptual immersion* – a user's feeling of being engaged and immersed by the VR environment. This framework combines two perspectives around the concept immersion to explore whether they could coexist and support each other rather than being mutually exclusive.

This model reflects findings from prior research indicating that users might still experience the sense of *presence* in virtual environments even with low objective *system-level immersion* while higher degree *of system-level immersion* may increase the likelihood of achieving presence. Despite the increased likelihood for achieving presence a high-fidelity system does not guarantee the sense of presence making this study more compelling to give insights how the perceptual immersion measured via engagement might be altered by the physical locomotion conditions and objective hardware performance metrics.

Presence and *perceptual immersion* as subjective user experiences might also shape each other via some extent. For example, a low fidelity system could in theory make a person still achieve the sense of presence which could make the user believe the system was more immersive than it technically is. This analogy was presented also by Slater et al. (2009) with the theory of colours. System-level immersion might describe the objective factors such as wavelength of a colour technically; however, it is still not guaranteed that the user's response to the colour would change if the wavelength was altered. It might not always be clear how the change in colour or in this case objective hardware specification will affect the response of each individual (Slater et al., 2009).

Slater then defined presence as a direct response to level of *system-level immersion* while this framework combines the two perspectives from previous studies to consider both *perceptual immersion* and *presence* as distinct user experiences, both derived by the same system specification. Other studies have defined immersion solely as subjective user experience along presence (Witmer & Singer, 1998; Arsenault, 2005; McMahan, 2003; Emmi & Mäyrä, 2005) while this framework introduces both technical and perceptual perspectives as factors for achieving presence.

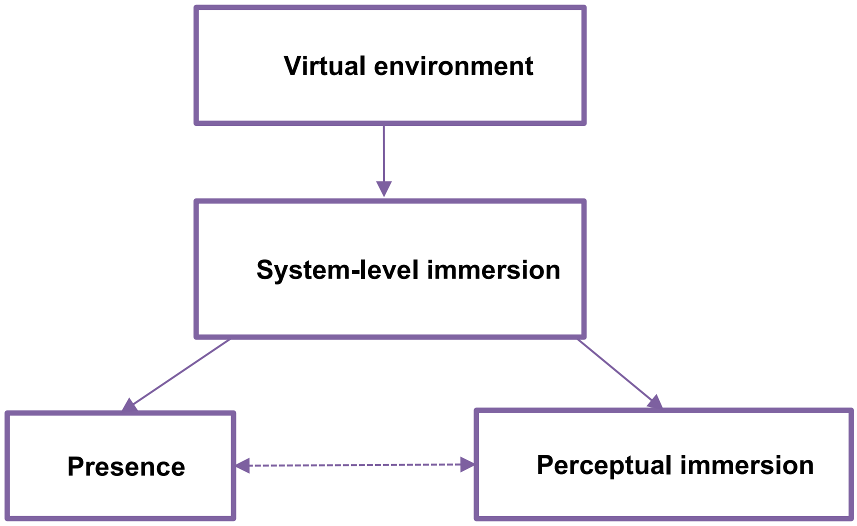


Figure 7. *Theoretical framework*

The key implications of this framework are that the three locomotion techniques and hardware used in this study will affect the objective *system-level immers*ion. This change should then be reflected by the user-reported *presence* and engagement questionnaire results (RQ1). Based on the framework two potential outcomes could be expected from the results.

1. The first scenario could be that the higher fidelity system would always produce higher *presence* and *perceptual immersion* indicating that the locomotion technique may be less critical when the fidelity of the system is sufficiently high.
2. The second scenario could be that the high-fidelity system might not always produce increased sense of *presence* and *perceptual immersion*. This could imply that the locomotion technique might potentially outweigh the fidelity and performance advantages.

This approach in theory supports the concept of achieving presence by two separate paths, either creating a high-fidelity system indistinguishable from the real world or achieving presence even with lower system-level immersion by studying the key factors of system-level immersion (Slater et al., 2009).

3. RESEARCH METHODOLOGY

This section covers the crucial parts of implementing this study considering research process, selection of approach, data collection, and procedure, the virtual environment and hardware specification. This research was conducted using a quantitative approach using presence and engagement questionnaires after participants were exposed to the virtual environment. The vantage point was selected to compare three locomotion techniques which were the omnidirectional treadmill (OT), omnidirectional slide mill (OS), and natural walk (NW) also described in the theoretical background. The virtual environment was developed before starting to write this thesis during the autumn of 2024 and development was continued along the writing of this thesis on spring 2025. The first participants were invited to the experiment during March of 2025 for pilot phase which was then followed by the official data-collection phase conducted between May and April 2025. The detailed steps of this research process have been conducted in the figure 8 below.

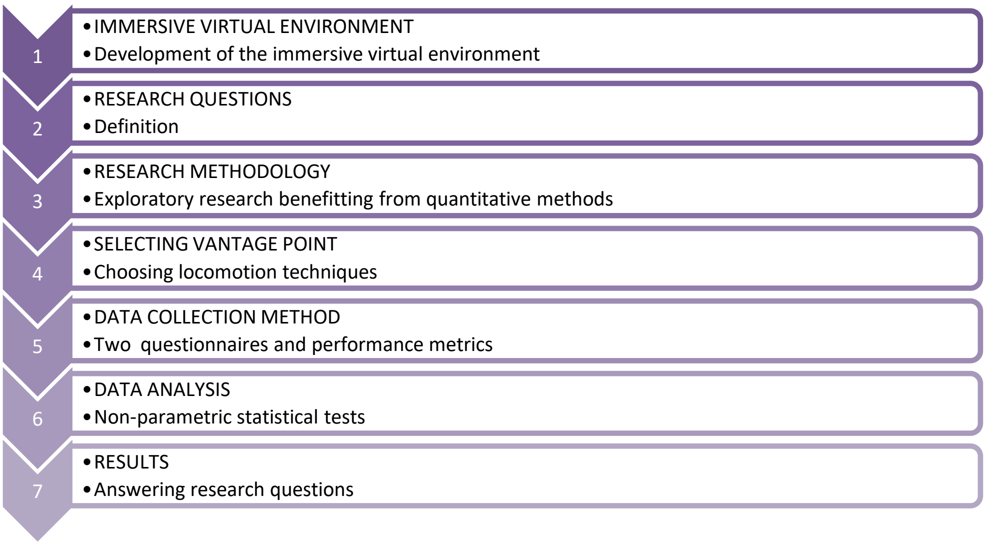


Figure 8. *Steps of the research process*

3.1 Measurement

When the virtual environment was ready to be tested the research questions for this thesis were formed. In early phase when working with the environment it became obvious that the concept of immersion has a crucial role in virtual experiences, and it was therefore picked as an interesting measure to be researched. When defining immersion, it became clear that the things affecting the degree of immersion seem to not be obvious and have been under academic discussion (Smith et al., 2001; Witmer & Singer, 1998, Slater et al., 1999). Therefore, immersion as a concept, provided an interesting research questions to build upon. Based on previous studies the use of hypothesis was natural since previous studies have mentioned a correlation between presence scores and natural walking (De Back et al., 2024). Hypothesis were also conducted due to the exploratory nature of this research to clearly establish what were the first-hand outcomes of this research.

Quantitative method was the best research method for this study since the goal of this research was to study a group of participants using experiments and to generalize immersion and presence scores with different locomotion techniques. Quantitative approach allows to test a new theory which this study presents with the theoretical framework considering relations between system-level immersion, presence, and perceptual immersion (Swanson, 2010). Quantitative approach was therefore chosen as the best method for measuring how the locomotion techniques affect presence and immersion scores.

