Andreas Rojahn Sunde
Torje Dahll-Larssøn Thorkildsen

Virtual Reality with Omnidirectional Treadmills

The Impact on Immersion, Cybersickness, and Memory Retention

Master's thesis in Computer Science
Supervisor: Alexander Holt
Co-supervisor: Tomas Holt
June 2023

Master's thesis

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Abstract

Virtual reality (VR) has seen rapid advancements and growing popularity in recent years, offering immersive experiences in a variety of fields such as entertainment, education, and training. However, VR still faces challenges related to movement within the virtual environment and the discomfort caused by conflicting senses, often called cybersickness. A technology that can help with these challenges is Omnidirectional treadmills (ODTs). An ODT is an infinite space solution that allows physical movement to mirror the virtual one. Our research compares the effects of ODTs to those of traditional joystick-based VR setups, focusing on three key aspects: immersion, cybersickness, and memory retention. We conducted the study with 40 young adults and divided them into two equally sized groups. One group navigated the VR environment using an ODT, while the other group employed a joystick for movement. Apart from the method of movement, both groups had an identical VR setup. Each participant was subjected to three distinct tests in virtual environments. Following these tests, participants filled out a questionnaire about their individual experiences, including any occurrences of cybersickness and their perceived level of immersion.

Our study found notable differences between the two groups regarding cybersickness. The group using the ODT reported fewer symptoms compared to the joystick-based movement group. The two groups both reported high levels of immersion, though the data showed no significant statistical difference between them in this aspect. Similarly, when it came to memory retention, both groups exhibited comparable performances in this study.

While there were certain limitations in our study, such as the specific age range of the participants and their geographical location, our findings provide a significant contribution to understanding the potential benefits of integrating an ODT with VR. The findings from this might have implications, including potential influences on VR game design, training simulations, and overall user comfort and accessibility of VR technology.

Sammendrag

Virtuell virkelighet (virtual reality, VR) har gjort store sprang i utvikling og popularitet i løpet av de siste årene. VR tilbyr fordypende (immersive) opplevelser innenfor en rekke områder som underholdning, utdanning og yrkesrettet opplæring. Likevel er det fortsatt utfordringer med å ha tilstrekkelig plass til fysisk bevegelse ved bruk av VR. I tillegg kan det oppstå ubehag som skyldes motstridende sensoriske inntrykk. Ubehaget som oppstår kalles cybersyke (cybersickness). En teknologi som kan bidra til å løse disse utfordringene er en omnidireksjonell tredemølle (omnidirectional treadmill, ODT). En ODT er en tredemølle som lar brukeren bevege seg fritt i alle retninger uten å forlate et definert fysisk område.

I vårt forskningsprosjekt har vi sammenlignet effekten av å bruke en ODT for å bevege seg, i forhold til å bruke joystick-basert bevegelse i VR. Vi fokuserte på tre hovedelementer: fordypning, cybersyke, og hukommelsesbevaring (memory retention). Vi utførte studien med 40 unge voksne, delt inn i to like store grupper. Den ene gruppen navigerte i det virtuelle miljøet ved hjelp av en ODT, mens den andre gruppen brukte en joystick. Med unntak av bevegelsesmetoden, var VR-oppsettet identisk for begge grupper. Hver deltaker gjennomførte tre separate tester. Etter testene, svarte deltakerne på et spørreskjema om deres individuelle opplevelser, inkludert eventuelle opplevde symptomer på cybersyke og graden av fordypning.

Vår studie avdekket ingen betydelige forskjeller mellom de to gruppene knyttet til fordypning. Begge gruppene rapporterte en høy grad av fordypning, men det var ingen statistisk signifikant forskjell mellom dem på dette området. Studien vår avdekket heller ingen forskjell mellom gruppene når det kom til hukommelsesbevarine og begge gruppene viste en lik ytelse i løpet av testene. Når det kommer til cybersyke, så ble det avdekket en forskjell på symptomene mellom gruppene. Gruppen som brukte en ODT rapporterte færre symptomer sammenlignet med gruppen som brukte joystick for bevegelse i VR.

Selv om funnene beskrevet evenfor er betydningsfulle, så er det viktig å påpeke at studien ble utført med noen begrensninger, som deltakernes aldersgruppe, kjønnsbalansen i testgruppen og begrenset geografiske spredning. Likevell kan studien fortsatt ha betydning på flere områder, som f.eks. innvirkning av design av VR-spill, simuleringer ved opplæring, og ved den generelle brukeropplevelse.

Acknowledgements

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Thanks are also due to Xiaomeng Su, who provided indispensable help with data visualization and statistical analysis. Additionally, Xiaomeng offered valuable feedback on our written report, improving its clarity and comprehensiveness.

Acronyms

API application programming interface. 1, 22

AR augmented reality. 1, 19, 22

BCI brain-computer interface. 1, 13

EEG electroencephalogram. 1, 13

FOV field of view. 1, 9, 16

FPS frames per second. 1, 15

HMD head-mounted display. 1, 7, 14

IPD interpupillary distance. 1, 12, 13, 21, 39, 68

IR infrared. 1, 17

ODT omnidirectional treadmill. 1–5, 7, 13, 17–19, 21, 34, 38, 39, 44–54, 56, 57, 62, 64–70, 72–75

SDE screen door effect. 1, 16

VR virtual reality. 1–5, 7–22, 32, 38, 39, 41–49, 53, 55, 58, 59, 64–72, 74, 75

XR extended reality. 1, 22

Glossary

Degrees of freedom Number of ways an object can be tracked. 3 degrees of freedom in virtual reality typically means all rotation is tracked, while 6 degrees of freedom means all rotation and all translation is tracked. 1, 15

Immersiveness The quality or degree of being immersive. Immersion in virtual reality is the perception of being physically present in a non-physical world. 1, 3, 46

Inside-out tracking A virtual reality device using inside-out tracking looks out to determine how the position of the device changes in relation to the environment. When the headset moves, the sensors are used to calculate the location of the device in the room and the virtual environment responds accordingly in close to real-time. 1, 14, 17

Marker-based inside-out tracking An inside-out tracking method that relies on external markers that sensors on the devices get information from. An example is the SteamVR lighthouse tracking which uses external casters (markers) emitting invisible light signals. These signals are picked up by sensors on the devices and used to calculate their positions. 1, 14, 17

Motion-to-photon The time it takes for a movement to be performed on the display. A virtual reality example could be the time it takes for the user to start moving their controller until this movement is represented in the head-mounted display. 1, 12

Outside-in tracking Outside-in tracking uses cameras or other sensors not integrated into the tracked devices to track movement. The user can move freely around a designated area defined by the intersecting visual ranges of the cameras or sensors. 1, 14, 17

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1 Introduction

This section provides an overview of our research project, delving into the background and motivation for our thesis. We outline our objectives and research questions, highlighting the purpose of our study and the gaps we aim to fill. Furthermore, we describe our methodology for tackling the research questions and provide a description of our research stages. We also discuss the contributions and significance this thesis offers to the field. Finally, we provide an overview of the structure of our thesis, outlining the organization of the subsequent chapters.

1.1 Background and Motivation

Virtual reality (VR) and omnidirectional treadmills (ODTs) are two emerging technologies that have gained popularity in recent years and have the potential to revolutionize the way we interact with digital content [24].

VR is a computer-generated simulation of a three-dimensional environment that can be interacted with in a seemingly real way [4]. VR allows for an immersive and interactive experience for the user, and one of the ways a user can immerse themselves in a digital world is by using a VR headset. The VR headset is worn by the user to provide visual and auditory feedback and to track their head movement. The user can also receive haptic feedback from the VR controllers to enhance the sense of touch and presence in the virtual world. VR technology has many applications, from gaming and entertainment to education and training [12, 20]. Using VR allows for experiences that are impossible in the physical world, and it is rapidly advancing as a tool for creating new and innovative forms of human-computer interaction.

Even though traditional VR can allow for an immersive and interactive experience for the user, it lacks the ability for real locomotion. Typically, users are confined to a limited area and remain relatively stationary during VR sessions. To address this limitation, traditional VR employs two common approaches for user movement within the virtual world. The first approach simulates movement using a joystick on the VR controller. Users can control their virtual motion by manipulating the joystick, allowing them to navigate the virtual environment. The second approach is teleportation. The user aims and selects where to teleport using the controller. Both these approaches enable the user to move around in the virtual environment without physically moving in the physical space [65]. These approaches are used instead of allowing the users to move around because it would require an obstacle-free space and good body awareness from the user. Besides, most VR systems have limited tracking areas, making moving over large distances difficult.

On the other hand, ODTs are physical devices that enable users to engage in locomotive motion in any direction while staying in the same spot or area [46]. Combining an ODT with a virtual environment allows unhindered movement within the virtual space.

In traditional VR, it is common for some users to experience cybersickness. A meta-analysis on VR and cybersickness found sensory mismatch to be one of the leading causes of cybersickness, due to the discrepancy between the sensed movement and the visual perception of movement within the virtual world. While users may visually perceive themselves moving through the VR environment, their physical bodies remain stationary, which can lead to feelings of nausea and dizziness [15]. Here, ODTs can provide a potential solution by physically allowing users to move within a confined space. By physically allowing users to move while interacting with the virtual world, the sensory cues align more closely with what the brain expects during movement, possibly reducing the likelihood of cybersickness.

Incorporating an ODT with VR technology could also enhance memory retention by harnessing the cognitive benefits of physical activity. Research shows that regular movement improves physical health and stimulates brain function. Physical activity increases the oxygen supply to brain cells, encourages the generation of new brain cells, and aids synapse creation. Furthermore, it has been linked to better memory, reduced depression risk, and improved academic performance [54]. Leveraging these insights, a VR system paired with an ODT could provide a physically engaging, immersive experience, promoting both movement and learning, thus potentially improving memory retention.

The primary objective of our thesis is to expand on the existing knowledge of combining ODT with VR technology. We noticed a gap in the existing research in this area and were intrigued to investigate the potential benefits of these technologies. Our study focuses on three key aspects: immersion, cybersickness, and memory retention. The rationale of choice and significance of these aspects are elaborated in Section 1.4.

1.2 Research Questions

Based on our stated motivation, our research aims to investigate the use of ODT combined with VR across various tests. The primary objectives are to explore the potential differences between using an ODT as the movement method in VR compared to joystick-based movement. Specifically, we want to examine if the physical movement on an ODT impacts memory retention, cybersickness, and immersion for users in VR. The research questions guiding our thesis are as follows:

- **RQ1:** How does the physical movement on an ODT affect the perceived cybersickness of users compared to joystick-based movement in VR?
- **RQ2:** How does the physical movement on an ODT affect the immersiveness of users compared to joystick-based movement in VR?
- **RQ3:** How does the physical movement on an ODT affect the visual memory retention of the users compared to joystick-based movement in VR?

1.3 Research Stages

We divided our research into four stages to reach our goals and address our research questions. The first part was a literature review on ODTs, cybersickness, immersion, and memory retention. This part also contained a dive into background theory on VR history, VR headsets, and research methodology.

The second phase of our research project involved the development stage, where we focused on creating the necessary tests for our study. We designed and built four virtual environments to be used in our experiments, and the virtual environments all had one form of incentive for the participant to move around in the virtual world.

The third stage of the research method was the test phase. The main goal of the test phase was to gather data. Participants were recruited and subjected to the virtual environments we had developed. The tests were conducted using a qualitative approach, applying a questionnaire and evaluating the participants on their performance scores.

The final stage of our research project involved the analysis of the data gathered during the testing phase. We visualized the collected data and performed statistical analyses to determine the significance of the results. By applying appropriate statistical tests, we aimed to ascertain whether any observed differences or patterns were statistically significant, indicating that they were not due to chance.

1.4 Contributions and Significance

The main deliverable of this research is a detailed report that includes a literature review, research procedures, test results, and discussions of our findings. As mentioned in section 1.1, the motivation behind the research was the need for research on the combination of ODTs and VR. Most of the knowledge in this area is theoretical and needs more empirical evidence. Therefore, this research aims to contribute to the existing knowledge by conducting practical experiments that either confirm or challenge the existing theories. The report resulting from this research will shed light on the topic and potentially validate or refute the current assumptions in the field.

Research on immersion in VR can offer significant insights and benefits for VR training, game developers, and gamers. Immersion is a key component of the VR experience, describing the extent to which a user feels present in and engaged with the virtual environment. Furthermore, inadequate research has been conducted on how ODTs affect immersion. Advancing the field will aid in answering whether ODTs are equipment worth investing in. If ODT usage increases immersion, this could have important implications for the VR industry.

For VR training simulations, increased immersion could make the experiences more realistic and lifelike, preparing users better for what they might experience if they end up in the simulated scenario. On the gaming side, game developers might be encouraged to include ODT support for their games, which again will give gamers a greater reason to invest in the technology.

On the other hand, finding that ODTs do not affect or negatively affect immersion is also insightful. This could indicate a need for improved design or functionality in current treadmill models or a shift towards different methods for facilitating user movement within the VR environment. In terms of VR training simulations, understanding the implications of these findings could lead to better decision-making when choosing and implementing equipment for specific training scenarios. If ODTs were found to detract from the immersive experience, trainers might opt for other technologies or simulation methods that align more closely with their training objectives and user needs.

Potential findings about cybersickness differences combining VR with ODTs could advance the field and offer much-needed solutions for those who struggle with this issue. Cybersickness can be a significant barrier to using VR technology. By better understanding the causes and triggers of cybersickness, researchers can develop methods to mitigate these issues, improving user comfort and expanding the accessibility of VR technology. Finding out how ODTs affect cybersickness in VR could also help in analyzing whether the people easily affected by cybersickness are in general sensitive to current VR headset technologies, or if the problem is more related to the joystick-based movement style.

Findings about memory retention when using ODTs with VR could improve education and training programs. Suppose research establishes a correlation and likely causation between using ODTs and improved memory retention. In that case, incorporating physical movement in VR can lead to better learning outcomes. In VR education, this could improve the learning outcome of experiences. For example, VR experiences that include physical movement using ODTs can make lessons more interactive and realistic in subjects like history and geography. This could potentially lead to stronger memory retention and understanding of these lessons. In training, particularly for physically demanding roles like firefighting, medicine, or military service, VR combined with ODTs could provide a safe, controlled environment to simulate real-life scenarios. The realistic physical movement facilitated by ODTs could result in more effective training, allowing users to practice real-world movements and actions and consequently improving muscle memory and decision-making in high-pressure situations. This more realistic form of training could lead to better preparedness and performance in the field.

Moreover, understanding the impact of ODTs on memory retention could guide the design of VR learning and training experiences. For instance, developers could emphasize physical exploration and interaction within virtual environments, thereby harnessing the potential benefits of increased memory retention linked to ODT use. However, more research is needed to confirm these potentials and understand how to maximize the effectiveness of VR and ODTs in education and training scenarios.

1.5 Thesis Structure

This master thesis is divided into nine sections.

1. Introduction presents an overview of the research topic, introduces the main research objectives and questions, highlights the significance and motivation behind the research, and briefly outlines the subsequent thesis sections.

2. Background delves into the existing literature, VR history, relevant research, and theories and describes different VR headsets and their specifications.

3. Materials contains the materials, tools, and resources used in this thesis.

4. Research Methodology presents the research methodology and elaborates on the specific research methodology and statistical analysis concepts used in this thesis.

5. Virtual Test Environments provides descriptions of the virtual environments used in our study.

6. Test Procedure outlines the specific procedures conducted to test the participants and gather data.

7. Results presents the findings obtained from the research. It includes the data collected, statistical analysis, and visual representations of the results.

8. Discussion investigates our findings in this research in the context of the research objectives, observations, limitations, and further work.

9. Conclusion summarizes the main findings and insights derived from the study.

2 Background

This section introduces essential VR and ODT concepts related to our research. First, we talk about the history of VR and follow a timeline through important discoveries in the field of VR. Then we look at VR theory and essential concepts in VR. Next, we show some of the most popular VR headsets, explain their specifications, and outline some differences between them. Finally, we describe the different types of ODTs and some related ODT research.

2.1 History of Virtual Reality

It is common to consider VR as new technology. VR had its boom and became more accessible to the public in the mid-2010s. However, the first VR technical developments date back to the 1830s. In 1838 Sir Charles Wheatstone was the first to describe stereopsis [26]. Stereopsis is the component of depth perception retrieved through binocular vision [62]. Wheatstone illustrated that seeing two stereoscopic pictures or photos side by side through a stereoscope gave the user a sensation of depth and immersion [25].

The second half of the 1900s contains a lot of technological advancements. Sensorama was the first VR machine, and Morton Heilig developed the device in 1956 (patented in 1962). The Sensorama was an arcade-style theatre cabinet that stimulated all the senses of the user. It had stereo speakers, a stereoscopic 3D display, fans, smell generators, and a vibrating chair. Heilig also created six different films for Sensorama. He shot, edited, and produced the films himself. As a result, the films could immerse the user fully [25]. Heilig also created the first head-mounted display (HMD) called the Telesphere Mask. The Telesphere Mask was a non-interactive film medium without any motion tracking. The headset provided stereoscopic 3D and comprehensive vision with stereo sound. In 1961, two Philco Corporation engineers developed the first motion tracking HMD. The HMD was the “Headsight” and had a video screen for each eye and a magnetic motion tracking device linked to a closed circuit camera [25].

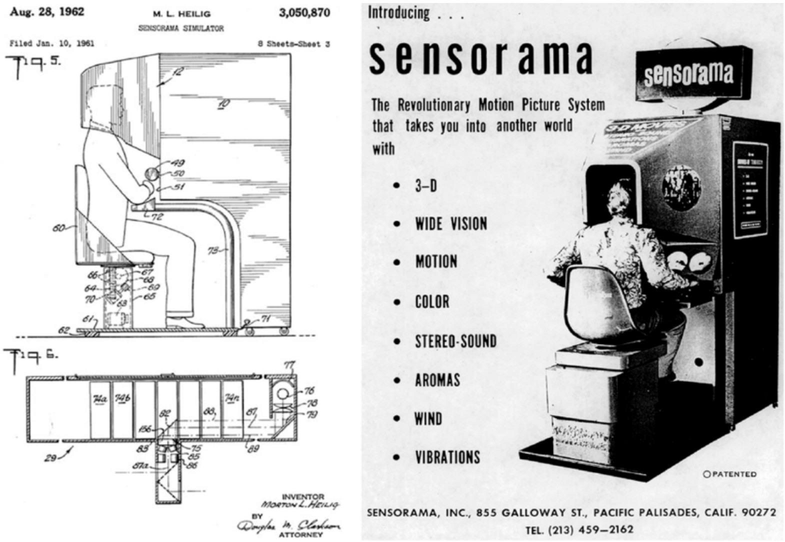

Figure 1: A picture of the Sensorama, the first virtual immersion system [19].

From the 60s to the 80s, many advancements happened in VR, especially for flight simulators. However, it was in 1987 that the term virtual reality was born. After years of development, it was still not an all-encompassing term to describe the field. However, this all changed when Jaron Lanier, founder of the visual programming lab, coined the term. NASA also got involved with VR in 1989 with their own VR simulation. The simulation was used to train astronauts, and the VR equipment is recognizable as a modern example of VR and features gloves for fine simulation of touch interaction [25].

