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Bachelor's Thesis in Informatics: Games Engineering

Effects of Locomotion in VR on Motion Sickness and Immersion

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Wirkung von Lokomotion in VR auf Motion Sickness und Immersion

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I confirm that this bachelor's thesis in informatics: games engineering is my own work and I have documented all sources and material used.

Garching, 15.09.2019 Sebastian Walchshäusl

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Abstract

Locomotion is one of the biggest current problems for immersion in VR. Locomotion is needed if the virtual space needs to be walkable and is bigger than your tracked space. But when you use locomotion techniques you easily can induce cybersickness. To diminish cybersickness you need to make the player believe he stays static, which usually competes with the aspect of immersion.

The goal of this thesis is to discover a viable trade-off in a working environment where cybersickness is low, while immersion is kept high. For those reasons two different approaches, a psychological and a physiological approach, were developed and tested by user studies. In the psychological approach the user should believe he moves via separate mechanics and is not moving himself, to diminish cybersickness. The physiological approach uses walking in place to move. Technology used is the HTC VIVE with 3 VIVE Trackers.

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1 Introduction

VR (Virtual Reality) is steadily increasing in popularity. VR already is widely adopted for commercial use. But it also has a big following within the serious part of the industry. Many companies use it for data visualization, cheaper prototyping, more effective training application and simulation of different, not easily reproduce-able situations, like flying an airplane, medical training or for the military. The commercial use still makes up more than half of the market [Gra17]. But for every usage whether industrial or commercial locomotion is a big problem. Locomotion is needed as soon as your virtual walkable world is bigger than your tracking space. There is still no good solution for locomotion, therefore a big variety of different locomotion techniques are used, with some more and some less effective. The kind of locomotion is chosen through consideration of constraints, necessities and availability. There are always trade-offs you have to take. Not only cost has to be considered, but also immersion, naturality, availability of space and especially how much cybersickness is created by its usage.

The goal of the study is to find a trade-off for locomotion techniques, which minimizes the induction of CyS(cybersickness) for a serious based environment, while keeping immersion at a high level.

You can classify locomotion techniques in different categories. One is the difference between hardware and software techniques. Typical hardware solutions are omnidirectional treadmills, like the Infinadeck (Figure 1.1) or Torus treadmill [Iwa99] and cat walk [Kat15] (Figure 1.2), but also more experimental ones like circular floor [Iwa+05]. These techniques usually are quite expensive and most of the time some movement is restricted, like crouching or lying on the floor. Especially the price is an important factor, as the audience of the application is quite broad and therefore we can't expect high end equipment. For those reasons the more affordable and available option is software techniques. The only additional hardware needed are VIVE trackers, but they are much cheaper and are additionally needed for other purposes apart from locomotion, like body tracking and full body interaction.

Common software approaches are teleporting, artificial locomotion (AL), flying, walking in place, redirected walking and some games use innovative and highly specific locomotion mechanics for their games. Examples of these are "To the Top" [Ele17] with climbing as the main gameplay mechanic, "Echo VR" [Rea17] with jets and pushing yourself around in zero gravity, "Windlands" [Psy16] (Figure 1.3) with its swinging mechanics and "sprint vector" [Sur18] with swinging your arms for movement. Most of these techniques are focused on a very specific use case, so they are mostly applicable for the application. The other solutions aren't used for the reason of not enough immersion or too high level of CyS. One example for this is teleporting which is a widely spread

Figure 1.1: Commercial varian of the Torus treadmill, Infinadeck

Figure 1.2: KATVR kat walk mini

Figure 1.3: Windlands Action Scene

locomotion technique because of its low rate of CyS generation, but at the same tim it only offers a low level of immersion.

Software techniques can be further categorized by their CyS minimization method, which are physiological and psychological effects. In this study one of each category is chosen to find a good technique that minimizes the CyS level, while keeping immersion on an acceptable level.

The two techniques chosen are Walking in Place (WIP) as the physiological and a modified AL by Hovering as the psychological category.