Presence questionnaire was chosen based on previous research length of the questionnaire and items fitting the research purposes. Igroup Presence Questionnaire IPQ was chosen as it had a medium length of 14 items and it combined questions from various other questionnaires. IPQ also combines questions from various other presence questionnaires making it relevant for this exploratory study. Unified database of previous results allows to compare levels of presence measured with this questionaire (Melo et al., 2023). At the same time, this questionnaire was found to be popular among other researchers being the third most cited presence questionnaire in 2018 according to Google Scholar (Zielasko et al., 2024). Additionally, a 6-item engagement questionnaire was added as a part of the other studies implemented within the same virtual experiment and was therefore also added to this study as a metric used for measuring *perceptual immersion.*

The engagement questionnaire was chosen using similar criterion with the goal of measuring *perceptual immersion* through engagement mentioned to be common approach by past research. The questionnaire contains items from original presence questionaire from Witmer & Singer (1998) targeting engagement, sensory fidelity and adaptation. Previous studies around presence and immersion have suggested that engagement might be required for experiencing perceptual immersion and that immersion might be higher for those individuals who can adapt faster (Witmer & Singer, 1998; Brockmyer et al., 2009; Oliveira et al., 2016). Therefore, while engagement is not directly investigated for the conciseness of this thesis the use of this questionnaire is justified to bring valuable data considering *perceptual immersion*.

3.2 Data collection and procedure

The experiments took place in Tampere University premises where the provided equipment for large locomotion devices omnidirectional treadmill and omnidirectional slide mill were placed. The natural walk also took a separate room large enough to fit the virtual environment (27m x 18m). The virtual environment presented a realistic nordic forest with crossing paths and set of landmarks placed along them. This environment was used for multiple other experiments measuring learning and space awareness in virtual environments with all the three locomotion techniques.

Participants were given a registration survey beforehand where they had to confirm that they pass set criterion for participation. Thid criteria included constraints for height, weight, and personal health. Before proceeding to VR, they were given spatial rotational task measuring their 3D cognition. After completing two 3-minute 3D rotational tests they proceeded to VR wearing HMD, headphones, and the olfactory device. The environment had a small tutorial where participant had the possibility to adapt to the locomotion technique, smells, and UI interactions with menus. Each participant spent approximately 10 minutes in this environment before starting the experiments in VR.

When the VR experiments started the participants were given a set of five different experiments were conducted in the virtual environment measuring their navigation and spatial cognition. First task was to learn the environment and visit all landmarks. After this they were moved to the next experiment inside the same environment and so on. The all four experiments are clearly described below in the separate section for the virtual environment. Between the scenes participants had the possibility to have a small break before continuing. The total VR experience with all the breaks included took approximately 2 hours per participant. The length of the sessions limited the total number of participants gathered for this study.

Once finished with all the experiments in VR they were given a Lime survey to fill on a separate computer. After finishing VR section, they were given an extensive Lime survey questionnaire to fill on dedicated computer. The Lime survey contained the Appendix A presence questionnaire and Appendix B engagement questionnaire among various other questionnaires used for the other studies. When they finished, they received a compensation of 20 € general store gift card.

3.3 The virtual environment

This research used a custom made three-dimensional virtual environment developed specifically for the NaviNord research project conducted in Tampere University. The environment represents a detailed nordic forest with crossing paths and a set of landmarks placed among them. The landmarks had different combinations of visual, audio, and olfactory stimuli, and several experiments were conducted in the environment measuring spatial memory and navigation. The figure 9 below represents a snapshot of the environment as well as the map layout used in the final version. The picture on the left is taken from the corner between the start and LM5 points.

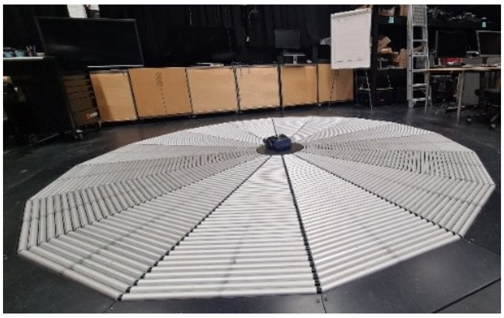
Figure 9. *The virtual environment (left) and map layout (right)*

The virtual environment was developed during the autumn 2024 when the map, textures, experiment logic, data extraction, and additional hardware support were developed. The development process contained various tasks in Unity varying from design to C# coding related tasks. At the beginning the project had a support for the Omnideck and HTC Vive headset with SteamVR. During the autumn 2024 and spring 2025 support for Oculus Quest HMDs, KatVR, and NW were added. The map of the environment was implemented so, that it presents a realistic nordic forest with crossing paths and set of randomized landmarks along the paths. The map was further optimized to maintain high level of immersion with good performance and the data extraction was finalized. Originally the map was approximately 60m x 60m but for the NW condition to be possible had to be cropped down to fit a 27m x 18m indoor space.

The environment shown in the figure 9 was used for four different experiments which some where repeated more than once. Additionally, a smaller environment was developed for tutorial allowing the participants to adapt to the environment before starting the experiments. The four experiments in order were to explore and learn the maze and the landmarks, placing the landmarks as you remember them, point to a specific landmarks direction and call adjacent landmarks from another landmark and lastly finding your way from a landmark to another. The task for pointing to a specific landmarks' direction is repeated twice and the wayfinding is repeated five times. Data from all the experiments is recorded in .csv file for each participant containing information about the landmarks, positions, time, participants answer and their routes in the forest. Additionally, the environment contains a start menu where each participant is given a unique user id group id and their selected locomotion technique. The ids are used for indexing the collected and stored data files. Additionally, a benchmark was added to the environment to test performance of the different hardware combinations in unified way. The benchmark traverses the map always the same way and can therefore produce more accurate and standardized results for comparing performance scores of different test setups.

3.4 Hardware

This section focuses on the set of hardware used for this project. Hardware includes the locomotion devices, HMDs, computers, olfactory devices, and their specifications as well as performance metrics achieved with the gear and virtual environment. Figure 10 below demonstrates the three different locomotion conditions used for this study.


A) Omnidirectional treadmill


B) Natural walking

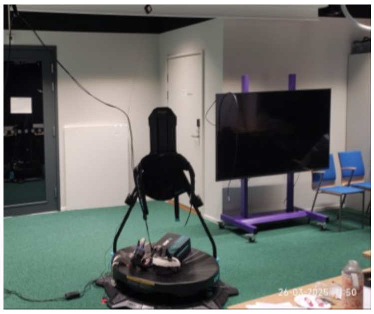

C) Omnidirectional slide mill

Figure 10. *The locomotion setups used by this study*

The selection of the used locomotion techniques was straight forward since the university had the Omnideck and KatVR available and they were already used during the autumn 2024 development and testing phase. Natural walk was the best possible control group for locomotion backed up by previous studies. (De Back et al., 2024) The system specifications for each locomotion technique are represented in the table below. This allows anyone to reproduce the research with same hardware but also document the important metrics affecting system-level immersion when evaluating the degree of immersion.