The gaming industry began developing VR equipment for games in the 90s. This meant that the public gained access to the technology, even though household ownership of cutting-edge VR equipment was still out of reach. In 1991, Virtuality Group Arcade Machines were available. The machines were equipped with VR goggles, and the players could play on a gaming machine with real-time immersive stereoscopic 3D visuals. Some devices were connected to the internet, allowing for a multiplayer experience. Gaming companies like SEGA and Nintendo also got involved with VR. SEGA announced their own VR glasses for their console SEGA Genesis in 1993. The prototype glasses had head tracking, stereo sound, and LCD screens in the visor. SEGA intended to release the glasses. However, development difficulties meant that the glasses would never be released, even though they had developed four games for this product. Another VR failure was the Nintendo Virtual Boy. Nintendo announced the Virtual Boy as the first-ever portable console that could display true 3D graphics. However, it promptly failed. One of the reported reasons that the Virtual Boy failed was that the games were only in two colors: red and black. There was also a lack of software support, and it was hard to use the product comfortably [25].

Figure 2: A picture of the Nintendo Virtual Boy [69].

The 2000s most prominent feature in the VR field was the Street View developed by Google and the creation of the Oculus prototype. In 2007, Google enhanced the maps by adding the Street View feature. Google had cars with special cameras drive around and capture the street view in 360 degrees. They also allowed the user to "drop in" to almost any street in the world and look around. Additionally, in 2010 Street View also gets a 3D mode [25].

From 2010 to 2020, a lot happens on the VR front. In 2010, a young man named Palmer Lucky created a VR headset kit that anyone can make, and met with John Carmack. This enabled his *Oculus Rift* to become more significant than he could have ever imagined. In 2012 a Kickstarter to fund the product and development of his prototype headset, the Rift, began. The Kickstarter does incredibly well and raises almost 2.5 million dollars. This marks a dividing line between the commercial failures of the past and modern VR. The social media giant Facebook (now Meta) caught some interest in the Oculus technology and bought it in 2014. 2014 was also a bumper year, as it was the year that Google Cardboard, PSVR, and the Samsung Gear VR launched and the year that made VR a hot topic.

2016-2017 is when we see an explosion in VR products. Hundreds of companies were developing VR products. Headsets such as the Rift and the HTC Vive led the way, and most of the headsets had dynamic binaural audio. Dynamic binaural audio means that the sound source appears to change position with the change of the position of the user [26, 25, 17].

In 2018 Oculus demonstrated a new headset prototype, the Half Dome. This is a VR headset prototype with a 140 degrees field of view (FOV). VR has also reached a point where it is used in various ways. Some use cases now provide immersive gaming experiences, help treat psychological disorders, teach new skills, and even take terminally ill people on virtual journeys. 2019 is the year that Forbes named as “The Year Virtual Reality Gets Real”. Facebook releases the standalone headset Oculus Quest which creates a lot of interest and momentum as it sells out in many locations. This marks a shift in the VR ecosystem, as standalone is much easier for the average user, as the user does not require a powerful computer to use VR. The game Beat Saber was also the first VR application to sell over 1 million copies in under a year. 2020 brought one of the most popular VR headsets: The Oculus Quest 2 (now Meta Quest 2). The Quest 2 was well received by the community, with mostly positive reviews, and it continued to sell in the millions worldwide. From 2021, huge companies such as TikTok and Facebook (now Meta) invested large sums of money in developing VR hardware, software, and content [25].

2.2 Immersion

Immersion in the context of VR refers to the sensation of being physically present within a non-physical world or a virtual environment [28]. The feeling of immersion can be achieved using a VR headset, and there are specific techniques that can be used to enhance the immersive experience within the virtual environment [32, 72].

Some good examples of techniques that strengthen immersion of the user are spatial sound, interactivity within the VR environment, and physical feedback. Spatial sound is a playback technology that allows the user to determine the direction of the sound. The gaming industry has applied spatial sound for a while, where the sound of the game follows the visual effects. But it can also be effectively used in VR. Since the users can look freely around in all directions, the gaze of the user can be controlled by the direction of the sound. For example, if users hear a large explosion behind them, they will likely get curious and turn around [29].

Increasing immersion by getting the user to interact with the content is also a technique used to strengthen the immersion of the user. Data gloves allow users to make motions like pushing or turning to interact with objects naturally. Data gloves use various sensor technologies that can capture data, such as bending fingers [73].

Physical feedback is the final example of a technique that strengthens the immersion of the users. Using haptic feedback on a controller or data glove makes it possible to replicate the feel of real-world interaction. Haptic feedback lets users touch and feel something unreal by sending vibrations to the controller or data glove [73].

Another important concept in VR is presence. There is a correlation between immersion and presence; the higher the immersion, the more real or presence the user experiences in the virtual environment. Presence typically refers to the sensation of being physically present. However, the meaning is slightly different when discussing immersion. The term telepresence is often used to describe the experience of feeling present in a remote or virtual environment. When our consciousness convincingly perceives that we are operating or interacting in an alternate location, such as within a virtual environment, we may experience an enhanced sense of presence [29].

Immersion is often linked with time perception, and gamers commonly report losing track of time during immersive experiences. However, scientific investigations have not consistently supported a strong link between immersion and time perception. A study at the University of York explored the potential correlation between attention, time perception, and immersion. The participants were divided into two groups, with one group assigned a secondary task while engaging in a game and the other group solely focused on playing the game. Surprisingly, the results of the study contradicted the prevailing belief that immersion is directly connected to time perception. The findings indicated that attention affected immersion and time perception differently, with the experimental manipulation primarily influencing time perception rather than immersion. This led the researchers to propose a dissociation between immersion and time perception, although they state that further investigation was needed to gain a comprehensive understanding of this relationship [43].

2.3 Cybersickness

Even though a VR headset can provide the user with a more immersive experience, it can also have certain drawbacks. A VR headset can induce a temporary state of illness in some users during and after use. This discomfort is known as cybersickness and common symptoms include eye strain, headaches, and nausea [32]. Two theories that try to explain why cybersickness happens are the postural instability theory and sensory conflict theory.

The postural instability theory suggests that disruptions to the postural control system of the body play a role in the occurrence of cybersickness. The human body has an innate instinct to maintain postural stability, and when this stability is compromised due to external stimuli, it can lead to cybersickness. According to this theory, addressing postural instability and improving postural control mechanisms can potentially reduce cybersickness symptoms. However, it is important to note that conflicting evidence exists regarding the relationship between postural instability and cybersickness. For example, some research has found that when the movement of subjects is restricted by adopting a sitting posture to minimize postural instability, cybersickness symptoms do not ease [22].

The sensory conflict theory is a concept that explains the occurrence of motion sickness or cybersickness in VR. The human body relies on various sensory organs, including olfactory, vestibular, and somatosensory systems, to gather information and perceive the physical state of the body. However, when the external stimuli received by these sensory organs differ from the expected information of the body, a conflict arises. The theory states that the severity of cybersickness depends on the extent of this sensory mismatch [22].

Multiple factors can contribute to cybersickness. According to a review paper by the University of Würzburg, one of the factors is latency. Latency refers to the delay between the movement of the user and the corresponding response in the virtual environment [60]. When there is a noticeable delay, it can disrupt the sense of presence for the user and cause discomfort. This delay can be particularly problematic in virtual reality experiences where real-time interaction is crucial, such as fast-paced games or simulations that require precise movements. The paper concluded that high motion-to-photon latency could worsen performance in interactive graphic applications and provoke cybersickness in VR applications. The effect latency has on cybersickness and how reducing latency improves the safety and usability of VR systems and apps is also discussed in this paper [60].

Another contributing factor that has been discussed in relation to cybersickness is the gender of the user. A study involving nearly 1,000 participants found that females generally report higher levels of cybersickness than males. The difference between the genders was attributable to females experiencing significantly higher oculomotor and disorientation symptoms than males. However, the study also found that the severity of nausea symptoms in females was slightly less than in males. The study also states that it could not identify the root of the gender differences and that it is unclear whether these differences are attributable to anatomical differences or an effect of hormones [59].

The role of interpupillary distance (IPD) in contributing to the observed differences in cybersickness between genders has been a subject of research interest. One study with 46 participants suggested that the primary determinant of these gender differences in cybersickness is an improper fit of the IPD. The study found that females with a VR headset that was not correctly fitted and a pronounced history of motion sickness experienced the highest levels of cybersickness, and had cybersickness symptoms an hour after the test. However, in an ensuing experiment, when females could correctly adjust their IPD to match the VR headset, they experienced cybersickness levels similar to the males. When the VR headset was fitted for IPD, the females recovered from the symptoms in under one hour. The study proposes that VR headsets should redesign to have a wider IPD adjustable range to reduce cybersickness rates, especially among females [58]. However, a contrasting study with 178 participants examined if the mismatch between the IPD of the user and the IPD setting of the VR headset contributes to immediate cybersickness. The study stated that no relationship was found between IPD mismatch and immediate cybersickness [16].

Various techniques have been proposed to mitigate cybersickness. Xiayuan Gong wrote a paper on minimizing VR motion sickness in the popular VR game "VRChat" and presented three possible solutions. These include deceiving the vestibular system via electrodes, implementing a brain-computer interface (BCI), and applying an infinite space solution. Regarding the first method, Gong expresses concerns about the safety and potential side effects of using electrodes to trick the vestibular system. The vestibular organs are inside the inner ear and primarily involved with balance [68]. Gong advocates for additional research to determine the safety and effectiveness of this solution. He also has concerns about the BCI approach. A BCI is a computer-based system that captures and analyzes the brainwave activity of the user, typically measured through electroencephalogram (EEG), and translates it into computer commands or actions [56]. Gong points out the complexity of extracting specific signal features and linking them to mental activities and notes that accurately interpreting and using these signals is challenging. Thus, he states that this solution also needs further research and development.

The third solution Gong proposed is an "infinite space" solution. An infinite space solution can give the user enough space to move around physically, and an ODT is a fine example of a platform that can provide "infinite space". Gong states that by matching the movement on an ODT with the movement in the virtual environment, the sensory conflict and cybersickness will not exist. However, Gong highlights a drawback to this solution. He describes that large ODTs can be relatively expensive for common VR users [22].

2.4 Memory Retention

Memory retention is the ability of the brain to retain and recall information. This process is vital for learning, decision-making, and other cognitive functions. It involves three stages: encoding, storage, and retrieval. Encoding is the stage where the individual takes in the information, storage refers to how the individual maintains the information over time, and retrieval refers to how the individual access the information when needed. The strength and accuracy of memory retention can be influenced by various factors, including attention, emotional state, health, and the context in which learning occurs for an individual [38].

VR has shown promising results in enhancing episodic memory and object recognition. A study conducted in 2011 investigated episodic memory by comparing active and passive navigation in VR. Participants in the active navigation group were free to explore rooms for 50 seconds. In contrast, the passive group observed a pre-recorded visual scanning of the rooms for the same duration. The findings revealed that participants who actively navigated the virtual environment demonstrated better object recognition compared to those who passively navigated. It is worth noting that this study utilized older VR technologies, where the active navigation group relied on a keyboard and mouse for movement instead of modern VR headset controllers [52].

A study conducted at the University of Surrey developed an immersive VR replica of an operational pilot plant situated within the university. The study aimed to evaluate if students would gain more knowledge from this VR simulation compared to learning from a multimedia instructional video and evaluated the students based on information retention and self-efficacy. The findings from the study indicated that both information retention and self-efficacy were comparable between the VR simulation and the multimedia-based activities [41].

2.5 Virtual Reality Headsets

This section lists some of the specifications and features of VR headsets that may be important to the outcomes of this thesis, as well as some of the most frequently used headsets. There are a variety of VR headsets to pick from, and headsets differ in pricing and hardware specifications. Table 2.1 below shows an overview of some of the most popular VR headsets.

HMD	Tracking	Horizontal FOV	Refresh rate (Hz)	Resolution (per eye)	Release year
Meta Quest 2	Inside-out	97	72/90/120	1832x1920	2020
Valve Index	Marker-based inside-out	108	80/90/120/144	1440x1600	2019
Oculus Rift S	Inside-out	88	80	1280x1440	2019
HTC Vive	Marker-based inside-out	108	90	1080x1200	2016
Oculus Rift	Outside-in	87	90	1080x1200	2016
Meta Quest	Inside-out	93	72	1440x1600	2019
HTC Vive Pro	Marker-based inside-out	98	90	1440x1600	2018
HTC Vive Cosmos	Inside-out	97	90	1440x1700	2019

Table 2.1: Some of the most popular VR head-mounted displays used on Steam in April 2022 [6]. Specifications are from VRcompare [70].

In addition to the specifications in Table 2.1, headset comfort is a crucial aspect that impacts user fatigue in VR experiences. The weight and center of mass of the VR headset have been shown to play a significant role in determining comfort levels. A study from 2021 found that fatigue in participants increased as the center of mass shifted toward the front of the head. Additionally, they reported that fatigue increased with the weight of the VR headset, even with an unchanged center of mass [31]. Therefore, adequately designed straps for the VR headset could help distribute the weight evenly across the head of the user, alleviating strain and enhancing comfort during extended VR sessions.

2.5.1 Degrees of Freedom

Degrees of freedom is a way of describing the number of ways an object can move in 3D. Most VR devices are either three or six degrees of freedom. If a device has three degrees of freedom, it usually means the rotation of the device can be tracked, but not the translation (position). For VR headset, the user will have their head rotation tracked while their movement in space remains untracked. Six degrees of freedom means that rotation and translation will be tracked, so the user has complete movement flexibility within the tracked space [23].

2.5.2 Refresh Rate

The refresh rate is based on how fast a display can re-draw the entire image on the screen. The measurement used is Hz (hertz), representing the maximum number of images the display can draw within a second. A refresh rate of at least 90 Hz is common for most modern VR headsets. The refresh rate of a display is tied to the frames per second (FPS) of a running application [11]. If the display runs at 90 Hz with an application running at 45 FPS, the experience will be similar to using a 45 Hz display. Some VR systems offer solutions to this problem. For example, SteamVR has a feature called Motion Smoothing, which uses previous frames to synthesize new ones when the computer has trouble producing an FPS matching the frame rate. This enables the application to output rendered frames at half the frame rate frequency while the user will experience the full display frame rate, although half the frames are approximated [61]. Low refresh rates or FPS are tied to more discomfort and motion sickness and should be kept to a frequency higher than 50 Hz with comfort increasing with increased refresh rate until at least 90 Hz [76].

2.5.3 Resolution

In computer hardware, the resolution is "the number of distinct pixels in each dimension that can be displayed", often listed as the *width x height* [15]. A full high-definition monitor has 1920 pixels across the screen horizontally and 1080 pixels vertically, distributed uniformly across the display. In VR, the lenses of the VR headset will bend the light from the pixels so that it appears to be coming from further away, enabling the human eye to focus on objects in the virtual environment [27]. Lower resolution VR headsets have a more pronounced screen door effect (SDE), meaning there is a visible square pattern around the pixels. The SDE occurs due to how close the display on the VR headset is to the eyes of the user, making it possible to notice the black space between the pixels. A solution to this problem is to increase the resolution of the display while keeping the same physical size. This increases the pixel density, making the space between pixels harder to notice. Modern headsets are close to eliminating the SDE [27].

2.5.4 Field of View

FOV refers to the visible area a person can see through their eyes or an optical device like a camera [72]. In the case of a VR headset, the FOV is typically specified in terms of horizontal and vertical degrees. However, measuring FOV accurately is challenging in VR headsets, as it depends on various factors such as the pupil location of the user, lens aperture, lens focal length, display size, and the binocular relationship between the eyes of the user [5]. Consequently, VR headset manufacturers often advertise a larger FOV than what most users can experience with their headsets [51].

The human vision has an approximate vertical FOV of 135 degrees and a total horizontal FOV of 200 degrees. The horizontal binocular FOV is around 120 degrees, which is where the horizontal FOV of the two eyes overlap, and we perceive depth accurately [5, 14]. In comparison, most VR headsets have a horizontal FOV ranging from 80 to 110 degrees and a vertical FOV ranging from 85 to 105 degrees. Increasing the FOV can contribute to a greater sense of presence in the virtual world and improve the perception of speed, as our peripheral vision registers motion and speed cues [30].

2.5.5 Tracking System

There are two main ways of tracking VR devices, inside-out and outside-in. Inside-out is based inside the VR device itself. The device typically has several strategically placed cameras that calculate movement in 3D space with an onboard processing chip. Outside-in tracking is based on external sensors that calculate the position of a device. This can, for example, be cameras placed around a room that track infrared (IR) light on VR headsets and controllers. One disadvantage is that devices lose the ability to track if objects in the room occlude the sensors [49].

A common approach for modern VR headsets is inside-out tracking, while controllers emit IR lights that are tracked outside-in by the headset cameras. Another popular approach is using light casters that emit IR light in the room, while the headsets and controllers have IR sensors that calculate their positions in the room. This is a form of marker-based inside-out tracking, as the tracked devices rely on information from outside sources [49].

2.5.6 PCVR and Standalone VR

VR headsets can be categorized as PCVR or standalone systems. PCVR headsets rely on a separate computer to run applications and transmit rendered frames to the VR headset through wired or wireless connections. On the other hand, standalone headsets contain their own miniature computer and battery within the device. While they may not match the power of modern PCs, they can self-track and run VR experiences independently [72, 48].

2.6 Omnidirectional Treadmills

ODTs could revolutionize VR experiences by offering more realistic movement in virtual environments. There are several ways to achieve this type of movement, but ODT are often divided into two types; sliding and conveyor belts. As the name suggests, sliding ODTs utilize a sliding mechanism. These treadmills often consist of a circular platform. Users are often strapped onto the treadmill, meaning they can not move freely in the actual space around them. The user usually wears special shoes designed for sliding or puts covers over their own shoes to move on the treadmill. Since they are securely fastened to the safety bar of the treadmill, they can walk or run with their feet sliding across the surface of the treadmill. In comparison, the conveyor belt ODTs use continuous conveyor belts to move the user in any direction. This type of treadmill is similar to a traditional conveyor belt treadmill but designed to move in multiple directions. The user can move around in physical space and be pushed back toward the starting point by the conveyor belts [40].

While ODTs offer the potential for a more immersive VR experience and can help alleviate sensory conflicts associated with cybersickness (as described in 2.3), they also come with certain limitations. A study conducted in 1997 identified several shortcomings when investigating the use of ODTs. One of the limitations was the mechanism used for centering the user on the treadmill. The study used a conveyor belt ODT, and they found that the process of centering could lead to balance issues and make users more aware of their movements, potentially affecting their experience. Another drawback of ODTs was observed during sidestepping, where users faced difficulties maintaining and recovering from a loss of balance [13].

A study by the University of Muenster compared three different gaming conditions: desktop gaming, traditional VR, and VR with sliding ODTs. The primary focus of the study was to examine the impact of VR technology and the use of ODTs on the gaming experience. The findings of the study indicated that VR gaming led to higher levels of flow, presence, and enjoyment compared to desktop gaming. However, using VR also resulted in a higher incidence of cybersickness among participants. Interestingly, the study states that the use of sliding ODTs did not significantly reduce the occurrence of cybersickness, nor did it significantly improve overall enjoyment compared to traditional VR without ODTs [71].

3 Materials

This section offers a detailed overview of the software and tools used in creating the VR environments. Furthermore, it describes the VR headset and ODT used in this study.

3.1 Unity

We used Unity to create our virtual environments. Unity is a powerful game development engine that enables developers to build 2D and 3D games and experiences for various platforms. This includes mobile devices, consoles, and PC. Since it is easy to use and has an extensive feature set, it is widely used by game creators and has a large community base. The engine has a wide set of tools for building detailed 3D models, realistic lighting, and special effects [67].