The techniques will be implemented in an application, which has the goal to simulate robots with neuronal networks in a virtual environment. Through this method robots can be tested before they are built. To test them thoroughly you should be able to interact with the robots in a virtual environment that is fitted to the usage. Because the virtual environment is in most cases bigger than the tracking space, the locomotion techniques have to be employed. For more productive working the immersion should be kept high [PPW97] and the locomotion technique should be natural.To make working inside virtual environments for a longer time possible, CyS should be kept as low as possible. Otherwise you have to limit your working time inside the virtual environment for the purpose of keeping your working efficiency high.

After the techniques have been developed, the methods will be verified through user studies. The user studies will divide participants in two equal groups, by criteria of CyS, motion sickness and VR experience. Each group tests a different locomotion technique first. Before and after each experiment the participants will fill out an SSQ (Simulator Sickness Questionnaire), which was taken from "Simulator Sickness Questionnaire_ Twenty Years Later" [BBI17]. Afterwards the values will be compared between the two methods to find an increase in CyS. Apart from the SSQ, an immersion and usability questionnaire will be filled out after each experiment. These ones focus on the difference in immersion between the two techniques. Lastly the users compare the two methods subjectively and can suggest improvements for the experiment. The results of the user studies will be used to fine tune the values of the methods.

The application uses the Unity engine and the whole code for the locomotion techniques will be written in C#. Additional plugins used are the SteamVR plugin [Val], which is used for general VIVE usage, "VR Tunneling Pro" [Sig] for the tunnelling effect and some free asset packets [Tin; Reg; Uni; Avi; Tha; Car].

2 Fundamentals

2.1 Cybersickness

2.1.1 Definition

Per definition cybersickness (CyS) is a psychology simulator sickness, pronounced as cyber side effects. It's not a recognised illness but a constellation of clinical findings, which may affect those subjected to virtual reality (VR) [Far]. This definition was obtained from the medical lexicon "The Free Dictionary". Other definitions attach the term to motion sickness appearing while interacting with VR. Therefore, the question arises whether CyS isn't motion sickness.

2.1.2 Difference and Similarity to Motion Sickness

In a study motion sickness and CyS were tested with a user's subjective level of cyber-/motion sickness. They discovered that the terms are clinical identical, at least for later stages. But equality can't be concluded from these recent results (2018), therefore it's still an open question. A difference observed is the different root causes for CyS and motion sickness. Usually motion sickness confuses the brain because no visual movement is detected but the vestibular system registers movement. CyS on the other hand recognises movement visually, but the vestibular system doesn't recognise movement. Concluding for the sake of simplicity, CyS in this thesis is used for sickness induced by VR devices and similar devices.

2.1.3 Causes

The question of what exactly causes CyS still has no definite answers. One of the most approved causes is a conflict between the vestibular system and visual signals as mentioned before. A different theory is the poison theory which says that the brain perceive the effect as a poison and therefore generates sickness. Another theory says CyS occurs through postural instability. Another hypothesis is that unnatural eye movements are the cause for motion sickness. Lastly the reference frame, which is assumed by the user as static, isn't stable.

Apart from the more philosophical approach for what is the cause for CyS, some other causes have already been discovered. People with more experience in VR are less affected than people with none. Older people get more easily sick, also woman get more CyS. Another factor is flicker frequency that also generates high levels of CyS. People with more postural stability experience less. Mental rotation ability also reduces CyS.

Another factor, which increase the severity instead of the occurrence, is the FOV (Field of View), which has more detrimental effects with bigger FOV. Others are latency, motion parallax, viewing angle and user position [Ass]. For the application itself unexpected movement and acceleration induce CyS, as does rotation.

2.1.4 Symptoms

The symptoms appearing while experiencing CyS are categorized into nausea, oculomotor and disorientation [KDK10]. Nausea symptoms are nausea, general discomfort, stomach awareness, sweating, increased salivation and vertigo. Oculomotors include difficulty concentrating, difficulty focusing and eyestrain. Lastly disorientation symptoms are dizziness with open and closed eyes. Other symptoms are burping, fatigue, headache, blurred vision and fullness of head which are categorized in the first study about CyS symptoms in 1993 [Ken+93], but after a confirmation study it was discovered that these symptoms can't be clearly put into any of these categories. Additionally some symptoms, which before were categorized with more than one category, were put in only one category, which is a desirable property in a factor analysis.