Table 4. *Hardware specification for locomotion conditions*

Locomotion	Natural walking	Omnidirectional Treadmill	Omnidirectional Slide mill
HMD	Oculus Quest 3	HTC Vive Pro	Oculus Quest 3
HMD Visible FOV vertical (degrees)	96	98	96
HMD Visible FOV horizontal (degrees)	110	98	110
HMD per-eye resolution (pixels)	2064x2208	1440x1600	2064x2208
HMD Refresh rate (Hz)	90	90	90
HMD Tracking Frequency (Hz)	120	1000	120
HMD average vertical pixel density (PPD)	23	13,36	23
HMD average horizontal pixel density (PPD)	18,76	14,58	18,76
HMD weight (g)	515	800	515
GPU	NVIDIA Geforce RTX 3090	NVIDIA Geforce RTX 4070 SUPER	NVIDIA Geforce RTX 3090
CPU	Intel Core i9-11900KF	Intel Core i7-6700K	Intel Core i9-11900KF
Ram	32 GB 3200Mhz	32 GB DDR4 2133 MHz	32 GB 3200 Mhz

From the above table the Natural Walk and KatVR ended up using the same Oculus Quest 3 headset while the Omnideck was forced to use the older HTC Vive Pro headset. This was due to the Omnideck tracking system being built with another physical laboratory space using the HTC Vive headset with dedicated tracking equipment. The Oculus on the other hand offered a more modular approach which was best for the natural walk since it has a markerless tracking system which works both standalone and tethered. KatVR on the other hand didn’t require additional software for tracking the headset like the Omnideck which allowed to use Oculus Quest 3 also for this experiment. As can be seen from the table above these headsets do have differing hardware specs which means they will need to be considered with the analysis. The setup also included a separate harness for wearing the olfactory device. This can be seen in the figure 11 below.

Figure 11. *Image of the harness for wearing olfactory device*

One limitation of the research test setup was that it was not feasible to keep everything else the same except the used locomotion technique. This was mainly because Omnideck and KatVR was implemented to receive player movement from HTC Vive sensors located in the university labs while natural walk was not possible to be implemented using the same sensors, the same headset or even the same space. This was because the natural walk required a larger space which was too large to be tracked with the Vive sensors. Using The HTC Vive for natural walk would have also required disassembling the HMD setup to move it into another space repeatedly which was not an option. Oculus quest headset with a separate cart for moving the PC was chosen for this purpose instead to run the environment.

4. RESULTS

This section goes through the key results for key variables of this study which where *system-level immersion*, *perceptual immersion*, and sense of *presence*. This section describes the methods used for analysis in detail. The results are represented in the order of objective data-analysis section containing detailed analysis of presence and engagement questionnaire results followed by system-level immersion. The data-analysis section is followed by a separate validity and reliability section which critically represents the factors affecting reliability and validity of the received results.

4.1 Data-analysis

The data-analysis for analysing questionnaire results was conducted using Python programming language. For this a separate program was developed to parse and collect exported data from the questionnaire results. Data was exported from Lime survey in csv form and parsed into a data frame using Python. During the analysis some of the participants were excluded from the data-analysis due to major distractions caused by loud noise during their experiments or faulty equipment. The analysis used Kruskal-Wallis non-parametric significance test for Likert scale questionnaire data. This was followed by the Dunn's non-parametric multiple comparisons pairwise test when results of the previous tests were statistically significant. This combination was chosen based on previous research, 7-point Likert items and low sample size (Dinno, 2015) This section will first go through the presence questionaire results followed by the engagement questionnaire results.

4.1.1 Presence questionnaire results

The presence questionnaire used for measuring presence included subscales of presence, spatial presence, involvement and experienced realism. These subscales were measured using items such as "*In the computer-generated world I had a sense of "being there"* " (presence), "*I felt present in the virtual space*" (spatial presence), "*I still paid attention to the real environment?*" (involvement) and "*How real did the virtual world seem to you?"* (experienced realism). The IPQ questionnaire used in this study is also listed in the Appendix A with the numbers and subscales. For the analysis IPQ presence questionnaire items 3. 4. and 9. were reverse scored before proceeding with the analysis to standardize the answers before moving on. This means that as these items were measured by lower values indicating higher presence, they were standardized by reverse-scoring them resulting higher scores indicating better result. The table 5 below contains the average IPQ score received by each group from the questionnaire. These results are normalized by the number of items to preserve the original Likert scale from 1-7 in which 7 indicates the highest presence and 1 represents the weakest presence. This method remains the same for all the questionnaire results and subscales.

Table 5. *Average IPQ scores for each group*

	Natural walking (N=14)	Omnidirectional Treadmill (N=20)	Omnidirectional Slide mill (N=19)
IPQ Average	4,842	4,807	4,320

The above table shows that NW group reached expectedly (H1) the most presence on average while the omnidirectional slide mill (OS) group resulted in the lowest score (H2). The below figure 12 contains a boxplot of the average scores per each group.

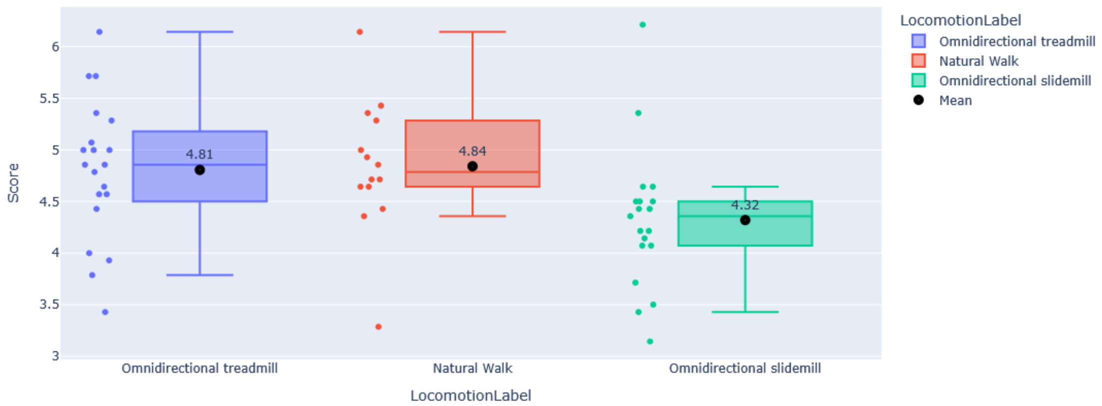


Figure 12. *Boxplot of average IPQ scores for each group*

Based on the figure above the average scores of the treadmill group have a larger variance to both directions compared to natural walking. Compared to the slide mill group the results of NW and OT seem to be closer to each other with similar outliers. The following table 6 contains average scores of individual subscales of the IPQ questionnaire.

Table 6. *Average scores of IPQ subscales for each group*

IPQ Subscale	Natural walking	Omnidirectional Treadmill	Omnidirectional Slide mill
Presence	5,500	5,950	5,158
Spatial Presence	5,771	5,720	5,358
Involvement	4,625	4,275	4,066
Experienced realism	3,732	3,913	3,066

Based on the table 6 the omnidirectional treadmill group (OT) reached the highest average score for presence subscale. Additionally, OT group produced the highest score for experienced realism subscale despite using older HTC Vive pro HMD with less performant PC. The omnidirectional slide mill group resulted with the lowest score for all subscales of the IPQ questionnaire despite using the newer Oculus Quest 3 headset and more performant PC. These results are potential indicators for support of H3. The received results were tested using non-parametric Kruskal-Wallis test and these results are listed in the below table 7. The values with p <.05 considered as significant are marked with an asterisk (*).

Table 7. *Kruskal-Wallis significance test results for IPQ scores*

IPQ result	p-value
IPQ Averages	0,009*
Presence scores	0,072
Spatial presence scores	0,201
Involvement scores	0,178
Experienced realism scores	0,046*

The table above reveals statistically significant differences for IPQ average scores and the experienced realism subscale results. These findings were further confirmed using a Dunn's post-hoc test to see whether the differences were significant between the groups. Subscales which did not show statistical significance were excluded from Dunn's post-hoc comparisons as no significant difference was detected for overall group. Below is the table 8 containing Dunn's post-hoc test results for the IPQ average score. This table shows the p-value for the significance of the differences between the groups. The values with p <.05 considered as significant are marked with an asterisk (*).