Unity also has a large asset store where developers can purchase or download free assets. Unity supports VR and augmented reality (AR) development, and developers can quickly create immersive experiences thanks to the built-in support for both VR and AR. Therefore, Unity is a popular choice among developers aiming to build games and experiences for VR and AR platforms [66, 67]. The programming language of Unity is C#. C# is a modern, object-oriented, and type-safe programming language [10].

3.2 The Omnideck

The ODT used in this study is the Omnideck. The Omnideck, developed by Omnifinity, is a large ODT specifically designed to enable users to engage in physical movement within a virtual environment. This ODT weighs approximately 1500kg and boasts a diameter of over four meters. It features a circular platform that is divided into 16 motorized conveyor belt sections [47, 45].

To track the position of the user, a VR headset is utilized. The headset communicates the location of the user to the Omnideck system. When the Omnideck detects that the user has moved away from the center, it activates the section the user is standing on, as well as adjacent sections. The further away from the center that the user has walked, the quicker the sections move. These active sections then move toward the center of the platform, guiding the user back toward the middle. Through this mechanism, the Omnideck creates the illusion of an infinite platform, providing users with the freedom to explore and navigate within the virtual world while experiencing realistic physical movement [47]

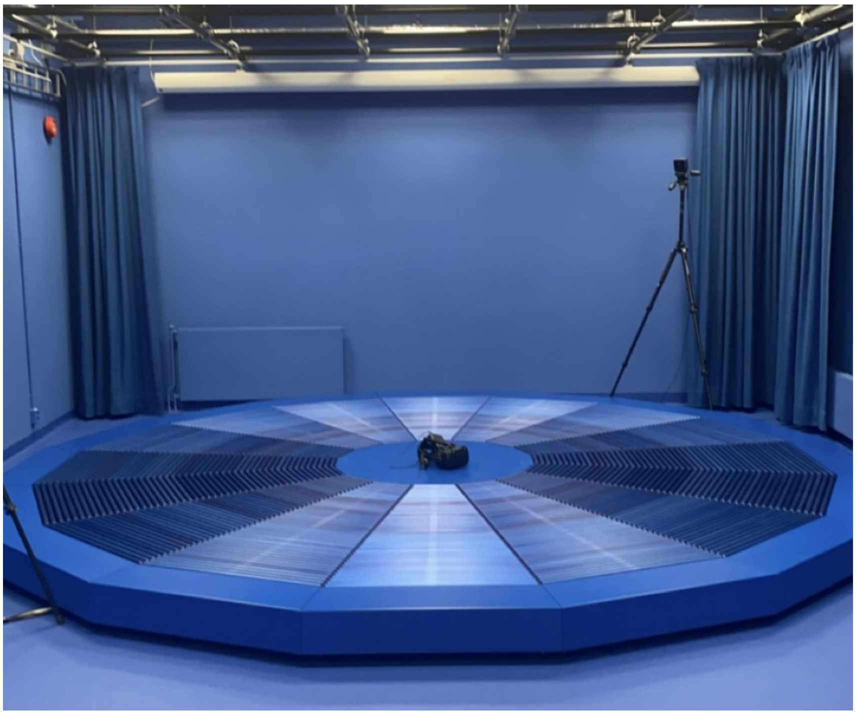

Figure 3: The ODT used in this study, the Omnideck

3.2.1 Omnitrack

The Omnideck is controlled through a software called Omnitrack. This software serves as an interface between the Omnideck and the VR setup. It provides the developer with vital information about the status of the Omnideck, the connection with the VR system, and data about the user, including their speed, distance walked, and current status within the VR environment.

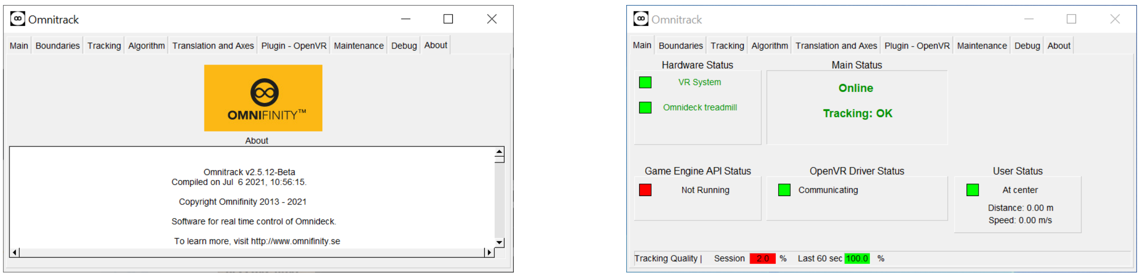

Figure 4: The Omnitrack software

3.3 Meta Quest 2

In this project, we used the Meta Quest 2 headset for the tests. The Meta Quest 2 has achieved over 10 million sales, as of 2021, and is a popular choice for VR headsets. It has several features that make it a highly capable VR headset [74].

One of the key features of the Meta Quest 2 is its high-quality display. As mentioned in Table 2.1, the headset has an LCD display with a resolution of 1832x1920 pixels per eye. This is higher than many of the other popular VR headsets referenced in the table and provides a clear visual experience for the user. Additionally to being a standalone headset, the Meta Quest 2 can be used as a wireless PCVR headset. This eliminates the need for cords that can hinder the movement of the user and allows for greater freedom of movement. This is especially useful when paired with an ODT [39]. The headset has three different settings for IPD. Additionally, the Meta Quest 2 headset offers a good selection of refresh rates. It provides users with the option to select a refresh rate of either 70, 90, or 120 Hz. As discussed in the section on refresh rates (2.5.2), lower refresh rates have been associated with discomfort and cybersickness. A refresh rate of 90 Hz was used on the headset in this thesis. As mentioned in Section 2.5.2, a refresh rate of 90 Hz should not pose any significant problems for users in terms of discomfort or cybersickness.

Regarding comfort, we upgraded the headset to avoid terminating tests due to strain and discomfort. The standard headset strap was replaced with the Quest 2 Elite strap with battery, produced by Meta. Due to the included battery, the strap weighs in at 179 g, pushing the center of mass of the headset closer to the center of the head. As mentioned in Section 2.5, the center of mass significantly affects comfort levels in VR headsets. Although the new strap increases the total weight of the VR headset, it shifts the center of mass towards the back. While we believe this trade-off is worth it, the included battery also allows for more frequent testing due to the doubled battery life of the headset [39]. The standard foam interface was also replaced with a softer leather-covered interface, which is easier to clean between participants.

Figure 5: Picture of the Meta Quest 2 headset and controllers used in this study

3.4 Virtual Desktop

The Virtual Desktop software was used with the Meta Quest 2 headset for our tests. Virtual Desktop is an application capable of streaming the content from a computer directly to a VR headset wirelessly. It allows for a shared viewing experience by concurrently displaying the rendered content on both the computer screen and the VR headset. The content is transmitted via the internet from the computer to the VR headset. However, it is important to note that a stable and high-quality internet connection is required to ensure a seamless and immersive user experience [55].

3.5 OpenXR

OpenXR is an open standard for access to extended reality (XR) platforms and devices, which includes AR and VR. It aims to simplify XR development by providing cross-platform, high-performance access to XR devices through the OpenXR application programming interface (API) that handles the underlying hardware [35]. As a result, developers will only need to program their application to work with a generalized XR device. They can then focus more on application development without adjusting for platform-specific code for each of their targeted XR systems individually. This thesis will use OpenXR to integrate VR equipment with Unity.

3.6 Version Control

To manage and track the code for this thesis, Gitlab was utilized as the hosting platform. Additionally, Git was employed to manage the code repository.

Git

Git is a distributed version management system that is free and open source. Linus Torvalds created Git in 2005, and it is commonly used to coordinate work among developers during a software project. Additionally, it is used to track and manage changes to the code in a project [21].

GitLab

Gitlab is a website that provides a platform for storing and hosting code. GitLab provides developers with the same capability as Git but with a more user-friendly interface than traditional Git.

4 Research Methodology

The term research methodology refers to the systematic design of a study aimed at producing valid and reliable results [37]. This section delves into different research methodologies and statistical analysis methods. Furthermore, this section details the type of data we aim to collect from the participants and the means of acquiring it. Lastly, it provides a comprehensive description of the research methodology decisions made for our study, encompassing the chosen methodology, analysis techniques, and data collection methods.

4.1 Qualitative and Quantitative

Qualitative, quantitative, and mixed-methods are different methodologies, distinguished by whether they focus on numerical data, non-numerical data, or both.

4.1.1 Qualitative Research

Qualitative research collects and analyzes non-numerical data such as text, video, or audio to understand concepts, opinions, or experiences. Qualitative research can be utilized to gain in-depth insights into a topic or to generate new research ideas. Some qualitative research approaches are grounded theory, ethnography, and action research. Each one of these research approaches involves using one or more data collection methods. The most common qualitative methods are observations, interviews, surveys, and focus groups [8].

Qualitative Variables

Qualitative variables represent non-numerical data where their values fit into categories. Qualitative variables can be nominal or ordinal. A nominal variable has no ordering of its values. An example of a nominal qualitative variable is eye color, as a categorical color has no implied order. Ordinal variables are variables with an implied order of their possible values. An example of an ordinal qualitative variable is the health of a person with the possible values poor, reasonable, good, and excellent. There is an implied order going from poor to excellent [57].

4.1.2 Quantitative Research

The process of collecting and interpreting numerical data is known as quantitative research. It can be used to discover patterns and averages, as well as to make predictions and verify causal linkages. Quantitative research methods can be used for descriptive, correlational, or experimental research.

- Descriptive research aims to find an overall summary of the study variables.
- Correlational research aims to analyze the link between the study variables.
- Experimental research aims to determine whether there is a cause-and-effect relationship between study variables.

Both correlational and experimental research can be used to test hypotheses or predictions formally. Collecting quantitative data through self-ratings is common, and some of the most common quantitative research methods are experiments, surveys, systematic observation, and secondary research [9].

Quantitative Variables

Quantitative variables are variables that represent quantitative (numerical) data. These variables can be categorized as either discrete or continuous. Discrete variables are countable and have a finite number of possible values between two points [57]. For example, the number of children a person has is a discrete variable that takes up a finite set of values between two chosen points. There are four possible values between 0 and 3 children (0, 1, 2, 3). Continuous variables can take on infinite values between two points [50]. For example, weight is a continuous variable that theoretically can take on infinite values between 0 and 3 (0.0, 0.1, 0.01, 0.001,..., 3.0) of the chosen weight measurement unit. Continuous variables can be transformed into discrete variables by placing ranges of continuous values as single values, for example, by rounding off weight measurements. Quantitative variables can also be converted to qualitative ones. An example is calculating the body mass index (continuous) of a person and then categorizing the person as either underweight, normal, or overweight [57].

4.2 Data Sampling Design

The sampling design is crucial as it determines the group from which data will be gathered. The two primary types of sample design are probability sampling and non-probability sampling. In probability sampling, a group of people is chosen randomly, which increases the likelihood of generalizing the findings of the study. As the sample is random, it is plausible to expect similar results throughout the entire population without collecting data from every individual. Conversely, non-probability sampling does not involve a random sample. This method often employs a convenience sample, implying that data is gathered from easily accessible individuals such as acquaintances, friends, family, or colleagues. Consequently, the results from a non-probability sampling technique are not as generalizable as those from probability sampling [33].

4.3 Data Collection Method

There are many ways to collect data for a study; some are referenced in Section 4.1. In our master thesis, we will employ a survey method for data collection.

4.3.1 Survey

Survey research means collecting information about a group of people. It is an effective way to gather data and can be done physically or online. The test group receives questions regarding the experiment, and the researchers analyze the result. There are two main types of surveys. The first type is a questionnaire. A questionnaire is a list of questions that the respondents fill out themselves. The second main type of survey is interviews. An interview involves asking the respondents questions and recording the responses [37].

4.3.2 Likert Scale

A Likert scale is a rating scale used to measure opinions, attitudes, or behavior. The scale consists of five to seven answer statements and the participants chose the options that best correspond with how they feel [7].

4.4 Statistical Analysis

Inferential statistics are used to analyze a larger population based on the sample of collected data from the population. The purpose is to answer a hypothesis about the general population, where a hypothesis is an attempted explanation for a phenomenon. A null hypothesis (H_0) states there is no difference between an observed property in the population based on some variable change. An alternative hypothesis (H_a) states the opposite, that a difference between the observed property is true in general for this variable change. A p value is calculated while assuming the null hypothesis is true. It gives the probability of getting a result at least as extreme as the one observed by random chance. If the p value is less than some chosen significance level, the null hypothesis can be rejected, and the alternative hypothesis is considered significantly likely to be true. It is common to consider $p \leq 0.05$ significant and $p \geq 0.05$ nonsignificant (not significant). The null hypothesis should not be discarded if the result is nonsignificant, as the effect is not unlikely to be due to chance. An incorrectly discarded null hypothesis is a type I error or a false positive [3].

4.4.1 Student's T-Test

Student's t-test is a statistical hypothesis testing method widely used for assessing the significance of differences between two sample means. The null hypothesis suggests that the two sample means are equal (no significant difference exists). If the calculated p value is lower than the significance level, we reject the null hypothesis, inferring a significant difference between the two means. There are two main types of Student's t-test: independent (two-sample) t-test and paired t-test. The former is used when two separate groups are compared, while the latter is applicable for pre-post comparison on the same group or unit [34].

Student's t-test is a parametric test, meaning it makes assumptions about the underlying population distribution. Parametric tests in statistical analyses typically rest on four key assumptions. One of these is the normality assumption, which posits that the analyzed data follows a normal distribution [18]. Testing whether data follows a normal distribution can be done using several tests. Razali and Wah (2011) compared the power of several well-known normality tests using a Monte Carlo simulation of sample data. They found the Shapiro-Wilk test to be the most powerful test, followed by the Anderson-Darling test, the Lilliefors test, and the Kolmogorov-Smirnov test in the listed order [10]. The Shapiro-Wilk test checks if the given data significantly differs from a normal distribution [64]. The test will be used with a significance level of 0.05 in the analysis.

The second assumption is the homogeneity of variances, also known as homoscedasticity, which assumes that the variance of each group being compared is equal. One method to test for this assumption is Levene's test. The test sets a null hypothesis that the variances in the two groups are equal and an alternative hypothesis that the variances are different. Suppose the test gives a p value lower than the significance level. In that case, the null hypothesis is rejected, and the alternative hypothesis is accepted, meaning the variance is considered different in the groups [18]. The analysis will use a significance level of 0.05 in this report.

Furthermore, parametric tests assume that the data are measured at least at the interval level, meaning that ratio and continuous-level data both fulfill this assumption. Interval level data means that equal intervals between values in the data represent equal differences in the measured property [18]. Likert scale data is often considered ordinal instead of interval level as the differences between intervals of values are challenging to define [75]. For example, interval-level would imply that the difference between “strongly disagree” to “neutral” is the same as “disagree” to “agree” on a 5-level Likert scale.

Parametric tests also often assume that the data is independent between the participants. These assumptions are not trivial, and violating them can lead to incorrect interpretations of test results. Specifically, violation of these assumptions can impact the type I error rate, reducing the accuracy and reliability of the test results. Therefore, it is crucial to assess and ensure these assumptions are met before using parametric tests [18]. When the assumptions of parametric tests are not met, non-parametric tests such as the Mann-Whitney U test can be used.

4.4.2 The Mann-Whitney U Test

The Mann-Whitney U test (also known as the Wilcoxon rank sum test) is a non-parametric statistical test that compares two independent groups without requiring large normally distributed data. However, the test gets more prone to type I error in cases of heteroscedasticity, meaning the variance is non-constant for the observed random variable over different values of an independent variable.

This test has the following assumptions [42]:

- The two groups are randomly drawn from the target population.
- The data is independent between the participants in the groups, and the groups are mutually independent.
- The data is measured on an ordinal or continuous scale.

This test can analyze Likert scale data (4.3.2). Likert scales are ordinal with an implied order from “strongly disagree” to “strongly agree”. If the group samples are randomly drawn and are independent of each other, the test will meet all the assumptions.

4.4.3 Correlation Analysis

Correlation analysis is used to identify relationships between two variables. The character r often denotes correlation coefficients and is a number between -1 and

+1. An r value close to 0 means there is close to no correlation between the variables. In contrast, an r close to -1 or +1 indicates a strong negative or positive relationship between variables, respectively [2]. A positive or negative correlation does not mean the variables have a causal relationship. Conversely, a correlation value close to zero does not mean the variables are independent or do not affect each other. Correlation analysis can help identify variables that should be investigated further and aid discussion [1].

Spearman's Rank-Order Correlation

Spearman's rank-order correlation is a correlation method that does not carry any assumptions about the data distribution of the variables [1]. This method can be used for ordinal data such as Likert scale data [44]. Table 4.1 shows the correlation coefficient interpretation used in this thesis. Values closer to another category range than 0.05 will have that category noted after the main category. For example, a value of $r = .37$ will be described as a positive *weak to moderate* correlation.

Correlation coefficient $\|r\|$ (absolute)	**Interpretation**
$0.9 \leq \|r\| \leq 1.0$	Near-perfect
$0.6 \leq \|r\| < 0.9$	Strong
$0.4 \leq \|r\| < 0.6$	Moderate
$0.1 \leq \|r\| < 0.4$	Weak
$0.0 \leq \|r\| < 0.1$	Negligible

Table 4.1: Interpretation of correlation coefficients in this thesis as absolute values, showing the words used to describe positive and negative correlation.

Correlation coefficients are subject to statistical uncertainties, and a larger sample size and higher correlation values are better to increase the significance of the results. A null hypothesis may propose that two variables are linearly uncorrelated, with an alternative hypothesis proposing that a correlation exists. If the calculated p value is lower than the significance level, the null hypothesis is rejected, and the variables are said to show a significant correlation. However, a significant correlation does not mean a high degree of correlation, and vice versa [2]. For example, a low correlation coefficient $r = .10$ might be significant with $p = .01$ if the sample size is high enough. Conversely, a high correlation coefficient $r = .80$ might have a $p = .30$ if the sample size is low. Additionally, a significant correlation coefficient in a sample does not mean the general population correlation has the same correlation values, but it is significantly unlikely that the variables are truly uncorrelated.

Simpson's Paradox

Simpson's paradox is a statistical phenomenon that can occur when causal inferences are made across different explanatory levels. In short, Simpson's Paradox says that when looking at different groups together, the direction of a relationship can reverse or change compared to each group individually. Although not actually a paradox, this can lead to potential pitfalls in data correlation analysis. For example, a study might find that a certain drug dosage is linked with better recovery from an illness. However, when divided into age groups, the drug might show a negative correlation with each age group individually. The truth might be that each age group has a different baseline for recovering from the illness and that the drug actually worsens the recovery. This example illustrates that correlation links should be drawn carefully and could otherwise have negative consequences. Potential subgroups should be analyzed to deal with Simpson's Paradox [36].

4.5 Choices in This Study

Throughout this thesis, several decisions had to be made to ensure a valid result while under constrained time and resources. This section describes why these choices were suitable for this thesis.

4.5.1 Research Approach

In this thesis, we have decided to use a quantitative research approach (4.1.2). This enables us to test many participants within a shorter time span. We want to study differences and links between the variables of immersion, visual memory retention, and cybersickness between the two chosen groups and analyze if these differences are significant. Due to the numerical nature of quantitative variables, the approach is ideal for statistical testing of many samples, for example, testing for significant correlations and differences in population averages.