2.1.5 Techniques for diminishing Cybersickness

Some techniques were implemented to minimize the CyS inducing effects from before. One example is tunneling, where you dynamically reduce the FOV while movement or rotation takes place. Another implementation technique is to put a stable reference frame inside the scene, like a cockpit, the windowing technique and similar [Ocu], or even a nose. Another factor, which is something important in general, is keeping latency low and refresh rate high. For that reason, which is not that important in desktop applications, it's much more difficult to develop VR applications because you almost always have to optimize heavily.

2.1.6 Techniques for obtaining User Data

Usually the best method for getting user data is the SSQ (Simulator Sickness Questionnaire) [BBI17] which asks for the 16 symptoms. Usually you compare a base value, which is taken before the experiment, against the values taken after the experiment. These values are still subjective, but with the baseline you get more accurate results.

2.2 Immersion

2.2.1 Immersion and VR

Immersion is one of the highest priorities and goals for VR. Therefore, almost everything that is developed for the advancement of VR technology is catered to making it more immersive. Because motion sickness can break immersion, it also needs to be minimized.

But is immersion also needed in not game related environments, like research and business?

2.2.2 Usefulness of Immersion

Immersion is not only useful for escapism and entertainment. Another factor is productivity. Many benefits of immersion aren't yet fully discovered but some study already found some advantages. For example, the spatial memory is better while immersed. Another advantage is improved interaction task performance. It also reduces information clutter [BM07]. These factors are also all desirable in a productive environment.

3 Related Work

3.1 Simulator Sickness Questionnaire: Twenty Years Later

The first study [BBI17] is a summary of many different SSQs (Simulator Sickness Questionnaire) from studies, for finding a simulator sickness index. The study first talks about conflicting vestibular system and visual motion signals that result in CyS (cybersickness). The study uses an old SSQ and aims at finding an index for the severity of CyS, distinguished from motion sickness, discovering a subscale to be able to closely look at different problems and a scoring approach for monitoring the answers easily. In the old SSQ 16 symptoms are evaluated with a score from 0-3, which contain symptoms of the 3 categories oculomotor, disorientation and nausea and weights each symptom by their category for getting an overall sickness score. The cause for dropout of studies is almost always CyS. The dropout rate will also be evaluated and may be an indication for cancelling the test. The study uses 9 SSQ of different studies, which use the same driving simulator. Because illnesses decrease the motion sickness threshold any participant who wasn't healthy or consumed alcohol recently was not allowed to participate.

Two SSQs were administered, before and after the experiment, but only the test afterwards was counted. Under certain conditions some participants data were not used (ending the experiment not for motion sickness, sticking through even so motion sickness appeared). From the 530 participants 72 experienced enough simulator sickness to quit the experiment, which corresponds with the exceptions across all 9 studies with 14%. The old SSQ weighted symptoms with multiple categories which violates the single factor loadings best practice. After the results were analysed it was discovered that the weights from the earlier study could only be attributed to one category. Some didn't qualify for any category, namely burping, fatigue, headache, blurred vision and fullness of head. The dropout rate had a significant relationship with the SSQ scores. The correlation between symptom and dropout showed that nausea and the other symptoms of the nausea category contributed most strongly. But the prediction dropout from scores was not reliable.

A multiple logistic regression analysis was performed to factor out not important reasons for dropouts. After 10 iterations the values found were nausea, discomfort, dizziness with eyes open, sweating, burping and difficulty concentrating. If none of these symptoms was felt, the dropout rate would drop to about 0.01%. The dropout probability increases exponentially for additional points on the SSQ score. With a formula for predicting dropouts, false negatives were only about 3.3%, but 47.3% were false positives. When looking at the application content, simulations with the least dropouts were long straight roads with only differing speed and the simulation that generated the most dropouts, was a simulation with many turns and many stops. The result leads to the conclusion that simulators with high discrepancy between vestibular system and visual motion generate more CyS.