Table 8. *Dunn's pairwise comparison test for IPQ average score*

	Natural walking	Omnidirectional Slide mill	Omnidirectional Treadmill
Natural walk	1,000	0,003*	1,000
Omnidirectional Slide mill	0,003*	1,000	0,026*
Omnidirectional Treadmill	1,000	0,026*	1,000

Based on table 8 there are statistically significant differences between the groups of NW and slide mill, and between the treadmill and slide mill. There is no statistically significant difference between treadmill and NW groups. Table 9 below contains the Dunn's post-hoc test results for the experienced realism subscale. The values with p <.05 considered as significant are marked with an asterisk (*).

Table 9. *Dunn's pairwise comparison test results for IPQ experienced realism subscale*

	Natural walking	Omnidirectional Slide mill	Omnidirectional Treadmill
Natural walk	1,000	0,149	1,000
Omnidirectional Slide mill	0,149	1,000	0,073
Omnidirectional Treadmill	1,000	0,073	1,000

Based on the above table 9 for Dunn's post-hoc significance test for experienced realism subscale there are no significant differences between the groups. Differences have been detected between the groups of NW and slide mill, and treadmill and slide mill yet these results yield statistical significance due to *p-value* higher than 0.05. The difference between slide mill and treadmill groups are slightly closer to the limit but lacking statistical power makes this a speculative result. The figure 13 below presents the individual average scores of the questionnaire items per each locomotion condition for detailed comparison between the groups.

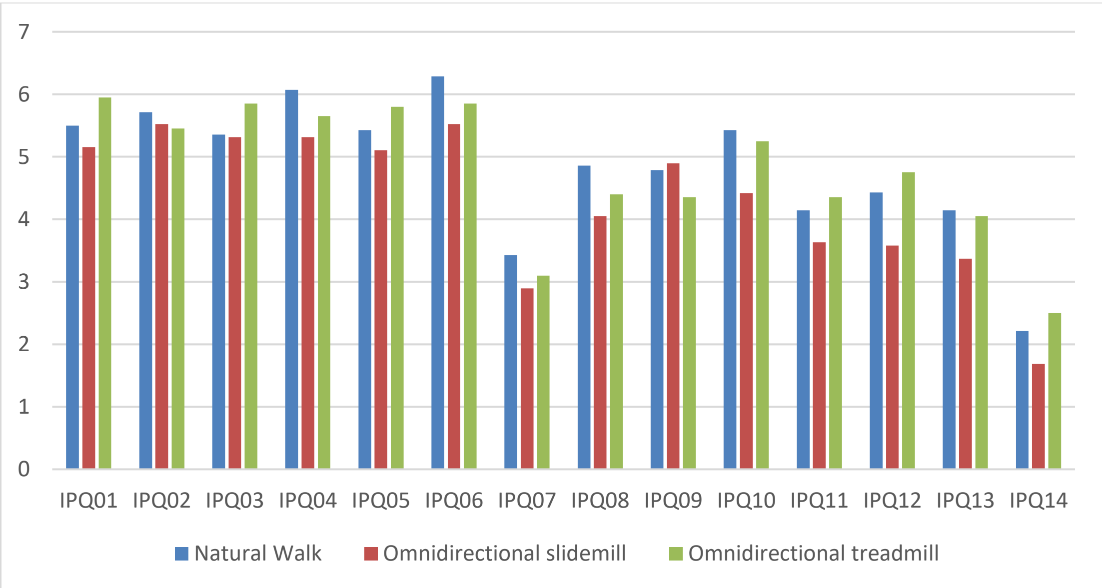


Figure 13. *Average scores of IPQ items for each group*

The highest average score was received by the item number six (*"I felt present in the virtual space"*). Natural walk resulted in the highest score for this item and OS the lowest. This item is included in the spatial presence subscale which NW condition also resulted in the highest average score. The slide mill resulted in the highest score for one item which was number nine (*“I still paid attention to the real environment?”*). The item number nine was reverse scored meaning that the higher score of the slide mill implicates they paid less attention to their real environment compared to other groups.

The lowest score from all the items with every condition was received by the item number 14 (“*The virtual world seemed more realistic than the real world”*). This item was part of experienced realism subscale and received the highest average score by the omnidirectional treadmill group which used the older HMD and weaker PC. The slide mill resulted in the lowest score for this item with the better HMD and PC and best average performance scores. In total the OT group resulted in the highest average score on items 1, 3, 5, 11 12 and 14.

4.1.2 Perceptual immersion results

This section covers the results received by the engagement questionnaire used in this thesis to measure perceptual immersion. This questionnaire used the same Likert scale as the presence questionnaire above. Due to this the similar method was used to analyse the results. The table 10 below shows the average score of each locomotion group for the total questionnaire result.

Table 10. *Average Perceptual Immersion Questionnaire scores for each group*

	Natural walking (N=14)	**Omnidirectional Treadmill (N=20)**	**Omnidirectional Slide mill (N=14)**
Perceptual immersion average score	6,071	5,675	5,211

From the above table it is clear, that NW group reported the highest level of perceptual immersion while the OS group reported the lowest. This result is in line with the presence questionnaire results. The figure below contains a boxplot of the distribution of average questionnaire scores per group.

Figure 14. *Boxplot of the average Perceptual Immersion Questionnaire responses for each group*

The figure 14 above shows that OT and NW are closer to each other than the slide mill group. Variance of OT and NW groups is less significant compared to the slide mill group. The table 11 below shows the average results for the separate subscales of the perceptual immersion questionnaire.

Table 11. *Average scores for Perceptual Immersion Questionnaire subscales for each group*

Perceptual immersion Subscale	Natural walking	Omnidirectional Treadmill	Omnidirectional Slide mill
Engagement	6,071	5,400	4,500
Sensory fidelity	6,107	5,950	6,026
Adaptation	6,036	5,675	5,105

The above table 11 represents the average score for questionnaire subscales for all three locomotion conditions. For each subscale NW resulted in the highest average score. Omnidirectional slide mill resulted in a better score for sensory fidelity subscale than the group using the omnidirectional treadmill. Otherwise, the OT group resulted in higher average score than the slide mill. Like the presence questionnaire results also these results were checked using the same Kruskal-Wallis non-parametric test followed by Dunn's post-hoc test. The following table 12 contains the Kruskal-Wallis test results for the received IPQ results. The values with p <.05 considered as significant are marked with an asterisk (*).

Table 12. *Kruskal-Wallis significance test results for Perceptual Immersion Questionnaire scores*

Perceptual immersion results	p-value
Average	0,013*
Engagement	p < 0,001*
Sensory fidelity	0,768
Adaptation	0,024*

Based on the above table 12 statistically significant differences were found with all other subscales except the sensory fidelity. To confirm these differences between the groups the same Dunn's post-hoc test was done. The table 13 below shows the average score significance between the groups. The values with p <.05 considered as significant are marked with an asterisk (*).

Table 13. *Dunn's pairwise comparison test results for average Perceptual Immersion Questionnaire scores*

	Natural walking	Omnidirectional Slide mill	Omnidirectional Treadmill
Natural walk	1,000	0,011*	0,521
Omnidirectional Slidemill	0,011*	1,000	0,253
Omnidirectional Treadmill	0,523	0,253	1,000

The above table 13 shows that the groups of omnidirectional slide mill and natural walk have statistically significant difference with the engagement questionnaire average score. Below table 14 shows the results of engagement subscale. The values with p <.05 considered as significant are marked with an asterisk (*).