The thesis participant groups will be chosen using non-probability sampling. Due to a limited time frame, we will prioritize getting a substantial amount of participants to be tested instead of trying to force probability sampling through advertising for volunteers. We believe reaching out to friends and acquaintances will yield considerably more participants, which will strengthen the results and the analysis of the data. As completely anonymous game data and survey answers have been chosen as the data collection method, we do not believe testing acquaintances will affect the results to a noteworthy degree. Answering honestly can not have any consequences for the participant.

4.5.2 Continuous Data Analysis

For continuous data in this thesis, Student's t-test (4.4.1) will be used after checking that the assumptions are met by the data. The independent (two-sample) Student's t-test type is chosen as the two tested groups are independent and not a pre-post comparison. We will use the Shapiro-Wilk test to check for normality and Levene's test to check for homoscedasticity. Continuous data fulfill the assumption of the data being measured at least at the interval level. Our testing regime will fulfill the last assumption of independence between participants, although complete independence cannot be guaranteed due to our limited population demographic. Some participants might know each other and have certain expectations before their tests. For correlation analysis, Spearman's rank-order correlation (4.4.3) will be used since both continuous and ordinal data will be analyzed together.

4.5.3 Ordinal Data Analysis

Ordinal data has an implied order of the possible values. An example is Likert scale (4.3.2) data, as it has an implied order going from disagreement to agreement. These levels of agreement can be represented by integers increasing in values with the order of the ordinal levels. However, applying parametric tests such as Student's t-tests might not always be suitable due to violated assumptions. For example, the data can not be normally distributed if the mean of the data lies close to one of the extremes. In cases of Likert scale data, we will use the two-tailed Mann-Whitney U test (4.4.2). For correlation analysis, Spearman's rank-order correlation (4.4.3) will be used. Spearman's rank-order correlation can discover non-linear relationships in both continuous and ordinal data such as Likert scale data [63].

5 Virtual Test Environments

This section describes the virtual test environments. Four virtual environments were created for the testing process. The initial environment served as a preparation room, allowing participants to get used to the VR experience and familiarize themselves with the movement within the virtual space. The remaining three environments were specifically designed for conducting the tests. These virtual environments were developed using Unity (3.1).

The decision to implement three distinct tests was motivated by several considerations. Primarily, the objective was to prolong engagement with the games. This was done to ensure that our cybersickness results were not influenced by a short test duration. Secondly, we wanted to give the participants time to get comfortable with the movement. Therefore, we designed the tests to progressively increase the movement level required from the participants, starting with minimal movement in the first test and gradually escalating in the subsequent tests.

5.1 Preparation Environment

Ensuring that participants were comfortable with the VR equipment and movement controls was crucial for preparing them for the tests. With this in mind, we designed a specific preparation room. The goal of this preparation room was to provide participants with a comfortable area where they could get used to the VR equipment and learn how to move around in the virtual environment. By giving them this dedicated space, we could help participants focus more on the tasks during the actual tests rather than spending too much time trying to learn the controls and getting used to the virtual setting.

To uphold fairness across all participants, we established a time limit of three minutes for each individual to stay in the preparation room. This limit ensured everyone had an equal chance to prepare and get comfortable with the VR equipment and the virtual setting before they started the actual tests.

The preparation room, shown in Figure 6, was based on the lab where our tests were conducted. This was done to present the participants with a familiar scenario as when they were led into the testing lab. The virtual lab has a button on a stand at the end of the room, visible from the start. This button is used throughout the other tests and is meant to introduce the button mechanic, where the user needs to press the button with their VR controller to activate it. A successful button press is rewarded with a fireworks show in the preparation room. Another design choice in the preparation room was to include a hallway looping around to another part of the room. This was done to prepare the participants to turn and move 360 degrees in the virtual environment.

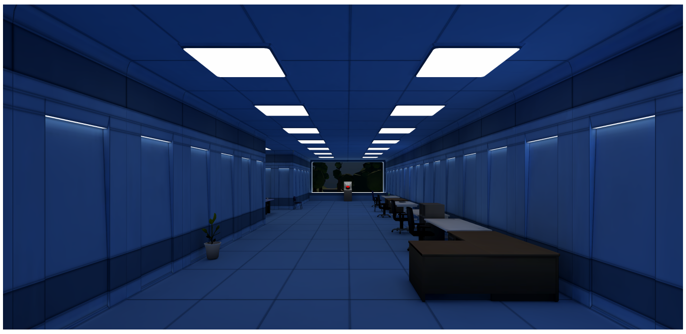

Figure 6: Picture of the virtual preparation room.

5.2 Test 1: Memory Hallway

Our assessment begins with a test called *Memory Hallway*, designed to measure the memory retention capacity of participants within a hallway setting. Before the main test, participants are guided through a demo room, serving as a simplified version of the forthcoming test and featuring fewer items to memorize. The primary function of this room is to familiarize participants with the procedures, controls, and assessment criteria of the test.

A 30-second window is given to the participant to explore and navigate the demo room. When the time is up, they are automatically moved to an evaluation room where they are tasked with recalling and selecting all the items they remember from the hallway. Following this, they proceed to the actual test room.

Figure 7: Picture of the first test, Memory Hallway.

In the main test room, the hallway is expanded to include more items for the participant to memorize. The participant is given 90 seconds to freely explore the virtual environment and familiarize themselves with the items present. A long straight hallway was chosen to force the participants to move across the entire distance to see all the items. This meant the participants had to move actively using their assigned movement option: joystick or ODT.

Other designs were considered, such as a large cube-shaped room with items placed around like a museum. However, this idea was rejected as it would be hard to guarantee that the users would notice all the items. Also, since most items would generally be closer to the users, the movement would not be as important to get a good look at those items. Once the allocated time in the hallway is over, the participant is automatically transported to the evaluation room.

In the evaluation room, the participant is prompted to recall and select all the items they can remember from their exploration of the hallway. The performance of the participant is assessed based on the accuracy of their item selections. Each correctly recalled item earns points, contributing to the score of the participant. Conversely, incorrect selections lead to deductions of points.

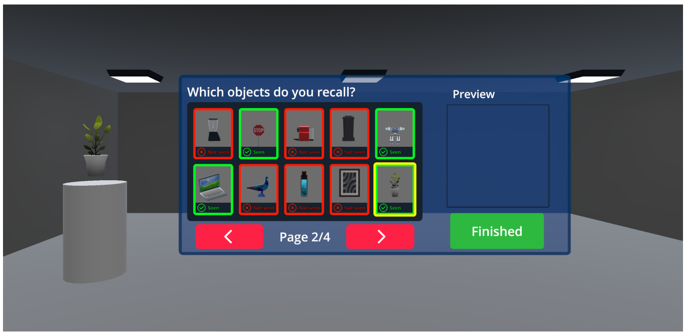

Figure 8: Picture of the evaluation screen after the memory hallway test.

5.3 Test 2: Memory Pattern

The second test, called *Memory Pattern*, presents the participants with a grid of white squares. A path is then illuminated, one square at a time, guiding the participant through the grid. Once the entire path is illuminated, it disappears. The objective of the participant is to recall and navigate the correct path to reach the end square. Before they begin the test, they are shown a demo of how the game works.

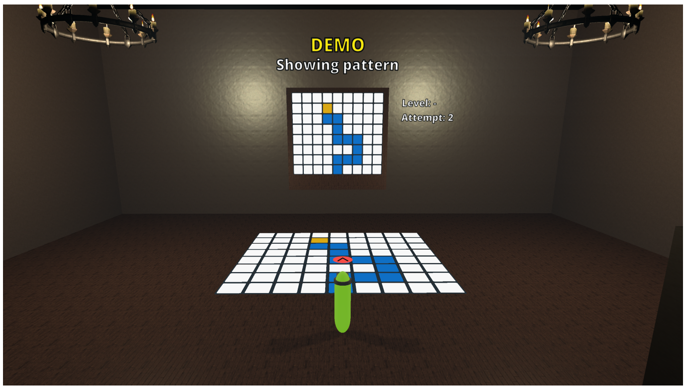

Figure 9: Picture of the Memory Pattern demo.

The game begins with a relatively easy path, and the difficulty level gradually gets harder as the participant progresses, by increasing the pattern length and complexity. There are a total of five levels. If the participant steps on the wrong square, they must start over from the beginning of the path after the full pattern is displayed again. The evaluation of the game is based on the number of attempts or tries the participant needs to complete each level.

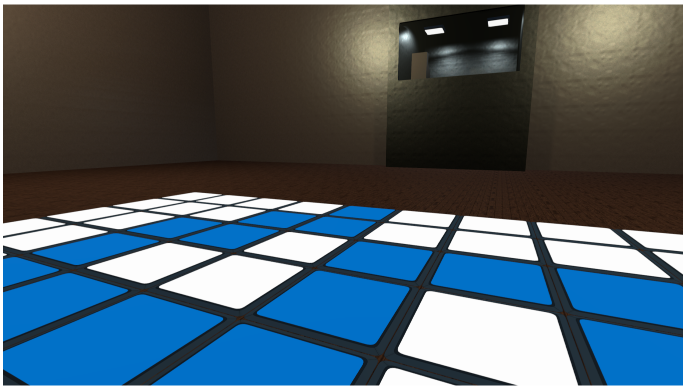

Figure 10: Picture of the second test, Memory Pattern, from the point of view of a participant.

This test uses a grid to incentivize movement in different directions while testing memory with a clear pattern. The user will have to move forward, backward, left, and right while keeping the pattern memorized. A collider visualization is also placed at the feet of the user. This was done to make the user aware of when they were close to touching grid tiles and to avoid the potential frustration of unintentionally hitting them.

5.4 Test 3: Puzzle Walk

The third test, called *Puzzle Walk*, involves presenting the user with a grid of squares. Obstacles block certain parts of the grid, and the objective is to reach the end square by walking across all the tiles in the room. However, each tile can only be touched once, and the room is reset if the user fails. Graphical changes indicate which tiles have been touched. The test is made up of five levels, with the first level being simple and designed to help the player understand the game mechanics. The puzzles then increase in difficulty as the user progresses.

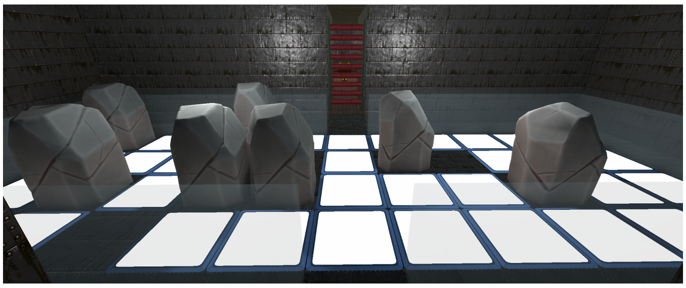

Figure 11: Picture of the third test, Puzzle Walk.

Additionally, there is a time limit, where the user starts with only 10 seconds to complete each level before the puzzle resets. If the time runs out, the number of attempts increments by one, and the user must start over at the current puzzle. However, if the user walks over a square, the time limit is set back to 10 seconds. The number of attempts to complete each puzzle is used to evaluate the performance of the user.

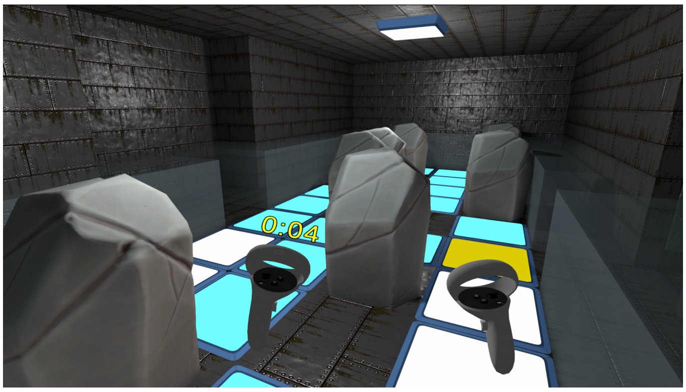

Figure 12: Picture of Puzzle Walk from the point of view of a participant.

The task is designed to incentivize user movement while the user has to figure out solutions to the puzzles simultaneously. Similarly to the Memory Pattern task (Section 5.3), a grid is used to make the player move in many directions while being a simple representation of the puzzle mechanics. The timer also forces the user to move between tiles frequently to refresh it. If they do not, the time will run out, costing the user an attempt while the puzzle restarts. The user starts at the introductory level, and each level increases in complexity. This makes each subsequent level familiar to the user, while they have to further develop their skills in the task.

5.5 Pilot Study

Before conducting the main tests, a small-scale pilot study was conducted with six participants. The pilot study followed an iterative process, where participants provided feedback, and adjustments were made to address bugs or improve aspects of the tests based on the feedback. The primary objectives of the pilot study were to evaluate the clarity and comprehensibility of the assignments, identify any issues or bugs in the games, and gather feedback on the questionnaire.

The pilot study was instrumental in gathering valuable insights and making necessary adjustments before proceeding with the main tests. The feedback from participants helped identify potential problems in the virtual environments and the questionnaire, leading to refinements and improvements in the testing process. For instance, some participants reported difficulties comprehending the test concept. In response to this feedback, the wording of the instructional text bubbles was revised. By conducting the pilot study, the project was fine-tuned, and shortcomings were addressed, resulting in enhanced quality and reliability for the subsequent main tests.

6 Test Procedure

This section delves into the chosen test procedures for this thesis. The following provides a description of how the tests were carried out, encompassing processes such as obtaining informed consent through a consent form and employing specific data collection and analysis methodologies.

6.1 Participant Selection

The participant selection for this test employed a non-probability sampling method (4.2). Specifically, participants were recruited through social media channels. Due to the requirement of utilizing the Omnideck (see 3.2), the selection was confined to individuals located in Trondheim, Norway.

6.2 Test Groups

The participants were divided into two groups for the study. The first group utilized traditional VR equipment, specifically a VR headset with joystick-based movement controls. The second group tested the same environment using a VR headset with ODT-based movement. The participants were assigned to each group randomly, ensuring that both groups represented the larger population and minimizing the potential for selection bias.

6.3 Consent Form

Before commencing the tests, all participants had to read and sign a consent form. The purpose of this consent form was to provide participants with detailed information regarding the objectives, duration, data collection procedures, potential risks, and the confidentiality measures implemented to protect their privacy. The consent form used in this project can be found in Appendix C.

6.3.1 Risk of Harm

The consent form highlighted two aspects of potential harm. Firstly, the risk of cybersickness was outlined. It was made clear to participants that using a VR headset could result in symptoms such as motion sickness, nausea, disorientation, blurred vision, eye strain, eye fatigue, or general discomfort while engaging with virtual reality content. Participants were informed that they may experience these effects during the study.

Half of the participants would be using an ODT for their VR movement. It was discovered in Section 2.6 that using an ODT could cause a loss of balance, especially during sidestepping movements. This raised the possibility of participants experiencing a fall. However, participants were reassured that the likelihood of such an event was low. Extensive testing had been conducted prior to the test. Additionally, all participants would receive training in a preparation room (5.1) to familiarize themselves with the VR movement and environment. This training aimed to enhance their comfort and minimize the risk of any accidents.

6.3.2 Personal Information

The participants were told to fill out a questionnaire after the test. The participants were informed that they would receive a randomly generated candidate number, ensuring they were anonymous. They were also informed that the data gathered about them in the questionnaire was their gender, age group, and previous experience with VR. As for the other questions, they would be related to the VR environments. Additionally, the participants were told that we also gathered data on how long they spent on each game, how they scored in the different virtual environments, the time spent in the game, and the position and rotation of the headset.

6.3.3 Right to Withdraw

The participants were told they had the right to withdraw anytime during the recruitment phase or the tests.

6.4 VR Setup

The participants in the study experienced the virtual environment through the Meta Quest 2 headset, as mentioned in Section 3.3. The eye width of the participants was measured to configure the IPD setting of the Meta Quest 2 headset, ensuring an optimal visual experience. Additionally, two hand controllers were provided to the participants, enabling them to interact with the virtual environment, including selecting items from menus or performing actions. Both experimental groups utilized the same VR setup, with the only distinction being the mode of movement. One group walked on the Omnideck (3.2), while the other group remained stationary in the center of the Omnideck and controlled their movement using a joystick.

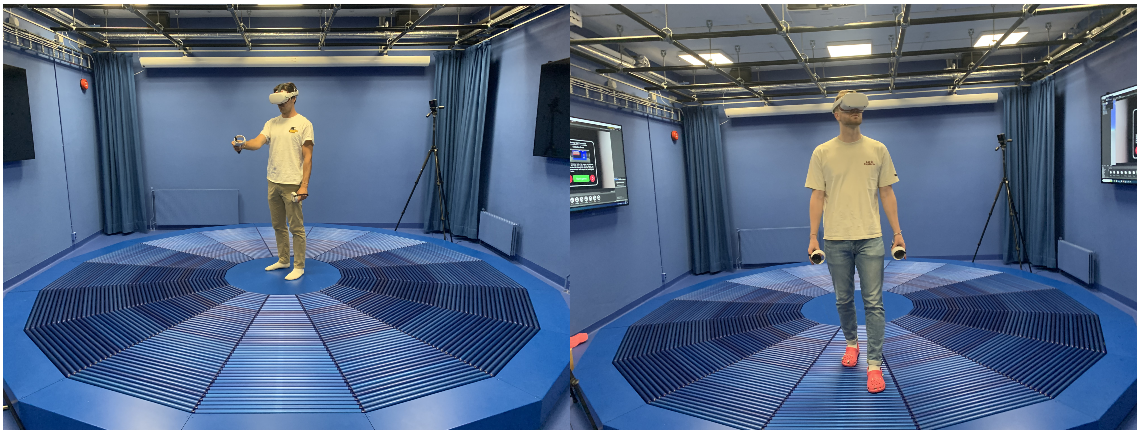

Figure 13: The VR setup. The left picture shows the joystick setup and the right picture shows the ODT setup.

The Virtual Desktop software was employed to connect the headset and the computer, as referenced in Section 3.4. This software allowed the virtual content to be streamed from the Meta Quest 2 headset wirelessly. Furthermore, a computer monitor was available to display the same content as seen by the participant in the virtual environment. This setup served multiple purposes, such as providing assistance to participants, answering their questions, and offering a shared viewing experience for the researchers involved in the study.

Figure 14: The screen, headset, and controllers used during the tests.

6.5 Candidate Number

Before the participant began the testing, they received a randomly generated candidate number. This candidate number was only revealed to the participants, and the participants were instructed to write it down for later use in the questionnaire. This was to ensure the anonymity of the participants and to link their survey data to their VR application data.

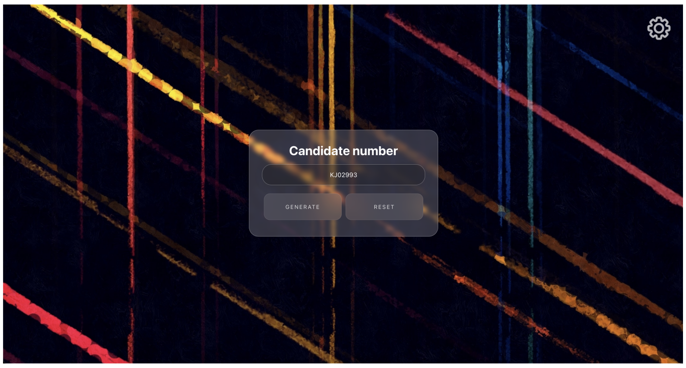

Figure 15: The website created to generate candidate numbers for the participants

6.6 The Tests

After the participants received their candidate numbers, they were instructed to fill out the participant input page in the game, previewed in Figure 16. This is a simple form with two inputs; a text field for the candidate number and a drop-down selector for the group. The participant can start the VR tests by pressing a button after they have entered a valid candidate number and selected their assigned group.