The questionnaire from the study is used for my user studies, and the weighting together with the formula is also interesting.

3.2 Research in visually induced motion sickness

The next study [KDK10] examined VIMS (visually induced motion sickness). Motion sickness has been a reoccurring symptom for quite a long time. Especially the navy encountered this problem. Their soldiers became often inefficient through seasickness. VIMS is a similar concept but is solely created by visually perceived motion.

Motion sickness has many different symptoms like nausea, vomiting, sweating, salivation, apathy, fatigue, stomach awareness, disorientation, dizziness, and incapacitation. Physiological effects are changes in cardiovascular, respiratory, gastrointestinal, biochemical, and temperature regulation functions. Lesser known effects are postural and hand/eye incoordinations and sopite syndrome. Because aftereffects of motion sickness can last hours to days, these symptoms can result into safety mishaps, wherefore special care should be taken to avoid them. Motion sickness isn't limited to humans, it also appeared in different animals like fish, rats, dogs and monkeys. Nausea is created through environmental motion within 0.2Hz frequency and depends on the severity of motion and the time of exposure. These occurrences are most often present in vehicles but can also occur in attraction rides or in space, especially if there is a lot of head movement. VIMS can occur without any physical motion, which is the research theme of the paper and will be reviewed by three lines of investigation.

Many different applications were developed that induced motion sickness as a side effect. For that reason, studies have focused on understanding the difference between the symptoms and how they are induced.

After evaluating 25 years of data from simulator sickness questionnaires 3 different kinds of effects were extracted. These are nausea (N), oculomotor (O) and disorientation (D). Nausea(N) is related to gastrointestinal distress like nausea, stomach awareness, salivation and burping. Oculomotor (O) effect is related to visual disturbance, eyestrain, orbital pain and heavy eyelids, difficulties in focusing, blurred vision and headaches. Disorientation were related to vestibular disturbance like dizziness and vertigo. From the data it was discovered that space sickness has a high nausea and disorientation part but not as much oculomotor, while seasickness has a much bigger oculomotor part. Another confirmation of the results was the common sickness profile for helicopter simulators. With the categories you could perform an analysis of a variable to discover the cause for motion sickness of the simulator. Because the helicopter simulator had a high oculomotor value, they could conduct that the sickness was dependent on the VR devices.

The sopite syndrome, which contains drowsiness/sleepiness and fatigue, is another dangerous symptom. A user study was conducted where a group was split into a group who took melatonin and another group who took a placebo. A standard questionnaire with 27 question for motion sickness questionnaires (MSQ) of a previous study was used. The MSQ questions were asked every 10 minutes during the 1 h time slot. The results suggested that endocrine determinant may be involved in creating motion sickness.

Vection is an effect of motion which is used for increasing the immersion level but can generate motion sickness. If people are resistant against vection, they are also resistant against VIMS. To test that effect people got inside a rotating device with different coloured panels. They conducted a qualifying questionnaire and afterwards a simulator sickness questionnaire (SSQ). They discovered that woman and older people become motion sick more easily.

Even though CyS is a name for simulator sickness and VR together, it is mostly used for VR only. Via much data and questionnaires, a real difference of sickness profiles between VR and simulator was found. But there were also clear differences within the groups. The main difference between simulator and VR HMD were that simulator induced more nausea while a HMD generated more disorientation.

With the result of the studies the NOD components could be separately controlled, analysed and diminished, to be able to focus on only one component.

With this study I got a great example for questionnaire resources and some insight in the general motion sickness study with a special focus on CyS.

3.3 Minimizing CyS in head mounted display

Another similar study [Por+16] first performs a requirement analysis to develop a control technique which meets those. The study wants to make locomotion as natural as possible. They want to develop a technique that can fulfill the high standards of military movement which consists of covering large distances, manoeuvring through tight spaces, reacting fast on unexpected occurrence and more. Desktop 3d applications aren't sufficient enough for training aspects, therefore dynamic, interactable situations have to be employed. The locomotion method affects how effective the simulation will be. Different movement methods change the behaviour of the users and therefore train unnatural movement. Feedback is another important part for the natural feeling and consequently has influence on the effectiveness.