Table 14. *Dunn's pairwise comparison test results for Perceptual Immersion engagement subscale*

	Natural walking	Omnidirectional Slide mill	Omnidirectional Treadmill
Natural walk	1,000	p < 0,001*	0,380
Omnidirectional Slidemill	p < 0,001*	1,000	0,054*
Omnidirectional Treadmill	0,380	0,054*	1,000

Based on the table 14 there is statistically significant difference between the slide mill and NW groups for engagement subscale. This result indicates the lower *perceptual immersion* of slide mill group is statistically significant compared to the highest scoring NW group. The below table 15 shows the Dunn's test result for the adaptation subscale. The values with p <.05 considered as significant are marked with an asterisk (*).

Table 15. *Dunn's pairwise comparison test results for Perceptual Immersion adaptation subscale*

	Natural walking	**Omnidirectional Slide mill**	**Omnidirectional Treadmill**
Natural walk	1,000	0,022*	0,745
Omnidirectional Slidemill	0,022*	1,000	0,268
Omnidirectional Treadmill	0,745	0,268	1,000

Based on the table 15 above there is statistically significant difference between the NW and slide mill groups. This result indicates that similarly to the engagement subscale the lower level of adaptation of slide mill group compared to the highest scoring NW group is statistically significant. Although there is also difference shown between the NW and treadmill groups those are not close to statistical significance. Figure 15 below shows the average scores of the individual items used for measuring perceptual immersion.

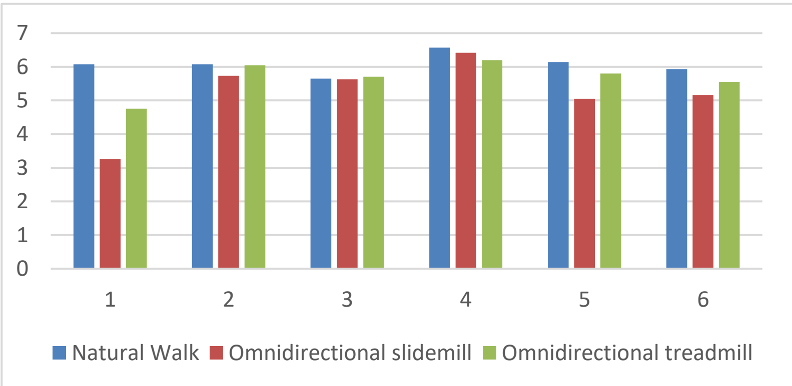


Figure 15. *Average scores of Perceptual Immersion Questionnaire items for each group*

The figure 15 above reveals that NW produced the highest score in almost all the items. The only difference is the item 3 (*"How well could you identify smells?"*) where omnidirectional treadmill group resulted in the highest score however the difference is only marginal. The largest variance between conditions was received by the item 1 (*"How natural was the mechanism which controlled movement through the environment?"*). KatVR produced the lowest score while OT was in the middle and NW produced the highest score.

The order of groups remains the same for the items 2 (*"How involved were you in the virtual environment?"*), 5 ("*How proficient in moving and interacting with the virtual environment did you feel at the end of the experience?*") and 6 *("How well could you concentrate on the assigned tasks or required activities rather than on the mechanisms used to perform those tasks or activities?"*)

4.2 System-level immersion

System-level immersion was measured by collecting the detailed hardware specification presented above in the table 4. Additionally, performance related metrics were recorded from the virtual environment to better understand potential differences in performance between the groups. This section focuses on going through the received performance metrics. The received performance values were achieved using a separate benchmark mode implemented in the virtual environment. This mode allowed to run identical runs of the environment with all the used test beds as they were used in the experiments with participants. For each locomotion setup the benchmark was executed five times, and an average score was calculated from the results. The green colour on table 16 represents the best score while red represents the weakest score and yellow is between the two for better readability.

Table 16*. Virtual environment performance metrics for each locomotion setup*

Locomotion	Natural Walking	Omnidirectional Treadmill	Omnidirectional Slide mill
Avg Minimum Frame rate (FPS)	38,1	38,8	48,4
Avg Maximum Frame rate (FPS)	173,4	165,5	181,6
1 % Low Average (FPS)	75,2	69,2	74,9
0.1 % Low Average (FPS)	57,8	52,7	65,5
Avg Frame Rate (FPS)	90	89,8	90,4
Avg Median (FPS)	90	89,9	90,1
Avg Adaptive STDEV	3,5	5,1	6,3
Avg P99 (FPS)	98,6	105,2	115,1
Avg P95 (FPS)	94,9	99	103,8
Avg P5 (FPS)	85,5	82,3	82,9
Avg P1 (FPS)	81,8	77,2	78,7
Avg P0.2 (FPS)	72,9	65,6	72,7
Avg P0.1 (FPS)	71	61,2	71,1

Purely based on the performance metrics presented above, it could be argued that the Omnidirectional treadmill (OT) group might result in lower level of perceptual immersion and presence due to the weakest performance. In fact, OT performance is not the highest in any metric, however it is still not the worst in all of them. The difference is significant with the 1% and 0.1% low average values for all the locomotion techniques. These values describe the lowest 1% or 0.1% of the frames recorded during the benchmark. Lower value therefore indicates weaker performance and could be a sign of noticeable FPS spikes which might affect overall user-experience.

The adaptive STDEV value was the highest for KatVR at 6.3 while the natural walking scored 3.5 using the same PC. This metric represents how much fluctuation the FPS value had during the test. The differences between the KatVR and Natural Walk could be related to additional communication with the KatVR locomotion device, but it is surprising that the fluctuation was worse than the Omnideck. Still KatVR on the other hand has close to the highest performance in almost every metric.

In some of the metrics KatVR performs the best while NW performs the worst while both recordings have been implemented with the same computer. Despite this all the conditions are in high or medium category for fidelity based on past research (Al-Jundi & Tanbour, 2022; Angelov et al., 2020).

4.3 Validity and reliability

The questionnaires used for measuring *presence* (IPQ) and *perceptual immersion* through engagement (IEQ) have been previously used in the context of VR research. The past research has therefore shown high reliability and consistency for these questionnaires in the context of virtual environments (Witmer & Singer, 1998; Usoh et al., 2000). Previous studies have found that presence questionnaires have failed to distinguish a clear difference between virtual world and real world (Usoh et al., 2000). However, the questionnaires have still proven to be consistent across measures implemented within same environment. For full transparency, the internal consistency of results of this study was investigated with a basic Cronbach's alpha test to ensure stability across the chosen conditions within the sample size. Below table 17 represents a score of Cronbach's alphas for both questionnaires.

Table 17. *Cronbach's alpha reliability scores of both questionnaire results for all locomotion conditions*

Questionnaire	Natural walking (N=14)	Omnidirectional Treadmill (N=20)	Omnidirectional Slide mill (19)
Igroup presence questionnaire	0,741	0,706	0,732
Perceptual immersion questionnaire	0,681	0,691	0,708

Based on the above table 17, all the groups scored over the 0.7 universal limit for reliability with the presence questionaire. This result indicates good level of internal consistency within each group. For the engagement questionnaire only the slide mill group with 19 participants resulted in a score above the 0.7 mark. The NW resulted in 0.681 and OT in 0.691 yielding the universal limit of 0.7 for high reliability. Due to the Likert scaled data and lower than 0.7 Cronbach's alpha score the non-significant results should be interpreted with caution. Results of the reliability test are still considered acceptable in the context of small sample size per group and exploratory nature of this thesis however it needs to be acknowledged that the low sample size might not represent accurate consistency score due to lower statistical power.