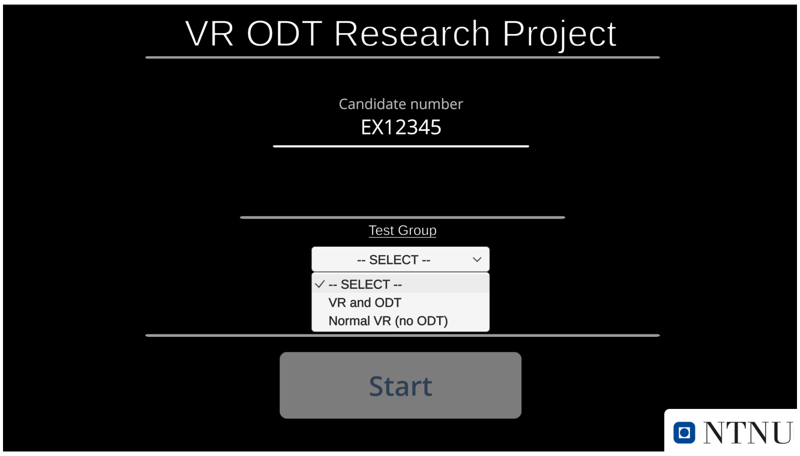

Figure 16: The participant input page before the VR tests start.

Once the start button has been pressed, the participant is sent to the preparation room (5.1). At the beginning of the preparation room, the participants are presented with text bubbles with information. Text bubbles were incorporated into all four virtual environments to give the participants the same information about the tests. This was done to ensure fairness and consistency among participants. The text bubbles were displayed at the beginning of the preparation room and before each test, ensuring that all participants received the necessary instructions and details. Additionally, participants were informed that they could ask questions at any time if they needed clarification about the tests.

Figure 17: A text bubble explaining how the evaluation room in Memory Hallway works.

The participants got three minutes to walk around and get familiar with the movement in the preparation room. When the time runs out, they are automatically sent to the demo scene for the first test, Memory Hallway (5.2). In this scene, the participant got a short introduction to how the actual test will be conducted, and they got to try out the user interface for selecting memorized items. Once the answers have been submitted, the participant is sent to the actual test. At this point, the game stops automatically sending the participant to the next scene, and the test supervisors gain control. This was done to ensure that participants were feeling well and that the equipment was still attached comfortably.

Once ready, the participant is sent to the second task, Memory Pattern (5.3). This test starts with a looping animated demo that the participant can watch until they understand the task. They can then press the start button to be teleported to the test. Once finished, the test supervisor can send the participant to the last test, Puzzle Walk (5.4). Once the participant is done with this test, their VR testing is over. While removing the VR equipment, the participant is instructed not to check the time on any time-keeping devices, and they are sent to complete a questionnaire on a nearby computer.

6.7 Data Collection

During the tests, we collected general data from the participants, including how long they spent inside the virtual environment, their position, and their head rotation. We also recorded their scores for each test. After completing the tests, participants were asked to fill out a questionnaire. The questionnaire consisted of four groups of questions.

- General information about the participant
- Immersion, enjoyment, and discomfort
- Questions about the VR environment design and games
- Memory, concentration, and distraction during the games

The questions in the questionnaire used a Likert scale. The Likert Scale (4.3.2) is shown in Figure 18 and was used to measure the opinions of participants on the questions.

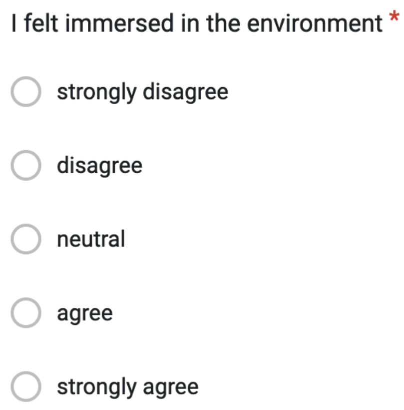

Figure 18: The Likert scale used for the questionnaire.

We employed a Likert scale to capture a range of responses and degrees of agreement. However, we recognized that participants might exhibit response biases such as agreeing or disagreeing with all claims due to factors like fatigue or social desirability. To address this, we created overlapping questions that assessed different aspects, such as enjoyment and discomfort, to cross-check responses and reduce the bias of the participants. We also considered the impact of social desirability bias, where participants may provide responses that they believe are socially desirable rather than their genuine thoughts or experiences. To counteract this bias, we ensured that the questionnaire was answered anonymously using only the generated candidate number of the participant. This anonymity aimed to encourage participants to respond sincerely and minimize the influence of social desirability bias [9].

6.8 Data Analysis

After collecting the data, various analyses were performed. These analyses were carried out in Python, and the code can be found in Appendix D. The data was divided into two groups: the ODT group and the joystick-based VR group. Diagrams were created to visualize the data, and statistical significance was assessed using Student's t-test (4.4.1) and the Mann-Whitney U test (4.4.2). These were used as two-tailed tests. Additionally, time and cybersickness analyses were conducted. The results of these analyses are presented in Section 7.

7 Results

In this section, we will present the results of our tests. We will delve into the analysis and interpretation of the data collected, providing insights into the key findings and addressing the research questions outlined in Section 1.2.

7.1 Sample Characteristics

The study included a total of 40 young adult participants, consisting of 14 females and 26 males. The participants were divided into different age groups, with 1 participant in the 18-20 age range, 36 participants in the 21-25 age range, and 3 participants in the 26-30 age range. The participants were randomly assigned to two equal-sized groups: one group using an ODT (the Omnideck 3.2) and the other group using joystick-based movement.

Among the participants, 12 had no previous experience with VR, 11 had used VR headsets less than 5 times, 5 had tried VR 5-10 times, and 12 had used VR more than 10 times before. During the testing phase, it should be noted that three female participants experienced significant feelings of nausea. One participant was part of the ODT group, and the other two were part of the joystick-based VR setup group. The intensity of their nausea was to such an extent that they requested a break, and ultimately, two out of the three participants opted not to complete the tests. Those two were in the joystick-based movement group. This occurred during the third test of the study for all three of the participants. Table 7.1 summarizes the sample characteristics in this thesis.

	Joystick users Total (n=20)	ODT Users Total (n=20)
Male	14	12
Female	6	8
Age group (years)	18-20 = 0	18-20 = 1
	21-25 = 18	21-25 = 18
	26-30 = 2	26-30 = 1
Previous VR experience	No = 4	No = 8
	1-4 times = 6	1-4 times = 5
	5-10 times = 3	5-10 times = 2
	>10 times = 7	>10 times = 5

Table 7.1: The sample characteristics of the participants in the study.

7.2 Immersion

One of our research questions was if physical movement on an ODT affects the immersiveness of users in VR. This section presents our findings on the subject. After the participants were done with the tests, they were presented with a questionnaire. One of the questions in the questionnaire asked if the participants felt immersed in the environment. Figure 19 illustrates the responses of the two groups.

In the group that used the joystick-based movement setup, 30% of the participants strongly agreed that they felt fully immersed, while 50% agreed with the statement. Additionally, 15% felt neutral about their level of immersion, and 5% disagreed. In comparison, in the ODT group, 50% strongly agreed, 40% agreed, 5% felt neutral, and 5% strongly disagreed with feeling immersed.

The data indicates that in the ODT group, 18 out of 20 participants either agreed or strongly agreed that they felt immersed. In the joystick-based group, 16 out of 20 participants agreed or strongly agreed. However, a statistical analysis using a two-tailed Mann-Whitney U test did not reveal a significant difference between the groups ($p = .20$).

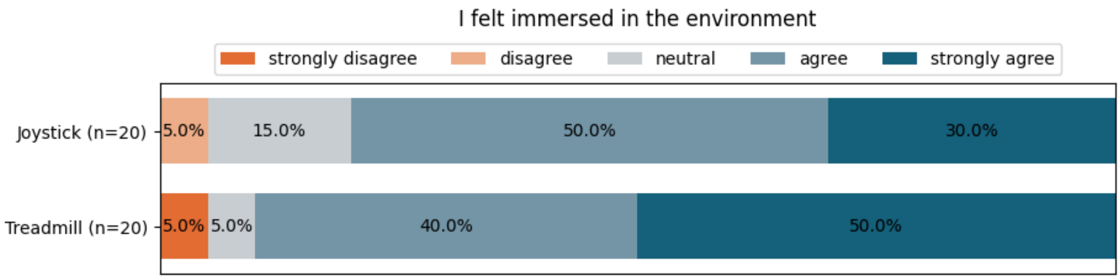

Figure 19: Questionnaire results: I felt immersed in the environment

Participants were also asked if they felt that the virtual environments helped eliminate the distractions of reality. Figure 20 presents the responses from the two groups. The majority of participants in both groups answered with either strongly agree or agree. In the joystick-based VR group, 30% strongly agreed, 65% agreed, and 5% disagreed. In comparison, the ODT group had 35% strongly agree, 55% agree, 5% disagree, and 5% strongly disagree.

The data distribution here is very similar between the groups. A statistical analysis using a two-tailed Mann-Whitney U test did not find a significant difference between the groups ($p = .96$).

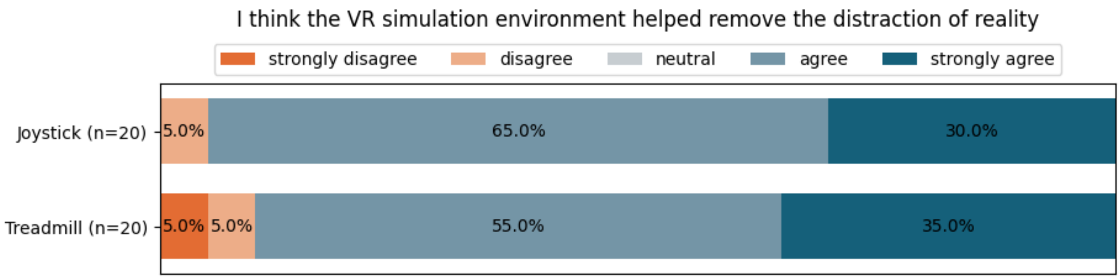

Figure 20: Questionnaire results: I think the VR simulation environment helped remove the distraction of reality

As part of the testing, participants were asked about concentration and distractions. Regarding their concentration, it was difficult to distinguish between the two groups as both reported high concentration levels. The joystick-based movement group reported that 45% strongly agreed to feeling highly concentrated, 45% agreed, 5% answered neutral, and 5% strongly disagreed. In comparison, in the ODT group, 65% answered that they strongly agreed, 25% agreed, and 10% answered neutral.

The data indicated that 18 of the 20 participants in the joystick-based movement and the ODT group felt highly concentrated on the task. The two-tailed Mann-Whitney U test does not show statistical significance between the groups ($p = .34$).

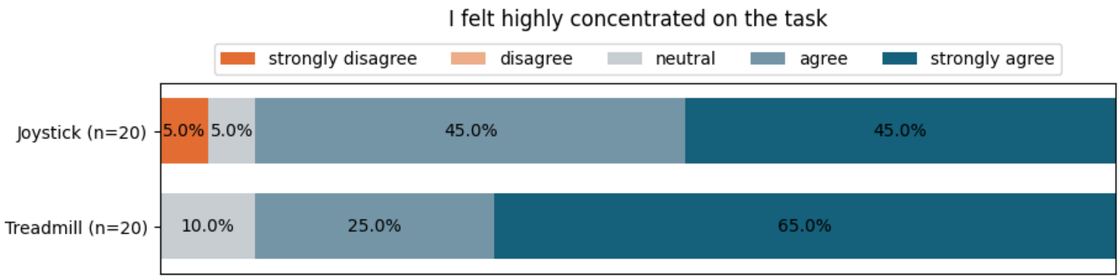

Figure 21: Questionnaire results: I felt highly concentrated on the task.

When the participants were asked if they felt distracted during the tasks, both groups responded quite similarly. In particular, 10% of participants in both groups agreed that they felt distracted. The joystick-based group had 15% of participants answer neutral. Moreover, 35% of the joystick-based group disagreed with feeling distracted, whereas the ODT group had 30%. Finally, 40% of participants in the joystick-based group strongly disagreed with feeling distracted, while the ODT group had a higher percentage of 60%.

The two-tailed Mann-Whitney U test does not show statistical significance between the groups for their perceived distractions ($p = .19$).

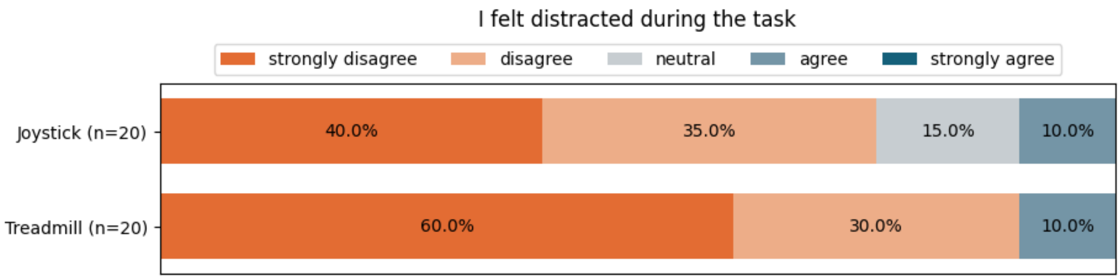

Figure 22: Questionnaire results: I felt distracted during the task.

7.2.1 Time Perception

In Figure 19, participants self-reported their level of immersion in the virtual environment. As referenced in Section 2.2, time perception can potentially be linked to the level of immersion. Therefore, we conducted an analysis to compare the time perception of the two groups.

The duration of each VR session was recorded when the participants completed their tests, and they were instructed not to consult any time-keeping devices before responding to the survey. One of the survey questions asked participants to estimate the duration of time they believed they had spent inside the virtual environment.

This analysis aimed to shed light on potential differences in time perception between the two groups, which could indicate their level of immersion. Figure 23 shows that the ODT group had a slightly larger average than the joystick-based group. The joystick-based VR group had an average time difference of 6.9 minutes (SD = 4.689), while the ODT group had an average time difference of 7.4 (SD = 4.523).

Both groups are normally distributed by the Shapiro Wilk test (p = .073 for the joystick group, p = .29 for the ODT group), and the variances are homogeneous by Levene's test (p = .80). In addition, the data is continuous. Assuming our population sampling method resulted in the independence of the data in each group and between them, all assumptions of Student's t-test are fulfilled. Using Student's t-test (4.4.1), the differences between the groups are nonsignificant (p = .73).

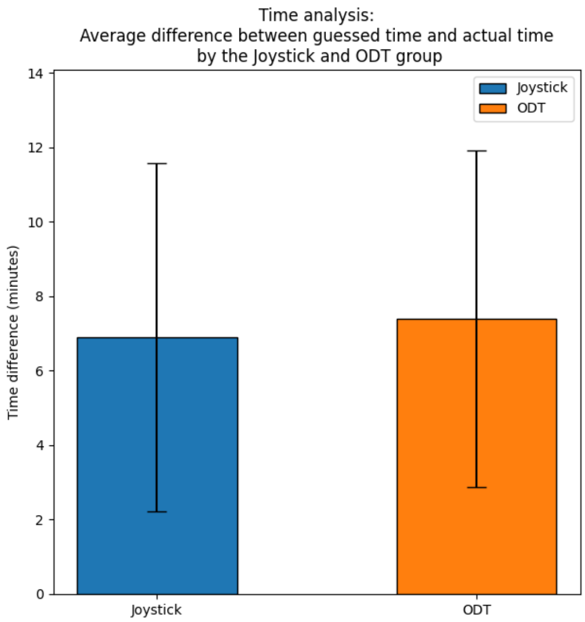

Figure 23: Time comparison between the ODT and joystick group.

Figure 24 illustrates the discrepancy between the estimated time and the actual time used by the joystick-based movement group and the ODT group. The data is segmented into four-minute intervals, commencing from negative 14 to negative 10 and concluding at positive 10 to positive 14. A negative time difference signifies that participants guessed a duration shorter than the actual time they spent. In contrast, a positive time difference indicates that their estimation exceeded the actual time used.

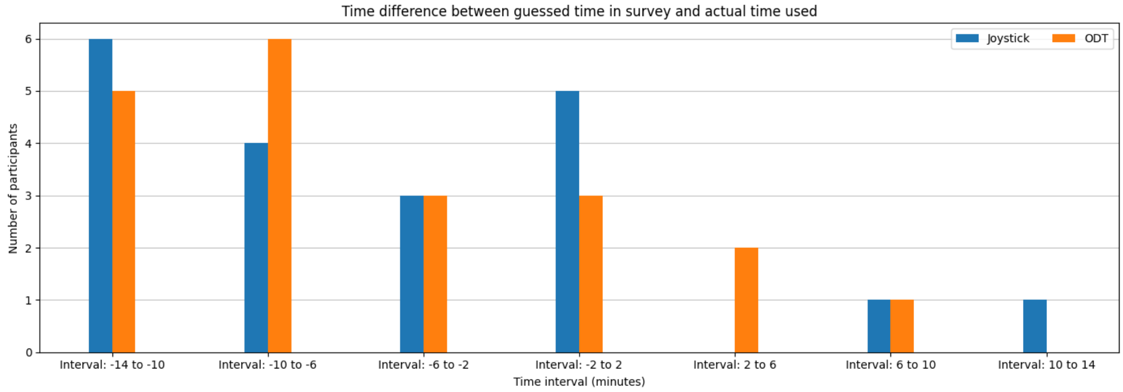

Figure 24: Time comparison between the ODT and joystick group in time intervals.

7.3 Visual Memory Retention

We also wanted to determine if the movement on an ODT affected the visual memory retention of the participants. Figure 25 shows the percentage of correctly guessed items of each group in the first memory test we conducted (5.2). The figure shows that the performance of each group is nearly identical, with the joystick group scoring an average of 88.846% (SD = 5.598) and the ODT group 88.205% (SD = 6.248).

Both groups are normally distributed by the Shapiro Wilk test (p = .29 for the joystick group, p = .088 for the ODT group), and the variances are homogeneous by Levene's test (p = .55). In addition, the data is continuous. Assuming our population sampling method resulted in the independence of the data in each group and between them, all assumptions of Student's t-test (4.4.1) are fulfilled. Using Student's t-test, the differences between the groups are nonsignificant (p = .73).

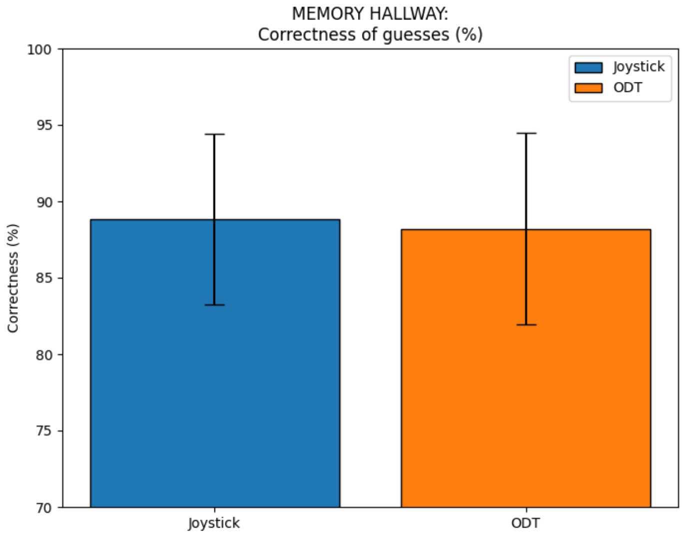

Figure 25: The average percentage of correctly remembered items with the standard deviation in each population.