The analysis of locomotion focuses on control of virtual action. This consist of a virtual control action with a corresponding natural action (walking, running. . .) and its natural effects (moving of natural body) and the control effect the locomotion itself. They focus on speed and steering through body orientation. Furthermore, interaction with other concurrent actions is important, like looking and manipulating objects at the same time. Each one of these aspects should simulate the corresponding natural phenomenon as close as possible. Another feature they wanted to implement is turning. This can be achieved through many different actions (stepping, pivoting. . .) and thus has to be explored closer. They also want to decouple walking direction from the looking direction. Compatibility with similar movements, like walking in the tracking area, needs to be considered as well. If the interaction or locomotion is unrealistic, practices from the simulation can't be transferred to the real world.

With this framework they analysed different available locomotion techniques. They discuss different steering techniques, which were steering through sensors, steering in the look direction, hand-based steering and leaning. Afterwards they cover different speed control techniques, like pressing a force sensitive button with the feet and walking in place. Mechanical locomotion systems mentioned are a unidirectional treadmill, stair-stepping devices, which uses robotic arms, Uniport, which is a unicycle like device with a seat that recognises rotation through applying torque to the seat, sliding motion inside a slippery platform and a nested treadmill. Other more software focused methods are leg-based locomotion, which detects steps though thresholds by sliding the feet and walking in place (WIP) with torso steering.

Their own system, named Gaiter, uses WIP, where the leg movement determines speed and direction. The movement is recognised by position trackers on the knees and force sensitive shoes. They determine steps by using pattern recognition software, which can distinguish in-place steps from normal steps. Sensors on waist, hands and head are used to synchronize the body position. Forward, side to side, diagonal and backwards steps are detected by the movement of the knees in the corresponding direction. Other movements are detected as natural actions and don't move the player directly. For that reason, many movements are possible. An example is manoeuvring through curved paths while your hands are free. Your position will be a combination of physical position and virtual displacement.

But there are still problems with the legs of the avatar. The physical in-place step must be translated in the VE and the combination of primary and excess leg motion is still difficult to depict. Starting of movement and endpoint depend on the force sensor. A walking movement can be separated in 3 different walk phases, down (feet on ground), excursion (knee forward) and reversal (knee backwards). Because the motion from your knees is different than the corresponding real motion the value has to be scaled accordingly.

The technical equipment used was a magnetic tracking device which at first used cables. Because of problems with the cables a wireless magnetic tracking solution was later used instead. The VR HMD is a V8 HMD from the Virtual Research Corporation. Another sensor was attached to it. They planned to use a surround-screen in later versions. The Gait system is easily couplable with optic flow. Additionally, the system is quite compact and cost effective. Some drawbacks of the solution are that no real running movement is performed and thus other muscles are used. Other drawbacks are the noisy hardware and its erroneous readings when metal and other electrical devices are present. The intended application field is military simulations and firefighting.

The information taken from this study is that they mentioned the WIP method as an already viable solution but erroneous through wrong steps. For that reason, I let the WIP be controlled by an action, like pressing a button. I can't exactly use the method they had because I don't have force sensor shoes. I also developed a framework of constraints to check the final solution and have some guidance for further development.

3.4 Software Techniques to Reduce CyS Among Users of Immersive Virtual Reality Environments

The next study [DF15] wants to employ different techniques to reduce CyS. They first talk about the different parts of visual immersion which are field of view, field of regard, display resolution and size, stereoscopy, head-based rendering, lighting realism, frame rate and refresh rate. CyS cannot be reduced to one factor but has many different aspects. The most effective method to reduce CyS is to limit the time of usage. This study focuses on other solution, to be able to use the HMD longer.