5. DISCUSSION

This chapter will combine the key results of the data-analysis and discuss these results in more detail based on previously represented theoretical background and the previously formed theoretical framework. This section will be divided into its own subsections focusing on each of them focusing on one key variable. Each subsection will be divided to separate sections discussing each condition in detail. The first section will focus on system-level immersion followed by presence and perceptual immersion. The subsections of each variable are ordered so that the highest scoring condition for that variable will be presented first, and the lowest will be presented last. Two research questions were formed in this thesis RQ1: "*How walking locomotion techniques influence subjective senses of presence and immersion in an immersive multimodal virtual environment?*" and RQ2: "*How does system-level immersion, as influenced by locomotion technique, hardware, and performance, impact subjective senses of presence and immersion?*". Based on the theoretical background and received results the selected locomotion technique can influence the sense of presence and immersion with slide mill resulting in a weaker result for both user experiences while natural walking results in the best scores. However, the results also revealed that omnidirectional treadmill is close to the natural walking group since no statistically significant differences were observed between these two groups. Based on the results the omnidirectional treadmill as a locomotion technique outperformed the slide mill in both questionnaire results despite using lower fidelity HMD and therefore having lower system-level immersion.

5.1 Presence

This section focuses on the received results for IPQ presence questionaire for all the locomotion techniques separately. The order from highest to lowest for average presence questionnaire score was natural walk, omnidirectional treadmill and omnidirectional slide mill. Dunn's post-hoc test results reveal that there is a statistically significant difference between NW and slide mill groups, as well as omnidirectional slide mill and treadmill groups. There was no statistical difference in average IPQ score between the NW and the treadmill group ($p = 1.00$). This result indicates that the treadmill is close to natural walking when it comes to sense of presence. Slide mill group having statistically significant difference with both scores is likely an outlier with the lowest score for IPQ average but also for all the subscales of this questionnaire.

5.1.1 Natural walking

This condition resulted in the highest average score for the used presence questionnaire results. This group also had a smaller sample size (N=14) compared to the treadmill (N=20) and slide mill (N=19), yet it still managed to produce the highest score for Cronbach's alpha indicating good level internal consistency. This group had the best score for involvement and spatial presence subscales. However, post-hoc test results revealed that with these samples the presence subscale yields statistical significance and was therefore not compared for post-hoc analysis. The experienced realism although interesting result reveals that the differences between the conditions do not reach level of statistical significance.

The results of the IPQ presence questionnaire have been qualified to categories (Excelent, Very Good, Satisfactory, Marginal, Unsatisfactory, Unacceptable) by past research around this questionnaire. The results of this locomotion condition would have been qualified as excellent (3 subscales), and satisfactory (1 subscale) (Melo et al., 2023). The one satisfactory score is for experienced realism which this technique unexpectedly did not produce the highest score.

5.1.2 Omnidirectional treadmill

Presence questionnaire results for this condition were close to the results of NW group. This condition was not expected to perform better in any of the subscales, but this group reported the highest average score for presence and experienced realism subscales. This result indicates potential support for H2 and H3 since an older headset with weaker performance reached higher score of realism subscale than the newer equipment used by the slide mill condition. When discussing these results, it is important to keep in mind that the difference between the groups for this subscale did not reach statistical significance between the groups. Such result indicates that although the subscale showed statistical significance the answers within the samples might have had variation between the participants.

Based on past research the subscale results of this condition would have been considered as excellent (3 subscales) and satisfactory (1 subscale). Although this condition resulted in an excellent score for experienced realism unlike NW the involvement subscale result would have been considered as satisfactory (Melo et al., 2023). Involvement of this group was low which could have been caused by additional noise from construction work near the lab or perhaps more attention required by the locomotion technique. (Slater et al., 2020) The outside noise was minimized by excluding participants with significant background noise from the analysis, but it is still possible that there would have been more breaks in presence due to noise. This finding might be supported by the lowest score for the item 9 ("*I still paid attention to the real environment?*") indicating this group did pay attention to their physical environment the most. However, this finding conflicts with the item 1 ("*In the computer-generated world I had a sense of "being there*") and past research due to this group still reporting the highest average score for presence (Witmer & Singer, 1989). This group also reported higher score than the NW group for items 11 (*"How real did the virtual world seem to you?"*) and 12 (*"How much did your experience in the virtual environment seem consistent with your real-world experiences?")* which indicates high level of realism which is also an interesting result as this group used the older HMD and weaker performance. These results are also in line with the item 3 *("I felt like I was just perceiving pictures"*) which was reverse scored so that the higher value indicates they felt less like they would have been perceiving just pictures.

5.1.3 Omnidirectional slide mill

This condition resulted in the lowest score for all presence questionnaire subscales the average score of this questionnaire included. Compared to other research these values still indicate that the level of presence and immersion would have been considered as excellent (2 subscales) satisfactory (1 subscale) and marginal (1 subscale). The satisfactory grade would have been given to level of involvement and the marginal grade for experienced realism (Melo et al., 2023).

The slide mill was found to produce the most cybersickness and aborted experiences during data-collection. Based on the theoretical background cybersickness and decreased realism could work as barrier for achieving and maintaining higher presence or immersion (Kim et al., 2024; Daşdemir, 2023; Chang et al., 2020; Slater et al., 2009) It is also possible that the locomotion technique itself or the harness of the device produced more breaks in presence than other techniques with less limited movement. Adaptation was reported to be the lowest on the slide mill and have been seen as indicator of lower degree of immersion in prior research (Witmer & Singer, 2005).

Although receiving the lowest score for the above metrics, there was one item in the questionnaire in which this condition resulted in the highest average score. This item was the question number two ("*I still paid attention to the real environment?*") Indicating that, the users of this technique were less aware of their physical environment than other groups. This could be due to the quiet space where this device was located and the fact that they did not move physically in the space and therefore did not get tangled to cables.

Also comparing to the omnidirectional treadmill the slide mill is more quiet due to less moving parts.

5.2 Perceptual immersion

This section focuses on discussing the results of perceptual immersion of the three groups. The order of average questionnaire scores is NW group reporting the highest score while slide mill group reporting the lowest. Dunn's pairwise multiple comparison test reveals that there is a statistically significant difference between the NW group and the slide mill group for adaptation and engagement subscales and the average score of the questionnaire.

5.2.1 Natural walking

This group showed statistically significant difference with the slide mill group in the engagement ($p = 0.001$) and adaptation ($p = 0.022$) subscales and the average score ($p = 0.011$) of this questionnaire. Since these two groups used identical PC and HMD devices these results indicate that the type of locomotion technique can significantly impact the user experience of perceptual immersion independent of the system-level fidelity.

Previous studies have revealed that immersion might be the highest for those individuals who manage to adapt faster to their new environment. (Witmer & Singer, 2005) At the same time, it is not a surprise that natural walking might require less adaptation and therefore result in a better score for this subscale. At the same time the engagement subscale was measured by items 1 ("*How natural was the mechanism which controlled movement through the environment?*") and 2 ("*How involved were you in the virtual environment?*") indicating that the slide mill mechanism (figure 4) was experienced significantly less natural than actual walking.

5.2.2 Omnidirectional treadmill

The group using the omnidirectional treadmill did not show statistically significant differences between the other groups however still produced better average score than the slide mill group. This result indicates that based on this data the experienced level of perceptual immersion did not significantly differ from the other groups despite the slightly weaker system-level immersion. Although differences have been detected for some of the subscales perhaps the sample size has not been large enough to establish statistical significance, or the fidelity of these HMDs is good enough that within this sample size no differences were detected.