Figure 26 shows the average number of attempts for the two groups at test number two, where the participants should remember a gradually increasingly more challenging path. The figure shows that, on average, the ODT group used more attempts on every level except level 3.

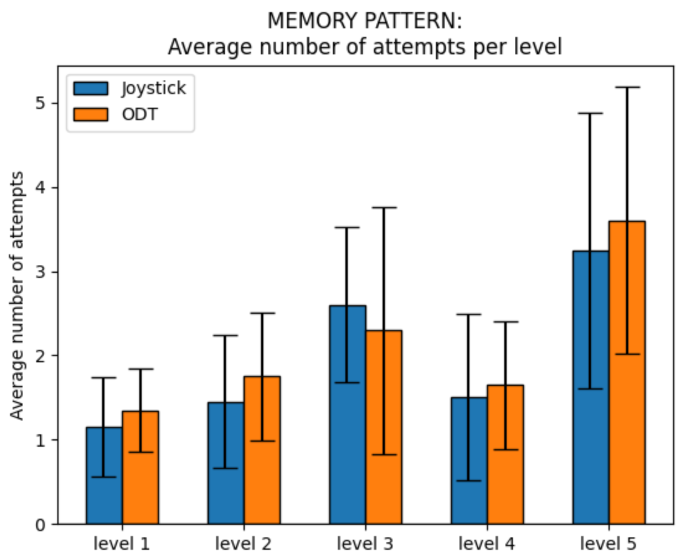

Figure 26: The average number of attempts per level with the standard deviation.

Figure 27 presents the total attempts for levels 2 through 5 in the Memory Pattern test. Level 1 was excluded from this analysis as it was an introductory level to check that the participants understood the mechanics.

The joystick group had a mean of 8.800 attempts for the four levels (SD = 3.122). The ODT group performed similarly with a mean of 9.300 attempts (SD = 2.849).

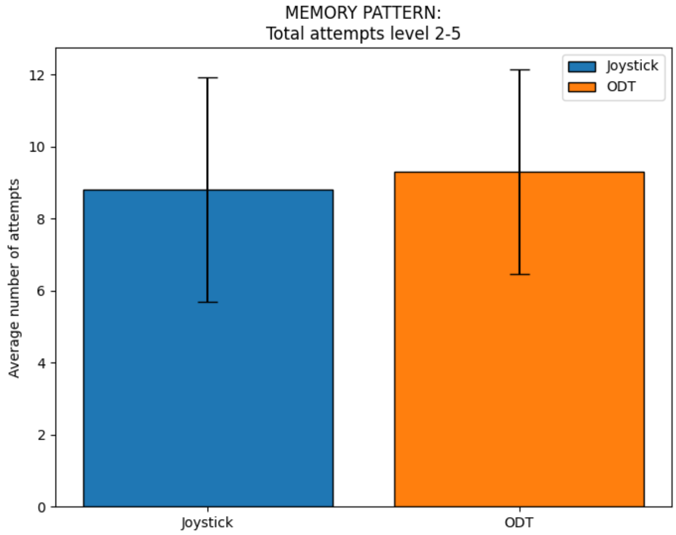

Figure 27: The total number of attempts in each group for Memory Pattern levels 2 to 5. Level 1 has been excluded as it was an introductory level.

Table 7.2 shows the mean attempts of each group on each individual level and levels 2 to 5 summed. Additionally, the Mann-Whitney U significance level has been calculated for each row, which does not find any significant differences.

	Joystick mean attempts	**ODT mean attempts**	**Mann-Whitney U *p***
Level 1	1.150	1.350	0.15
Level 2	1.450	1.750	0.16
Level 3	2.600	2.300	0.77
Level 4	1.500	1.650	0.65
Level 5	3.250	3.600	0.36
Level 2-5	8.800	9.300	0.48

Table 7.2: Mean attempts of each group on each level of the Memory Pattern test, and level 2-5 summed up. The last column shows the significance level of the differences according to the Mann-Whitney U test.

7.4 Cybersickness

Another aspect of our research focused on investigating the impact of ODTs on the cybersickness symptoms of the participants. In the survey, participants were asked about their experience of dizziness or disorientation and nausea symptoms while using the VR equipment, either during or immediately after the testing session. Figure 28 presents the responses from the two groups on dizziness/disorientation.

In the joystick-based group, the responses were diverse. 25% of the joystick participants strongly agreed, 30% agreed, 25% answered neutral, 10% disagreed and 10% strongly disagreed. On the other hand, the responses of the ODT group leaned more toward disagreement. 35% of the ODT participants strongly disagreed and 40% disagreed. Additionally, 5% answered neutral, 15% agreed, and 5% strongly agreed.

The data shows that out of the 20 participants in the joystick-based group, 11 agreed or strongly agreed that they experienced dizziness or disorientation during the testing session. In comparison, only 4 out of the 20 participants in the ODT group reported the same. A two-tailed Mann-Whitney U test reveals statistically significant results between the groups regarding the reported level of dizziness or disorientation after the test ($p = .003$).

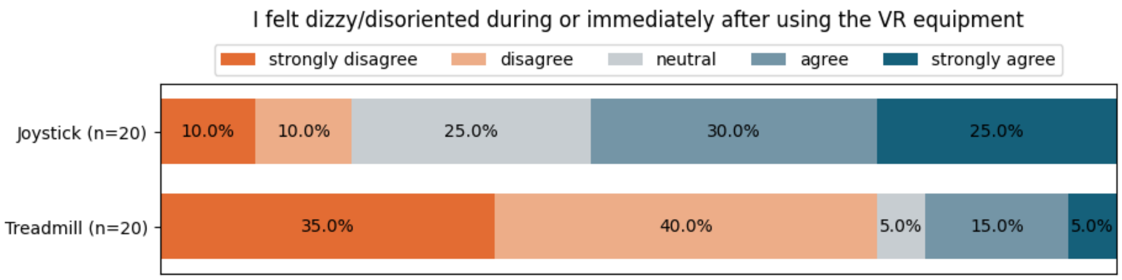

Figure 28: Questionnaire results: I felt dizzy/disoriented during or immediately after using the VR equipment

The results in Figure 29 showed how the participants answered when asked if they felt nauseous after the tests. A higher percentage of participants in the joystick-based group agreed or strongly agreed to experience nausea, with 25% strongly agreeing and 30% agreeing. In comparison, only 5% of the ODT group strongly agreed, and 5% agreed. The majority of participants in the ODT group fell under the disagree or strongly disagree category, with 40% disagreeing and 50% strongly disagreeing with feeling nauseous. Whereas 5% of the joystick-based movement group answered neutral, 25% answered that they disagree, and 15% answered that they strongly disagree with feeling nauseous.

This data reveals that 11 out of the 20 participants in the joystick-based group reported feeling nauseous to some extent, compared to only 2 in the ODT group. The two-tailed Mann-Whitney U test shows a statistically significant difference between the groups regarding the reported level of nausea after the test ($p = .002$).

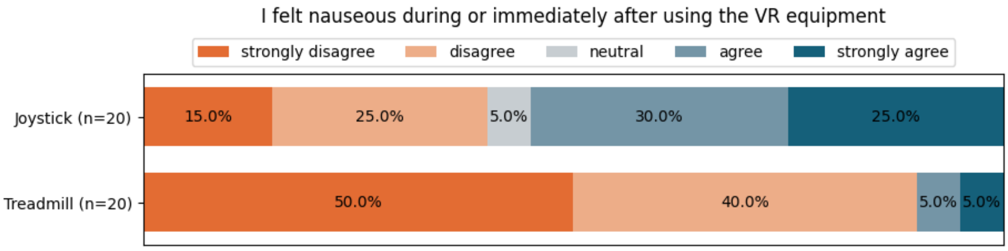

Figure 29: Questionnaire results: I felt nauseous

In our research, we also examined the perception of the naturalness of movement in virtual environments and its potential impact on cybersickness symptoms. Figure 30 presents the responses from the two groups. Among both groups, 35% of the participants disagreed that the movement felt natural. In the joystick-based group, 35% agreed that the movement was natural, while in the ODT group, 40% agreed. Both groups had 5% strongly agree and 5% strongly disagree responses. However, there was a difference in neutral responses, with 15% of the joystick-based group and 20% of the ODT group responding neutral.

Although the average movement speed of the joystick group was 25.602% faster than the ODT group, both groups reported similar values of how natural the movement felt. The two-tailed Mann-Whitney U test indicates that the difference in how natural the participants felt the movement was is not statistically significant between the two groups ($p = .89$).

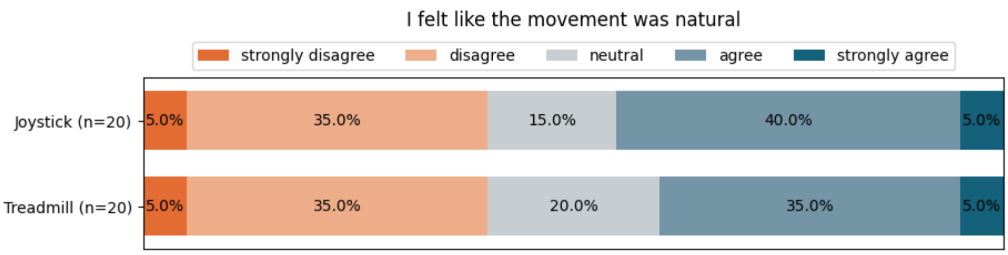

Figure 30: Questionnaire results: I felt like the movement was natural.

7.4.1 A Comparison Between Males and Females

Due to several participants experiencing cybersickness, we also wanted to investigate whether there was a difference in cybersickness between genders. Figure 31 shows that 42% of female participants either agreed or strongly agreed that they felt dizzy or disoriented during or shortly after using the VR equipment, compared to 35% of male participants.

The data shows that 6 out of 14 females felt dizzy or disoriented to some extent, while 9 out of 26 males did. The two-tailed Mann-Whitney U test shows no statistically significant difference between males and females in how dizzy/disoriented they reported to be after the test ($p = .42$).

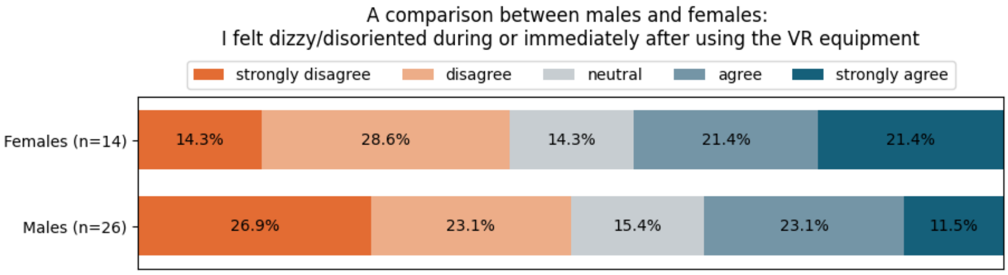

Figure 31: A comparison between males and females: I felt dizzy or disoriented during or immediately after using the VR equipment.

When participants were asked if they felt nauseous, a higher percentage of females reported feeling nauseous compared to males. Figure 32 shows 42% of females either agreed or strongly agreed that they felt nauseous, while only 27% of males did.

The data shows that 6 out of 14 females felt nauseous, compared to 7 out of 26 males. The two-tailed Mann-Whitney U test shows no statistically significant difference between males and females in how nauseous they reported being after the test ($p = .25$).

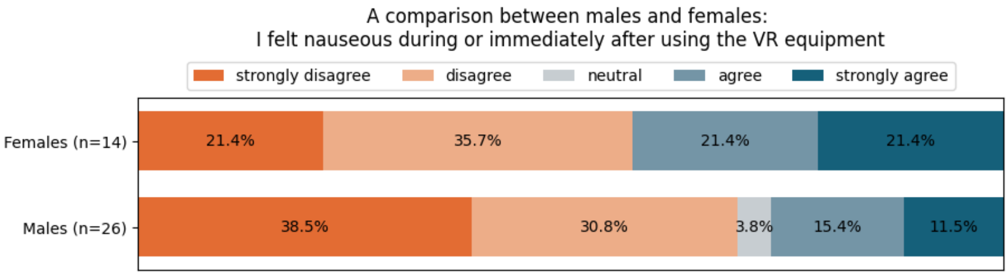

Figure 32: A comparison between males and females: I felt nauseous during or immediately after using the VR equipment.

7.4.2 Female Cybersickness

Further division of the data was conducted by separating the data based on gender and group. In Figure 33, it can be observed that 67% of female participants using the joystick reported feeling dizzy or disoriented, either agreeing or strongly agreeing. Additionally, 33% of female joystick users answered neutral. For female participants using the ODT, 25% agreed or strongly agreed to feel dizzy or disoriented, while 50% disagreed and 25% strongly disagreed.

Based on this data, it can be inferred that out of the 6 females using the joystick, 4 experienced dizziness or disorientation, whereas 2 out of the 8 females using the ODT reported the same symptoms. The two-tailed Mann-Whitney U test found a significant difference between the Joystick and ODT group ($p = .041$).

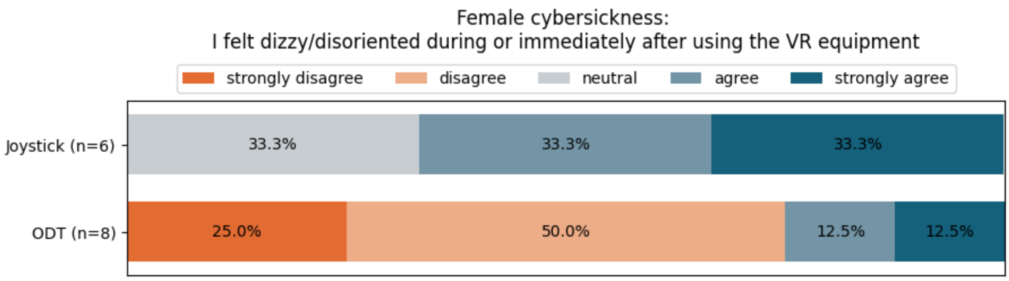

Figure 33: Female cybersickness:: I felt dizzy or disorientation.

A similar trend can be observed in Figure 34, where nausea symptoms among female joystick users show that 67% agreed or strongly agreed to feel nauseous, while the remaining 33% answered that they disagree. Among female ODT users, roughly 25% agreed or strongly agreed to feel nauseous, while 75% disagreed or strongly disagreed.

From this data, it can be deduced that out of the 6 females using the joystick, 4 experienced nausea, while only 2 out of the 8 females using the ODT reported feeling nauseous. The two-tailed Mann-Whitney U test did not find a significant difference between the Joystick and ODT group ($p = .094$).

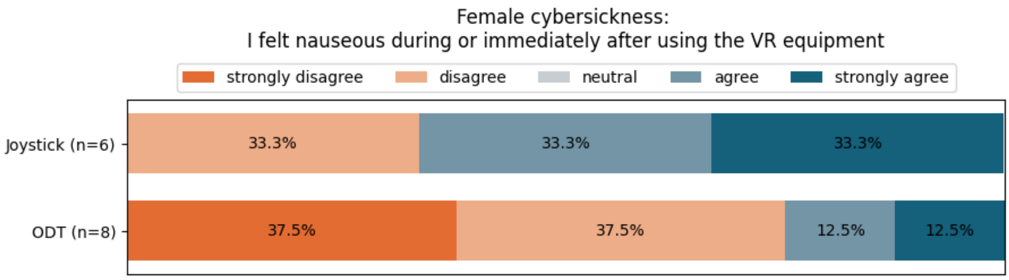

Figure 34: Female cybersickness: I felt nauseous.

7.4.3 Male Cybersickness

Moving on to male participants, Figure 35 reveals that 50% of male joystick users agreed or strongly agreed to feel dizzy or disoriented. Approximately 30% disagreed or strongly disagreed, and around 21% answered neutral. Among male ODT users, roughly 17% agreed to feel dizzy or disoriented, while approximately 75% disagreed or strongly disagreed. Additionally, approximately 8% answered neutral.

According to this data, out of the 14 males using the joystick, 7 experienced dizziness or disorientation, whereas only 2 out of the 12 males using the ODT reported the same symptoms. The two-tailed Mann-Whitney U test found a significant difference between the Joystick and ODT group (p = .023).

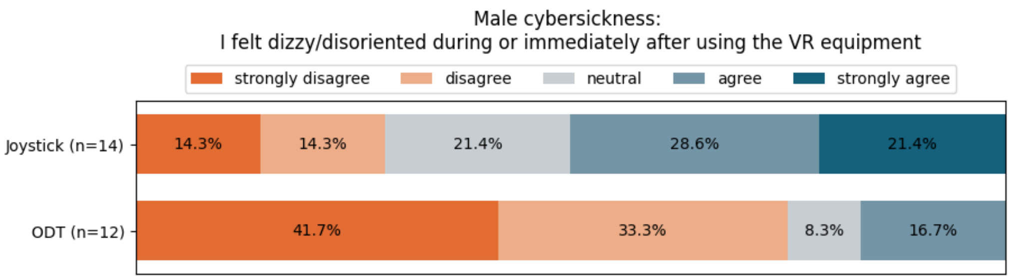

Figure 35: Male cybersickness: I felt dizzy or disorientation.

In Figure 36, it can be observed that 50% of male joystick users agreed or strongly agreed to feel nauseous. Roughly 43% disagreed or strongly disagreed, and approximately 7% answered neutral. Among male ODT users, all participants disagreed or strongly disagreed with feeling nauseous.

Based on this data, it can be inferred that out of the 14 males using the joystick, 7 experienced nausea, while none of the 12 males using the ODT reported feeling nauseous. The two-tailed Mann-Whitney U test found a significant difference between the Joystick and ODT group (p = .006).

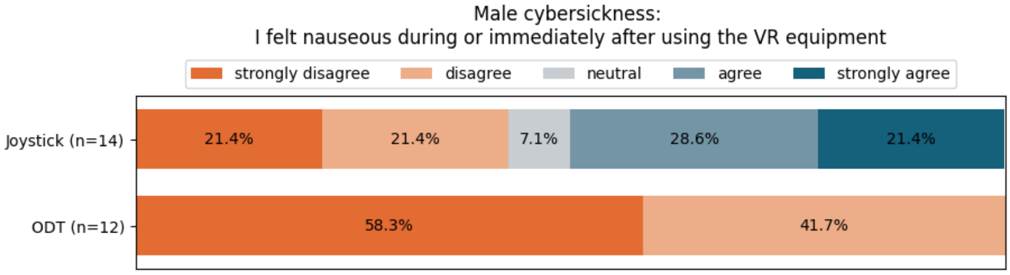

Figure 36: Male cybersickness: I felt nauseous.

7.5 Correlation Analysis

To investigate potential dependencies or relationships between survey answers and VR movement, several correlation matrices were calculated using Spearman's rank-order correlation coefficient (4.4.3). They all include the same survey question answers and VR test data. Likert scale (4.3.2) data has been converted to a scale from 0-4, where 0 is "Strongly disagree" and 4 is "Strongly agree". The first matrix (Figure 37) shows a heatmap of the correlation calculated from both groups. In contrast, the second matrix (Figure 38) shows the corresponding p values calculated using permutation tests, as recommended by the Scipy documentation for sample sizes $n < 500$ [53].

In figure 37, the bar on the right shows the scale of correlation values in the figure. Stronger red cells indicate a higher positive correlation between the variables named on the left and the bottom of the figure, and blue cells indicate a negative correlation between those variables. Whiter cells have close to no correlation in our sample.

In Figure 38, the green cells are statistically significant correlation values ($p < .05$). Orange cells are not significant but have a less than 20% chance of being uncorrelated ($.05 \leq p < .20$). Finally, gray cells are quite far from showing significant correlations ($p \geq .20$).

Key takeaways from this correlation matrix that will be discussed later:

- Nausea and dizziness show a strong significant positive correlation ($r = .750$, $p < .001$).
- Immersion shows a weak significant positive correlation with having fun ($r = .344$, $p = .036$).
- Both dizziness and nausea show a weak positive correlation ($r \geq .246$) with the average movement speed of the participant, though only nausea is significant ($p = .020$) while dizziness is not ($p = .13$). On the other hand, dizziness,

nausea, and discomfort show weak to moderate significant negative correlation with average head rotation speed ($r \leq -.329$, $p \leq .039$). In addition, dizziness and nausea correlate significantly and negatively with total rotation ($r \leq -.336$, $p \leq .038$).

- Total time shows a significant negative weak to moderate correlation with guessed time error ($r = -.391$, $p = .012$), meaning the participants who spent longer in VR tended to underestimate the time. Total time also weakly and negatively correlates with guessed time error percentage, though nonsignificant ($r = -.243$, $p = .13$). In contrast, increased average movement speed shows a weak positive but nonsignificant correlation with overestimating time spent in VR ($r = .268$, $p = .098$).

- Movement speed and total time in VR show negligible correlation with discomfort ($|r| \leq .008$).

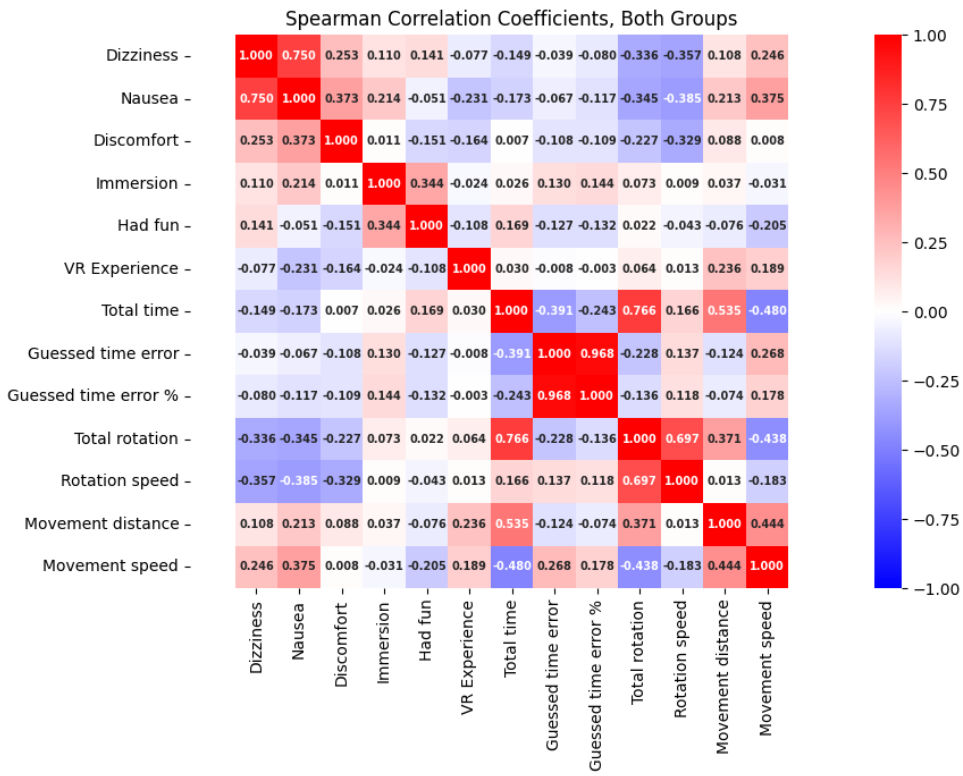

Figure 37: Spearman correlation matrix, all participants (ODT and joystick combined) of some survey questions and game data.

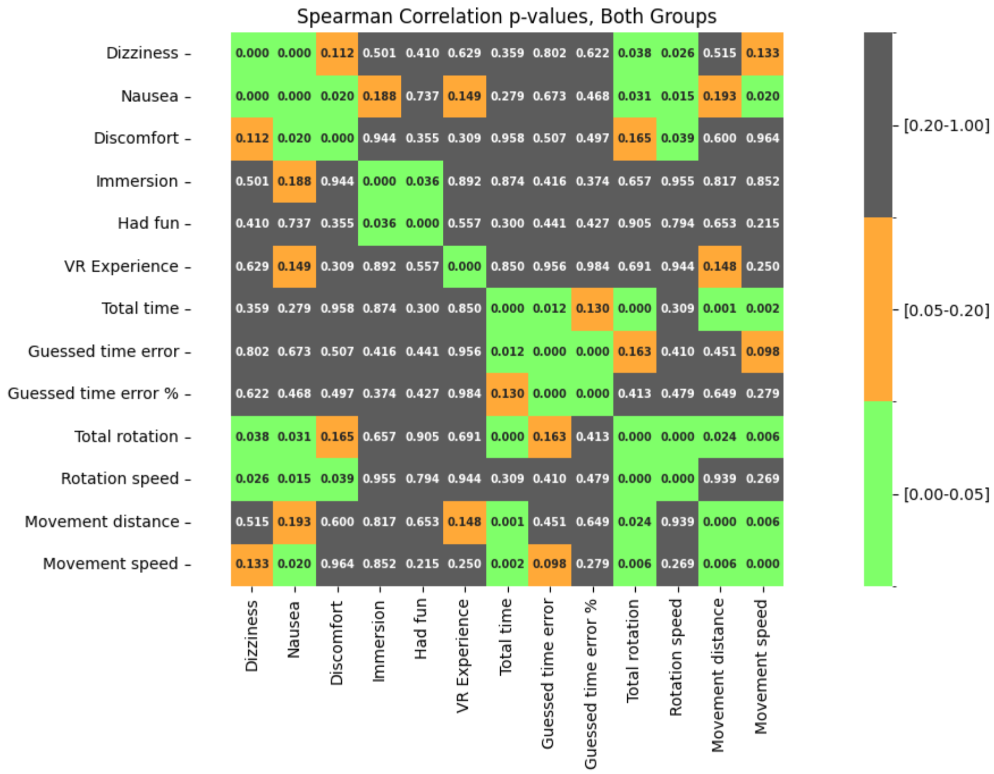

Figure 38: The p values of the Spearman correlation matrix, all participants (ODT and joystick combined).

Figures 39 and 40 show the correlation matrix and the corresponding p value matrix, respectively, with exclusively the joystick movement group. The halved sample size of 20 makes the correlation values more uncertain, meaning more extreme results are required to find significant p values.

While several trends are shared with the correlation matrix in Figure 37 of both groups combined, here are some key takeaways for further discussion from these two matrices:

- Nausea and dizziness show a near-perfect to strong significant positive correlation ($r = .916$, $p < .001$).
- Rotation speed shows a moderate significant negative correlation with discomfort ($r = .494$, $p = .030$).
- Immersion shows a moderate to weak positive correlation with dizziness and nausea, although both are nonsignificant by a small margin ($r \geq .418$, $p \leq .068$).
- Movement speed shows negligible correlation with nausea ($r = .002$).

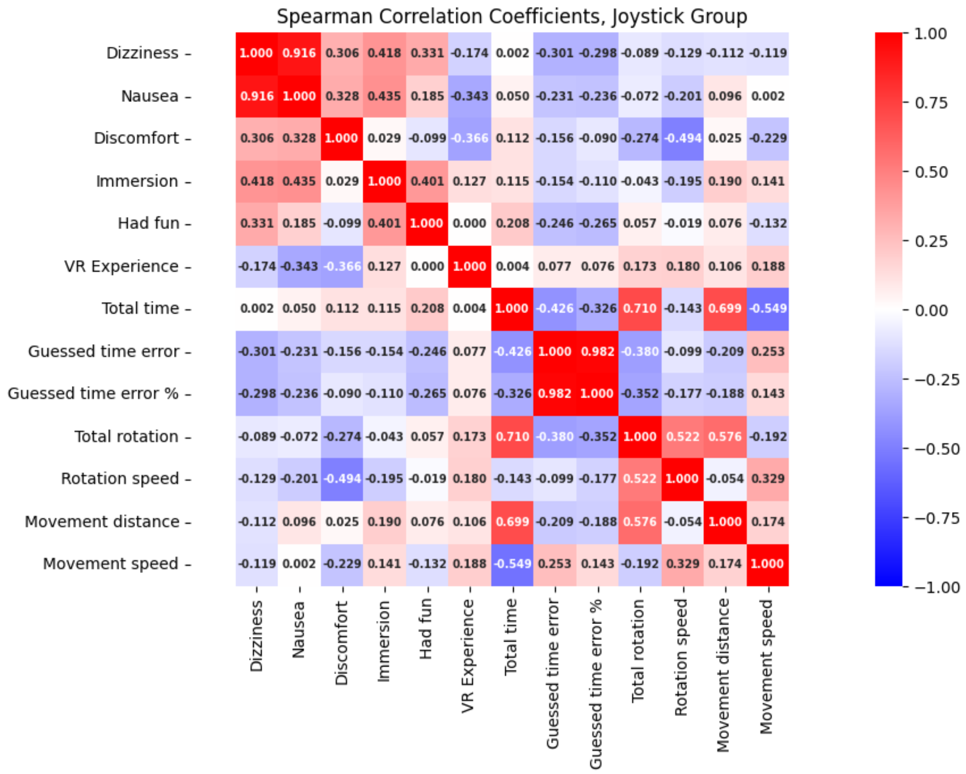

Figure 39: Spearman correlation matrix of the joystick group, including some survey questions and game data.

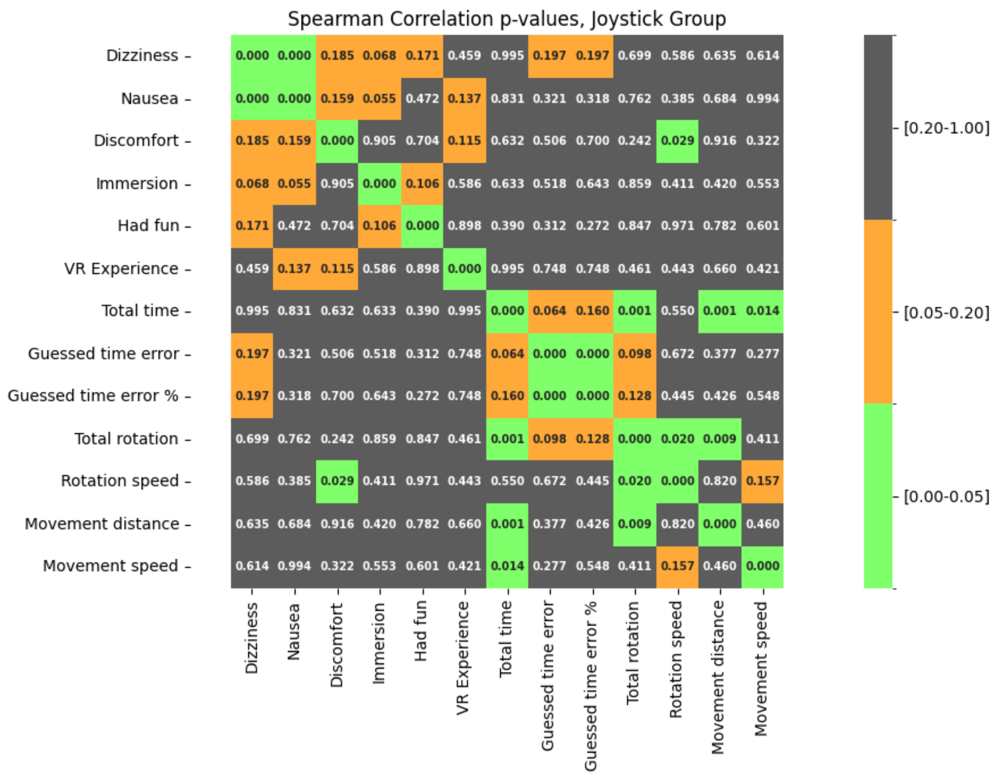

Figure 40: The p values of the Spearman correlation matrix of the joystick group.

Figure 41 and 42 show the correlation matrix and the corresponding p value matrix, respectively, with exclusively the ODT group.

These matrices also share trends with the previous two (Figure 37 and 41). Key takeaways from these matrices for further discussion:

- Nausea and dizziness show a moderate significant positive correlation ($r = .467$, $p = .040$).
- Movement speed shows a moderate positive significant correlation with immersion ($r = .509$, $p = .027$).
- Although nonsignificant, movement speed shows a weak to moderate negative correlation with dizziness ($r = -.388$, $p = .099$) and a negligible correlation with nausea ($r = .034$).
- Guessed time error and guessed time error percentage show a moderate positive but nonsignificantly correlation with both movement speed ($r \geq .375$, $p \leq .12$) and immersion ($r \geq .401$, $p \leq .81$).

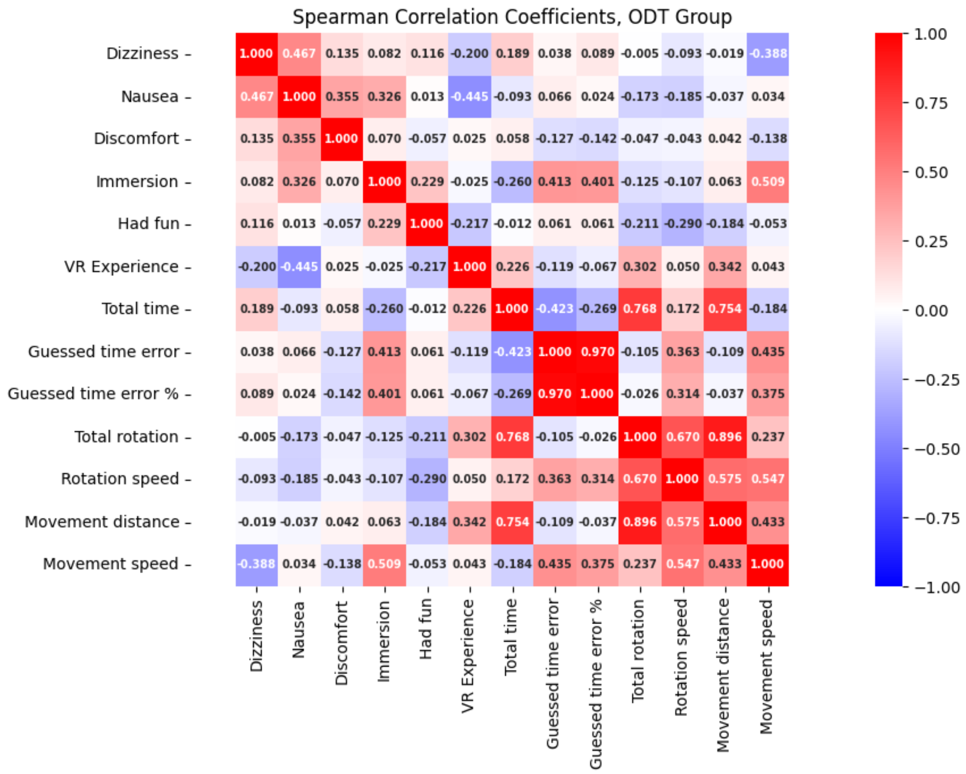

Figure 41: Spearman correlation matrix of the ODT group, including some survey questions and game data.

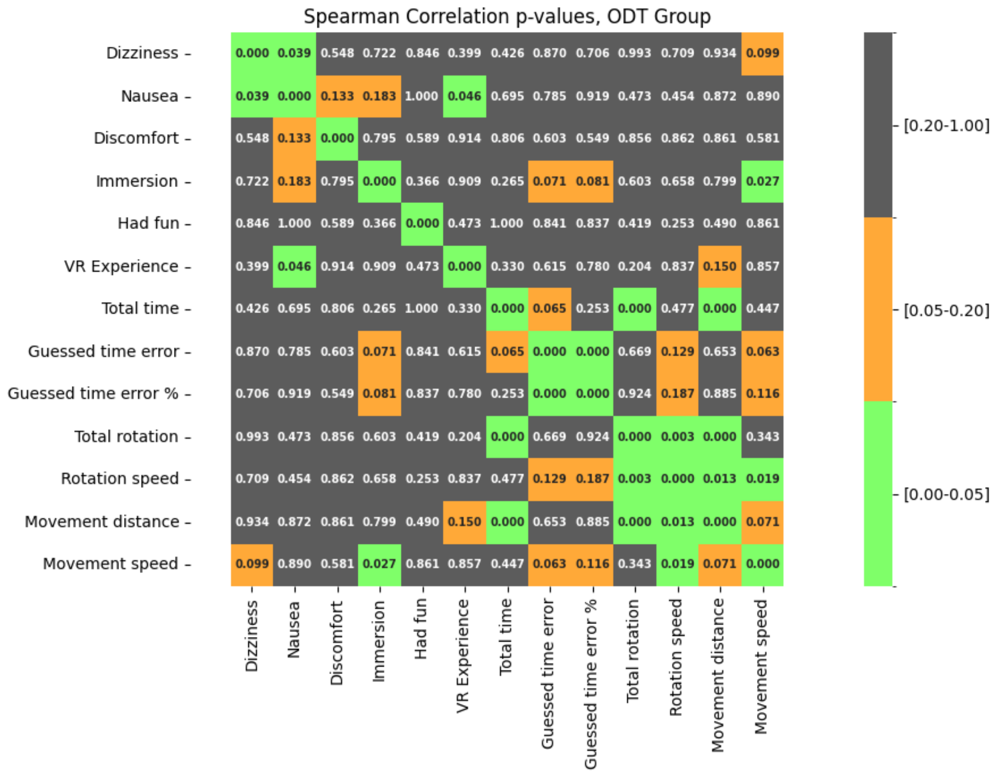

Figure 42: The p values of the Spearman correlation matrix of the ODT group.

8 Discussion

This section presents a discussion of the findings obtained from Section 7. The purpose of this section is to analyze and interpret the results in the context of the research questions outlined in Section 1.2 and evaluate their significance.

8.1 Immersion

The outcomes of our study revealed insights regarding the comparison between the two groups in terms of self-reported immersion. The ODT group did not demonstrate any statistically significant difference compared to the group utilizing joystick-based movement. However, the two-tailed Mann-Whitney U test revealed a relatively low p value ($p = .20$). This suggests that even though it did not prove to be statistically significant in our study, it could be worth researching further.

It is worth considering that immersion, as subjectively reported by participants, may be influenced by various factors beyond the inclusion of an ODT. Factors such as content quality, user interaction, and personal preferences might influence the perceived level of immersion more than the presence of an ODT alone. Additionally, both groups reported very high levels of immersion. Therefore, it is important to acknowledge that the use of a quantitative research method with a questionnaire may not have been sufficiently sensitive to capture nuanced differences in self-reported immersion between the two groups. In future research on immersion differences between ODT and VR and joystick-based VR, the researchers could employ qualitative approaches to understand the immersion experiences of the participants comprehensively. Future research could let the participants try and compare both variations and answer which variation they felt was more immersive.