Despite yielding statistical significance empirical findings were gathered during the data collection potentially indicating the experienced level of immersion. Many of the participants started to walk slowly on the device during the 10-minute tutorial phase, but towards the end of the 2 hours experience they started to increase their speed. Even so much that one person managed to walk faster than the treadmill stepping outside of it. This observation can be seen as a sign of high adaptation to the locomotion technique which have been mentioned to increase chances of experiencing immersion and presence (Witmer & Singer, 1998). This finding is supported by the result of adaptation subscale rank in between the other two conditions. Many participants also tried to physically interact with the environment by trying to pick items or touch trees or sit on the landmark representing a bench. These common interactions can be a sign of high immersion and presence (Usoh et al., 1999; Slater et al., 1995). However, studies have also revealed that the sense of presence might also decrease even from high initial level if these interactions are not responded in a realistic way (Slater et al., 2009).

5.2.3 Omnidirectional slide mill

Adaptation showed statistical significance between the slide mill group and the natural walk group. This was expected by the hypothesis H1 and H2 and due to the way movement has been handled with the passively repositioning system also described in the figure 4. The perceptual immersion results reveal that the only subscale which this group did not report the lowest score of the three conditions was sensory fidelity. This subscale was measured by asking how well they could identify sounds and smells during their experience. Kruskal-Wallis test reveals that this difference is not statistically significant.

For the item 6 (*"How well could you concentrate on the assigned tasks or required activities rather than on the mechanisms used to perform those tasks or activities?"*) this group reported the lowest score. This item was part of the adaptation subscale showing statistically significant difference (p = 0.022) between this group and NW group. Interestingly in the presence questionnaire the slide mill group reported to have paid less attention to their physical environment during their experience. Perhaps this finding suggests that despite paying less attention to their physical environment the mechanism controlling movement might have required more attention from them than other locomotion techniques. This finding is supported by the lowest score for the item 5 (*"How proficient in moving and interacting with the virtual environment did you feel at the end of the experience?"*) indicating lower level of adaptation compared to other locomotion techniques. As mentioned above this finding indicates that the mechanism was not experienced as natural as by the other groups and immersion might have been decreased due to this (Witmer & Singer, 2005). It is also possible that the less natural movement reported for item 1 of the immersion questionnaire might have decreased overall user experience by introducing imbalance or cybersickness (Chang et al., 2020, Kim et al., 2024; Diaz et al., 2024).

5.3 System-level immersion

This section focuses on discussing the system-level immersion in detail. The order of system-level immersion for the groups ordered from highest to lowest was found to be omnidirectional slide mill, natural walk and omnidirectional treadmill. This order was not expected due to unexpected differences between the NW and slide mill conditions. The treadmill was expected to be the last due to older HMD and weaker PC, but less significant difference was expected between the other two groups. The used system specification was documented as much detail as possible including details considering both performance of the virtual environment and the fidelity of used hardware. Tables 4 and 16 presented these metrics in detail. Based on the two tables the slide mill performs the best followed by NW followed by the treadmill. This does not support the expected outcome of H2 since the past research mentions that the chances of achieving presence increase with the fidelity of the system. (Smith et al., 2001) However, H3 was formed to expect that the locomotion technique might influence subjective measures more than the HMD fidelity and system performance. This was due to past research mentioning cybersickness caused by a stronger sensory conflict due to lag or lack of vestibular stimuli might decrease sense of presence (Chang et al., 2020; Al-Jundi & Tanbour, 2022).

5.3.1 Omnidirectional slide mill

The omnidirectional slide mill used the newer Oculus Quest 3 headset and the more powerful PC setup, and these specifications can be seen from the table 4 presented previously. This headset has better resolution, better pixel density and better horizontal field of view than the older HTC Vive pro. These metrics have been mentioned to be critical for the overall user-experience and presence (Al-Jundi & Tanbour, 2022; Angelov et al., 2020). This hardware setup was practically identical between the natural walk and slide mill conditions, excluding the locomotion technique. Despite this the slide mill achieved the best average performance scores presented in the table 16. What is interesting is that this condition and the natural walk condition have total of 4 metrics where either one has the worst score while the other has the highest score despite practically identical hardware setup. This result indicates either more fluctuations between the runs or significant difference in software performance between the locomotion techniques. Future work should focus measuring these metrics in closer detail.

All three conditions showed steady and consistent average score for FPS which is an indicator of consistent rendering performance between conditions. The slide mill had only one performance metric which resulted in the lowest score of them all. This metric was the Avg Adaptive STDEV. This metric measures standard-deviation of performance metrics over time. Higher values indicate more fluctuation while lower numbers indicate more steady performance. Technically it is possible that large fluctuations in performance could create more breaks in presence if noticeable by the participants (Angelov et al., 2020; Slater et al., 2009). However, none of the participants mentioned complaints about experienced lag or noticeable performance issues.

For omnidirectional slide mill it was noticed that the system was less user-friendly despite the highest score for performance. This device had the greatest number of aborted sessions due to increased symptoms of cybersickness. In total 2 participants could not finish their experiments with this device due to cybersickness and additionally 3 people felt dizzy during their experience but managed to continue. Purely based on the performance metrics this was unlikely to be caused by a performance issue. The passively repositioning system might have resulted in a physically more demanding user experience since at least one person felt sweaty during their experience. Additionally, this locomotion technique might have caused greater sensory conflict and imbalance due to harness keeping participant in place while they walk on slippery surface. (Chang et al., 2020, Kim et al., 2024; Diaz et al., 2024) It is also possible that the increased chances of cybersickness reduced the perceptual immersion presence scores of this locomotion technique in general.

5.3.2 Natural walking

The natural walk had the second-best performance metrics after the slide mill due to identical HMD and PC used. This condition had no participants aborted due to symptoms of cybersickness. Some dizziness was reported during the experiments where participants had to be moved from one physical location to another and their VR headset was blacked out during this time. The biggest challenge of this locomotion method was the synchronisation of virtual space within the limited physical space and the cart which had to be pushed following the participant with PC and long power cords. Crossing the cords or getting tangled when turning around might have caused additional breaks in presence for some participants (Slater et al., 2009).

The table 16 performance metrics show that the average adaptive STDEV performance shows the best score of all conditions indicating more steady performance throughout the benchmark on average. This condition on the other hand has lowest performance of the conditions in two other metrics which are average P99 and P95 for FPS. These metrics represent FPS values which were maintained 99% or 95% of the time. The results indicate that this setup maintained 99% and 95% of the time the lowest FPS score on average. However, this value is over 90 frames per second for all conditions and since all the HMDs used the same 90Hz display refresh rate it is technically not noticeable difference and is therefore unlikely to affect subjective user-experiences (Cuervo et al., 2018).

5.3.3 Omnidirectional treadmill

This condition expectedly resulted in the lowest score for system-level immersion due to the older HTC Vive pro HMD and the weaker PC used. This is a limitation since the HMD and PC devices couldn’t be kept identical between the locomotion conditions. However, this creates exploratory value to compare whether the locomotion condition could potentially outperform these hardware advantages (H3). This analogy could be argued to be valid since based on theoretical background if the locomotion technique would produce higher subjective presence and immersion scores it could be argued to at least not be caused by having weaker hardware and performance metrics. Instead, this could be seen as a potential indicator that the locomotion technique might be more critical for the subjective user experiences of presence and immersion.

The system used by this condition did not achieve highest performance score in any of the table 16 performance metrics, however it did not score the worst in all of them. For the metrics of average minimum FPS, Average adaptive STDEV, Average P99 and P95 for FPS this condition had the middle ground results indicating that 99% and 95% of the time this condition maintained a higher average score for FPS than natural walking. The better performance for this metric could be explained by the smaller display resolution of HMD for example. The adaptive standard deviation indicates that the performance did not have the highest fluctuations either that could have broken presence (Slater et al., 2009).