8.1.1 Time Perception

We also found no evidence of a difference in time perception between the ODT group and the joystick-based movement group. Student's t-test showed that the difference between the groups was nonsignificant ($p = .73$), when comparing the difference in time guessed versus actual time used in the virtual environment. This aligns with the research on time perception described in Section 2.2. The research states that they could not find any link between time perception and immersion [43]. In our case, it is hard to draw a conclusion from the results since the time perception and the immersion levels of the two groups are quite similar. However, it is important to note that according to our correlation matrices, participants using an ODT who experienced higher levels of immersion tended to overestimate their time spent in the VR environment. This overestimation occurred not only in their perceived duration of VR use but also in terms of the percentage relative to the total time spent in VR. These correlation values were moderate in strength, but although close, they were not significant ($p \leq .081$). It is also worth noting that the joystick-based movement group did not show a similar correlation between these variables.

8.1.2 Concentration and Distractions

We noticed that the Omnideck (3.2) made a lot of noise when the motorized conveyor belt sections ran and wondered if the noise made would affect the immersion of the users. Therefore, we included questions about the participant's concentration and whether or not they felt distracted during the testing. Contrary to our expectations, the participants in the ODT group reported higher levels of concentration and felt less distracted compared to the joystick-based movement group. However, the statistical analysis of concentration ($p = .34$) and distractions ($p = .19$), did not indicate a statistically significant difference.

8.1.3 Correlation

All three correlation matrices in Section 7.5 show a weak correlation between immersion and fun, though the value is only significant in the correlation matrix combining all participants (37). This indicates that there might be a link between the extent to which one feels immersed in a VR experience and the amount of fun one has. However, whether or not this is a causal relationship remains to be discovered. There are several potential scenarios here, but this correlational analysis does not have the means to decide on any of them. Increased immersion might result in users having more fun, or perhaps users having fun results in them reporting higher immersion levels. Both these scenarios could be part of the truth, or perhaps the variables are independent of each other. A future study could look into this, which can be especially relevant in VR, where immersion is a significant factor contributing to the user experience.

8.2 Cybersickness

The results of the study comparing the ODT and the joystick group revealed a statistically significant difference between the two groups in terms of cybersickness symptoms. Our study found that the joystick-based VR group experienced higher levels of cybersickness compared to the ODT group. This difference was observed for participants who reported feeling dizzy or disoriented and those who reported feeling nauseous. These findings contradict a previous conclusion from a study regarding the impact of ODTs on cybersickness. The previous study, referenced in Section 2.6, did not find any significant difference in cybersickness by using an ODT paired with VR [71]. Instead, our results align with the sensory conflict theory and Gong's propositions, as outlined in 2.3 [22]. The sensory conflict theory emphasizes the mismatch between visual perception and physical sensation. Gong suggests that an ODT could potentially resolve this sensory mismatch, a theory that our study further corroborates.

8.2.1 Correlation

In the correlation calculations (7.5), nausea and dizziness correlate positively and significantly for the three groups we calculated correlation matrices for. This suggests that the presence of one of these symptoms could be associated with the others. These values come from the survey answers, and the correlation could stem from confusion about the meaning of these words, as both convey uncomfortable feelings about the experience. However, the correlation value was near perfect in the joystick group ($r = .916$), compared to moderate in the ODT group ($r = .467$). This could be because the ODT group experienced less severe cybersickness symptoms overall, since correlation of Likert scale variables can hardly be discovered when most answers lie within the same category. Meanwhile, the joystick group had a more uniform distribution of cybersickness severity.

Another interesting point is the weak positive correlation between average movement speed and both dizziness and nausea in the correlation analysis of both groups combined. If this is a causal relationship, faster movements might slightly increase the chance of experiencing these symptoms. An opposing possibility is that the participants who are feeling unwell have a stronger desire to finish the VR testing quickly, rushing through tasks instead. Looking at the individual joystick and ODT correlation matrices, they both show negligible or negative correlations between these variables. This suggests that the correlation values discovered in both groups combined are likely due to Simpson's Paradox (4.4.3).

By analyzing the recorded participant data, we found that participants in the joystick group moved about 25% faster than the ODT group on average. This means that joystick users would be responsible for most of the fast average speeds used in the correlation analysis, while they were also the group with significantly more cybersickness. Conversely, the ODT group was responsible for the lower average speeds in the correlation analysis, while the group also experienced less cybersickness. This might show that higher movement speed correlates with more severe cybersickness symptoms. However, we now know that this was likely a case of Simpson's Paradox. This correlation result is likely due to the calculations involving both the joystick and ODT groups together.

On the other hand, the weak or negligible negative correlation found in all three correlation matrices between average head rotation speed and both dizziness and nausea might suggest that head rotation does not affect these feelings of cybersickness, or could even reduce them. Rotation speed shows a weak negative correlation with movement speed. This indicates that the participants who moved slower were more actively looking around. As the movement of the VR simulation moves with high precision and low latency to match the physical state of the user, there is a little mismatch between the physical rotational movement of the head of the participant compared to the perceived movement.

8.2.2 Comparison Between Males and Females

Our study revealed that a higher percentage of females experienced more severe cybersickness symptoms than males. However, the difference was not statistically significant, and it is important to note that there were more male participants than female participants (26 males to 14 females). These findings are also consistent with previous research in Chapter 2.3, which indicated that females generally exhibit higher levels of cybersickness [59]. The previous study identified oculomotor and disorientation symptoms as most prominent in females, with females reporting lesser instances of nausea compared to males. In contrast, our study indicated that a higher percentage of females reported more disorientation, dizziness, and nausea symptoms than males.

We also split the data about cybersickness into different groups based on the gender of the participant. When evaluating the reports of dizziness or disorientation in females who used an ODT compared to those who used a joystick-based movement setup, a notable difference was observed. The two-tailed Mann-Whitney U test showed a significant discrepancy between the two groups (p = .041). Conversely, when analyzing the self-reported instances of nausea from the same groups, the two-tailed Mann-Whitney U test did not establish a statistically significant difference (p= .094). However, this value still suggests a trend worth considering for future studies.

We also found a statistical significance between the males that used an ODT and the males that used a joystick-based movement setup on how they reported nausea symptoms. As depicted in Figure 36, it was observed that half of the males who utilized the joystick-based movement setup experienced some degree of nausea. At the same time, none of the males who used the ODT reported such symptoms. A two-tailed Mann-Whitney U test found a significant difference between the two groups (p= .006). This finding reinforces the earlier assertion that the use of ODTs can potentially reduce the occurrence of cybersickness symptoms in VR.

This difference between the two male groups is further illustrated by comparing the symptoms of dizziness or disorientation between the two groups, as depicted in Figure 35. Half of the males who used the joystick-based movement setup reported experiencing dizziness or disorientation. Conversely, only approximately 17% of the males who used the ODT reported similar symptoms. This indicates a notable difference in the user experience between the joystick-based movement setup and the ODT setup for the males. The statistical analysis using a two-tailed Mann-Whitney U test further validates this difference (p= .023). Therefore, these findings substantiate the potential advantage of ODTs in reducing cybersickness symptoms.

As mentioned in Section 2.3, several factors have been identified as contributing to cybersickness, one of which is the IPD of the user. One of the studies mentioned in Section 2.3 advocates for the redesign of VR headsets to include a broader range of IPD adjustments and states that such a design modification could potentially mitigate the occurrence of cybersickness, especially among female users [58]. The VR headset employed in our research was the Meta Quest 2 (3.3). This device offers only three distinct settings for IPD adjustment. Before the experimentation phase, the IPD of each participant was measured, and the headset was accordingly tuned. Regrettably, the individual IPD data were not retained, thus precluding our ability to examine potential correlations between the reported cybersickness among participants and their respective IPD measurements. Consequently, we are unable to confirm or refute the postulated link between cybersickness and the IPD values of participants.

8.3 Memory Retention

Our results showed little to no difference between the ODT and joystick groups regarding the difference in memory retention. In the memory hallway test (5.3), both groups scored upwards of 90% correct with a similar low variance within the groups. This could indicate that the test should have been more challenging. Perhaps there needed to be more items, the participants had too much time, the items were too recognizable, or the fake items stood out too much in the evaluation. Although a more advanced test environment could potentially find differences, the scores in the two groups were highly similar.

In the memory pattern test (5.2), the joystick group performed slightly better than the ODT group on average in all levels except level 3. However, the differences in each of the five levels are still nonsignificant. The difference in total attempts for levels 2 to 5 is also nonsignificant.

The ODT seems to have no significant effect on the measured memory retention of the participants. This does not necessarily mean physical movement does not affect memory retention in VR environments. Another explanation could be that the potential benefits of physical movement are neutralized by distractions of using new equipment like an ODT. The participants of this study also knew that their memory was being tested, so they actively tried to remember items. Another interesting aspect could be testing passive memory retention, where the participants focus on some other task without knowing they will be evaluated on what they saw during the task. Whether this would result in greater differences between the groups remains to be seen. All in all, there seems to be little to no benefit in the use of ODTs for memory retention when the users know that is what they are being tested for.

8.4 Statistical Discussion

The present study aimed to investigate the potential differences between individuals utilizing an ODT in combination with VR technology and those exclusively engaging in joystick-based VR experiences. While several statistical analyses did not yield statistically significant results, a substantial proportion of the obtained statistics exhibited trends suggesting dissimilarities between the two groups.

The lack of statistical significance in specific analyses may be attributed to several factors. Firstly, the sample size utilized in this thesis might have influenced the statistical power, reducing the ability to detect significant effects. With a larger sample size, some observed trends might have reached statistical significance. Secondly, complete independence between participants from the same demographic can be hard to guarantee or analyze. This could affect our statistical results where independence is an assumption, such as in Student's t-test (4.4.1). Therefore, future investigations employing larger and more diverse cohorts may provide additional insights into the potential differences between these experimental conditions.

The lack of statistical significance should be interpreted cautiously, as it does not necessarily indicate the absence of meaningful differences between the groups. It is possible that the sample size or other study limitations restricted the ability to detect significant effects. Future investigations with improved methodologies and larger participant pools could clarify the potential benefits of combining VR with ODTs.

When it comes to correlation, the data shows intriguing relationships between several variables, such as nausea, discomfort, dizziness, immersion, fun, average movement speed, and average head rotation speed. The moderate and weak correlations, though not strong, suggest that there may be meaningful interactions among these variables.

However, when working with correlation on a sample size of 40 or less, certain challenges can arise. Firstly, a smaller sample size may inflate or deflate the correlation coefficient, leading to either overestimating or underestimating the strength of the association. Secondly, with smaller samples, it is more difficult to detect smaller but potentially meaningful correlations. In other words, the statistical power to identify significant associations is reduced.

The results divide the correlation analysis into three groups; all participants, the joystick group, and the ODT group. The latter two groups have sample sizes of 20 participants each. Therefore, while these samples might provide some insights, caution should be exercised when interpreting the Spearman correlation derived from it, and findings should ideally be confirmed with larger sample sizes. While the respective p values have been calculated, these only indicate the likelihood of observing a correlation of that magnitude if the variables are truly uncorrelated (with the given sample size). Therefore, as mentioned in Section 4.4.3, a significant correlation value does not necessarily mean a strong correlation, but the variables are unlikely to be uncorrelated.

8.5 Developing for VR with ODTs

Setting up a VR experience with the ODT we used initially proved itself a simple task. The ODT used in this thesis was the Omnideck (3.2), which has a dedicated plugin for our development engine Unity (3.1). Therefore, an example project was easily set up using the included example code. The example code shows how to control the speed of the player based on the ODT output values so that the walking speed on the ODT is the same in the virtual environment.

However, this was initially done using the HTC Vive VR headset, which has been directly supported and tested by the company behind the Omnideck. Once we switched to using the Meta Quest 2 (3.3), the Omnitrack software (3.2.1) reported problems hindering the ODT from working with the headset. The solution turned out to be a missing connection between the Omnitrack software and the Quest 2

VR headset driver, which made the software unable to read the position of the VR headset. Once the missing connection was established through modifying software configuration files, we could proceed with the VR development using the example code.

8.6 Limitations

This section will provide a detailed overview of the limitations of our study.

8.6.1 Sample Limitations

This study has several potential sample limitations that should be considered. Firstly, the age range of participants was limited to individuals between 18 and 30 years old. This may restrict the generalizability of the findings to a broader population. Different age groups may exhibit diverse responses and behaviors. Secondly, all participants were students located in Trondheim, Norway.

The gender distribution was also imbalanced. There was a higher percentage of male participants, with 26 males and 14 females. This may impact the extent to which the findings can be generalized, as gender might influence several factors related to the research topics. We propose that future studies aim for a more balanced gender representation.

In addition to the previously mentioned limitations, recruiting participants through social media and personal acquaintances can introduce selection bias. Participants who are already familiar with the researcher may possess different characteristics or interests compared to the broader population, which could affect the representativeness of the sample and potentially limit the generalizability of the findings. As mentioned in the statistical analysis discussion (8.4), participant independence can be hard to guarantee when our participants come from the same demographic.

Moreover, the familiarity between participants and the researcher may lead to response bias, as participants may feel inclined to answer in a way they believe aligns with the expectations of the researcher or objectives rather than providing honest responses, as mentioned in Section 6.7. This can compromise the objectivity of the data collected and potentially impact the validity of the conclusions of the study.

8.6.2 Implementation Limitations

We employed a joystick-based movement solution for half of the participants during our tests. In the field of VR, there are two commonly used approaches to locomotion, as mentioned earlier in Section 1.1. The two most common approaches are joystick-based movement and teleportation. Each of these approaches has its own set of advantages and disadvantages.

When it comes to the issue of cybersickness, it is important to note that the two approaches differ from each other. Joystick-based movement provides users with a continuous and smooth navigation experience, allowing precise control over movement speed. However, this approach has the potential to induce cybersickness. On the other hand, the teleportation approach tends to offer users greater comfort and can help reduce the occurrence of cybersickness. Nevertheless, it is worth considering that frequent teleportation may disrupt the sense of immersion for the user [65].

While this study demonstrates that ODTs result in lower levels of cybersickness compared to joystick-based movement for our participants, it is important to recognize the limitations of generalizing these findings to the teleportation approach. As mentioned earlier, the two approaches are known to differ in how they affect the cybersickness levels of the users, and further research is required to specifically investigate the teleportation approach compared to movement on an ODT [65].

8.7 Further Work

Throughout this study, we have found several interesting results. Some of these do not yield significant differences between the groups. However, they do indicate that differences could be worth investigating further. The perceived immersion of the users on the ODT differs from the joystick group (p= .20). This is a good example of a subject that could be further pursued. This implies that the likelihood of the observed differences in the groups occurring randomly is below 20%. If there truly is a difference in these groups, further testing with a higher sample size could yield more confident conclusions. Statistical significance can, among other factors, depend on sample size, the degree of difference between the groups, and the variance within the groups. A larger sample size is necessary to make significant conclusions if the group differences are small or variance high [56]. Using other measurement methods or structuring questions differently for future tests could also affect the outcome of the statistical analysis.

In Section 7.4, we saw that a higher percentage of women experience cybersickness symptoms than men. Even though it did not prove to be statistically significant, it could be interesting to conduct a separate study that tried to uncover further if there is any difference between the genders and how they experience cybersickness.

Another aspect worth investigating is the disparity in immersion between the two groups. As mentioned earlier, the participants using an ODT exhibited a distinction in perceived immersion compared to the joystick group, although not significant ($p = 0.20$). In a future study, researchers could emphasize examining immersion by, for instance, incorporating the immersive experience questionnaire developed by University College London into their research methodology or conducting a qualitative study on the subject matter. These approaches would provide deeper insights into the subjective experience of immersion in the context of the two locomotion approaches. As mentioned earlier, a new study could employ qualitative approaches to understand the immersion experiences of the participants comprehensively. Future research could also let the participants try to compare both variations and answer which variation they felt was more immersive.

As for memory retention between an ODT group and a joystick group, there might be differences that we were unable to observe due to one of our memory tests being too easy, as mentioned in Section 8.3. The same type of test could be run with a higher number of items or another form of increased difficulty. Another interesting aspect would be testing passive memory retention, where the participants would not know their memory was being evaluated until the actual evaluation.

9 Conclusion

This thesis explored the potential advantages and challenges of integrating ODTs with VR technology. We focused on three key aspects: immersion, cybersickness, and memory retention. This research had 40 young adult participants: 14 females and 26 males. The age distribution of participants was mainly in the 21-25 age range, with a small fraction falling into the 18-20 and 26-30 age ranges. Participants were randomly assigned to two equal-sized groups: one group using an ODT and the other group using joystick-based movement in VR.

The participants took part in three different tests. The first test was designed to measure memory retention. It involved a long hallway filled with various items that participants had to remember until they were assessed. The second test involved remembering and navigating a route and tested memory retention, immersion, and cybersickness. The third test was a puzzle-solving game designed to evaluate the levels of immersion and cybersickness of the participants. During these tests, data such as the position and rotation of the headset over time and the scores achieved by participants on the tasks were collected. After completing the tests, participants filled out a questionnaire about their experiences, including any instances of cybersickness and how immersed they felt in the virtual environment.

The research questions guiding us through this thesis were *how does the physical movement on an ODT affect the perceived cybersickness, immersion, and memory retention of users compared to joystick-based movement in VR*. Our results indicated that both the ODT and joystick-based VR setups provided a high level of immersion. However, there was no statistical difference in immersion levels between the two groups. Similar outcomes were observed regarding memory retention, where both groups performed comparably. As for cybersickness, a notable difference was observed. The group that used the ODT experienced significantly fewer symptoms of nausea, dizziness, and disorientation compared to those who used the joystick-based VR setup.

It is important to note that this study was conducted under certain limitations. We had a limited age range, and there was a gender imbalance among the participants. We also recruited the participants from social media channels, which has the potential to introduce selection bias. Additionally, all participants in this study were located in Trondheim, Norway. Despite these limitations, we believe the findings provide a significant contribution to understanding the potential benefits of integrating ODTs with VR. The findings from this study might have implications, including potential influences on VR game design, training simulations, and overall user comfort and accessibility of VR technology.

This study has contributed to the knowledge of how the physical movement on an ODTs affects users regarding cybersickness, immersion, and memory retention. However, there is still a lot to research regarding the effects of combining ODTs with VR. We propose further research on the immersive effects of ODTs, with a focus on letting participants try both solutions and comparing them. Memory retention is also an aspect that we suggest further research on. Our tests might have certain flaws, as mentioned in Section 8.3, and we also suggest research in passive memory retention. Additionally, we encourage further research to focus on the gender difference regarding cybersicknes. We found that a higher percentage of females got cybersick than males. However, our test group had a gender imbalance which could affect the dependability of our results. For future studies, we recommend recruiting a group of participants with balanced gender representation. The new studies should aim to explore if there are any differences in how males and females experience cybersickness. It would also be interesting to see if these differences hold true across different VR setups, such as ODTs or teleportation-based movement in VR.

Overall, our work has reinforced the idea that ODTs and VR can enhance user experiences in VR settings. While we found no significant difference in immersion or memory retention between the ODT group and the joystick-based movement group, the fact that ODTs help reduce cybersickness symptoms is an important contribution to the field. The findings add empirical evidence to a subject that is mostly theoretical. Our thesis lays a solid groundwork for future research on combining ODTs with VR and how the combination can enhance comfort and usability in VR environments.

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Appendix

A Participants Performance Data

B Questionnaire Data

C Consent Form

D Analysis Code

E VR Application Code

NTNU

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Science and Technology