The active repositioning system of this device required some additional instructions to be given to the participants due to the way the treadmill guided their feet back to the centre. As presented in the figure 3, sharp turns had to be avoided while walking and sharp turns should only be done when the treadmill has guided the participant back to the centre. Moments of losing balance or otherwise having to wait before turning might create additional breaks in presence (Diaz et al., 2024). Also presented in the figure 3 sensory conflict might be increased momentarily when standing still while the treadmill is still moving the participant back to the centre (Chang et al., 2020). None of the participants on this device had to abort their experience due to cybersickness, but at least one person had to take a separate break due to symptoms of dizziness.

5.4 Limitations and Future Work

Limitations of the results of this study include the small sample size collected per each condition. Additionally, the internal consistency received with the Cronbach's alpha test was acceptable in the context of this thesis however would not be sufficient for universal high reliability score for the groups of omnidirectional treadmill and natural walk. The hardware combination used for this study is an additional limitation since it was not possible to use the same HMD or PC for all locomotion conditions due to both physical and software limitations with the locomotion devices. This was considered by extracting the average performance metrics and hardware information from the different test setups and evaluated them as qualitative system-level immersion.

Future work around immersive virtual environments and kinaesthetic modalities should try to focus achieving larger sample sizes per condition and more statistical power. Future work should also aim to standardize the hardware used for each condition and perhaps try to systematically alter the HMD used with each locomotion technique to achieve better understanding how performance and display quality might influence immersion and presence with different locomotion techniques. Although implementing less frequent modalities like smell this study did not systematically cover whether having smells in the environment would have made the experience significantly more immersive. The received presence scores reflect that the level of immersion was good for all three conditions, but future research should aim to also explore how less frequent modalities such as the smells might influence these user experiences. Since the some of the results presented yielded statistical significance, future research should focus on confirming these findings and finding locomotion techniques that could reach level of NW but without the need for a large indoor space.

6. CONCLUSION

This section combines the key answers to the research questions (RQ1, RQ2) and hypothesis (H1, H2, H3) based on the results and discussion presented above. Key insights are highlighted summarizing the outcomes and implications for future research around locomotion techniques and immersive virtual environments.

To answer the research question R1 ("*How walking locomotion techniques influence subjective senses of presence and immersion in an immersive multimodal virtual environment?"*) this study used three physical locomotion techniques and two pre-validated questionnaires measuring two subjective user-experiences; presence and perceptual immersion. The results of this study indicate that the selection of locomotion technique can affect both user experiences in a statistically significant way. Based on the received results the selected locomotion technique can both increase or decrease the sense of presence and perceptual immersion within the same environment. Results reveal that the slide mill and natural walk had a statistically significant difference in both average scores of presence and immersion questionnaires indicating that the slide mill results in weaker user experience compared to natural walking. In real world applications it could be argued that the slide mill as a locomotion technique cannot provide sufficiently similar user experience as NW. However, no significant difference in average presence and perceptual immersion scores between the treadmill and NW groups were detected. This result indicates that the treadmill was able to produce similar outcome for presence and perceptual immersion as NW potentially making it a good option when physical space is limited. The change in HMD between these two conditions is an acknowledged limitation of this study and should be considered by future research. However, based on theoretical background it would be contradictory that the slightly weaker HMD and PC performance of the treadmill group would have increased these sense presence and perceptual immersion scores.

In the light of these results the omnidirectional treadmill group outperformed the slide mill despite weaker performance. This result supports the H3 ("*The selected locomotion technique will be more critical to the user-reported presence and perceptual immersion than other system-level metrics."*) The other two hypothesis H1 ("*Natural walking as locomotion technique will result in a higher user-reported presence and perceptual immersion compared to treadmill or slide mill-based locomotion techniques.*") and H2 ("*Omnidirectional slide mill will result in the lowest user-reported presence and perceptual immersion compared to natural walk or omnidirectional treadmill.*") are supported since the slide mill resulted in the lowest average score while the NW group resulted in the highest average score from both questionnaires.

To answer the R2 (“*How does system-level immersion, as influenced by locomotion technique, hardware, and performance, impact subjective senses of presence and immersion?”*) the system-level metrics were measured from all three conditions. These results revealed that, the treadmill group using HTC Vive Pro had the lowest performance and fidelity compared to the other two conditions using the Oculus Quest 3 headset. Although described as low and high performance the overall fidelity and performance of both hardware combinations were classified as medium fidelity (Al-Jundi & Tanbour, 2022; Angelov et al., 2020). Based on the results the locomotion technique potentially influenced the subjective user experiences more than the differences between these headsets. This is because the identical headset and PC combination resulted in the highest score (NW) but also the lowest score (slide mill) indicating the locomotion technique influencing these experiences more. The weaker headset PC combination ranking between the other two conditions for these metrics potentially indicate support for H3 describing that the locomotion technique as able to outperform the advantages of better performance and higher fidelity or that the slide mill would have broken the sense of presence and perceptual immersion to that extent. Future research around immersion and locomotion techniques should focus on systematically studying how different headsets affect the user experience with different locomotion techniques.

In conclusion, this study described exploratory framework combining differing perspectives from past research. Objective system-level immersion was analysed and combined with subjective user-experiences related to presence and perceptual immersion. The results suggest that the higher fidelity of HMD technology might not guarantee stronger user experiences. Factors such as the used locomotion technique may have a more crucial role shaping presence, immersion, engagement and adaptation.

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APPENDIX A: ITEMS OF THE IGROUP PRESENCE QUESTIONNAIRE

No.	Question	Subscale	Answer
1.	In the computer-generated world I had a sense of "being there"	Presence	1-fully disagree — fully agree-7
2.	Somehow, I felt that the virtual world surrounded me	Spatial presence	1-fully disagree — fully agree-7
3.	I felt like I was just perceiving pictures	Spatial presence	1-fully disagree — fully agree-7
4.	I did not feel present in the virtual space	Spatial presence	1-fully disagree — fully agree-7
5.	I had a sense of acting in the virtual space, rather than operating something from outside	Spatial presence	1-fully disagree — fully agree-7
6.	I felt present in the virtual space	Spatial presence	1-fully disagree — fully agree-7
7.	How aware were you of the real world surrounding while navigating in the virtual world? (i.e. sounds, room temperature, other people, etc.)	Involvement	1-extremely aware — moderately aware-7 not aware at all
8.	I was not aware of my real environment	Involvement	1-fully disagree — fully agree-7
9.	I still paid attention to the real environment?	Involvement	1-fully disagree — fully agree-7
10.	I was completely captivated by the virtual world?	Involvement	1-fully disagree — fully agree-7
11.	How real did the virtual world seem to you?	Realism	1-not real at all — completely real-7
12.	How much did your experience in the virtual environment seem consistent with your real-world experiences?	Realism	1-not consistent — moderately consistent- — very consistent-7
13.	How real did the virtual world seem to you?	Realism	1-about as real as an imag-ined world — indistinguishable from the real world-7
14.	The virtual world seemed more realistic than the real world	Realism	1-fully disagree — fully agree-7

APPENDIX B: PRESENCE AND ENGAGEMENT QUESTIONNAIRE

No.	Subscale	Question	Answer
1.	Engagement	How natural was the mechanism which controlled movement through the environment?	1-7
2.	Engagement	How involved were you in the virtual environment?	1-7
3.	Sensory fidelity	How well could you identify smells?	1-7
4.	Sensory fidelity	How well could you identify sounds?	1-7
5.	Adaptation	How proficient in moving and interacting with the virtual environment did you feel at the end of the experience?	1-7
6.	Adaptation	How well could you concentrate on the assigned tasks or required activities rather than on the mechanisms used to perform those tasks or activities?	1-7