In a previous study an HMD was compared with a visual display. The person with HMD had much more pronounced symptoms after one hour of exposure. Another study used dynamic depth blur to reduce CyS. A third study used two in-place navigation with the result that reduction of self-motion changes is more effective for reducing CyS than reducing sensory conflict during self-motion. The next study discovered that the gravity centre of the body changed while experiencing motion sickness. Field of view reduction was another effective tool against CyS, discussed in another study. Other studies used static and dynamic rest frames and peripheral visual effects. CyS was also tested in driving simulators and a similarity between motion sickness and CyS was found. Other factors like separation between eyes, incorrect calibration and convergence accommodation conflict were also researched.

The study used 7 different techniques. The navigation method chosen at first was teleportation as it is the safest method, but has low immersion, as the second method AL, which induces CyS, and the final method using physical movement, which has the highest interaction. The virtual environments used simplified textures, the time was limited, the field of view was dynamically reduced, a reference frame was inserted, the path of movement was predetermined, and image quality was reduced for a better frame rate.

Two scenes, a city and a nature valley, were presented and the users were questioned with the 16 symptoms SSQ. The subjects were around 28 years old and did not experience sickness during travel. They found that CyS especially appeared by using AL. Textures had no influence, but time had a significant impact, as does the size of the field of view. The nose as a static reference point inside the game and landmarks with a predetermined path didn't help as much as expected.

3.5 An Evaluation of Extrapolation and Filtering Techniques in Head Tracking for Virtual Environment to Reduce Cybersickness

The next paper [Gar+17] talks about latency as the main cause for CyS and wants to predict head movement to minimize the impact of latency.

Some symptoms of CyS, also known as virtual simulator sickness, visually induced motion sickness and virtual reality induced symptoms and effects, is experienced by at least 60% of first-time users. About 5 percent will never adapt to CyS. The intensity of CyS strongly depends on the VR environment. Self-movement or vection can already be experienced by HMDs, which causes CyS to a varying degree for different users. CyS can occur 5 min after playing and last for hours. One of the most relevant factors for CyS is latency, which can induce CyS with only 40 milliseconds latency. The current acceptable standard is 20 milliseconds but the values should be as close to zero as possible. For that reason, predicting head movement to reduce latency is important for diminishing CyS. The aim of the study was to develop a tool for developers for reducing CyS via prediction.

Causes for CyS are locomotion with its head movements, more oscillatory movement, abrupt turns, increased number of degrees of freedom, sudden vection, gradual increasing navigational rotating speed, head rotations, specifically in vertical direction, and looking at your feet. Involuntary movements do not seem to be problematic. To prevent CyS, smoothing sudden movements and compensating head movements is a good solution. The most problematic issue are rotations around the roll/z-axes and rotation on two axes simultaneous.

A stationary VR Shooter was used for testing. The HMD was an Oculus Rift DK2 with about 13.33 milliseconds latency. If the head prediction is working with this quite high latency value, it should work even better with other lower latency HMDs. The head tracking data of 10 users was recorded 3 times for 80 seconds. The data was filtered and compared with the predicting algorithm to see, if the actual values aligned with the predicted ones. From the 5 methods for calculating used, only linear and polynomial extrapolation were considered. Roll axis extrapolation didn't seem to work, because of the infrequency of that movement.

According to the results linear extrapolation together with the savitzky-golay filter had the best accuracy. Three different latency values were tested. The lowest error rate, with about 4% for pitch and yaw rotation, was recorded while using 13 milliseconds latency and increased drastically with more latency. The error rate also increased over time. The extrapolation methods were chosen, because the others didn't match natural head movement, wherefore large prediction errors occurred. From these results it was concluded that the tool can be a viable reducer of CyS until latency in HMD decreases. But the tool still needs more work to also factor in roll rotation. Verification and recording data by more users would also be useful for improving the tool.

This study gave another inside in a factor of CyS. With this in mind I can better decide which headset to use and if a wireless module with the risk of more latency is viable in my study. SteamVR already uses a similar prediction method for reducing latency problems. It uses reprojection, when the target frame rate is not met, by forcing every game to render in 45fps and interpolate afterwards to 90fps.

3.6 Virtual perambulator - a novel interface device for locomotion in virtual environment

The studies "Virtual Perambulator: A novel interface device for locomotion in virtual environment" [IF96] is an omnidirectional platform where you slide to walk. A hoop around your waist is used to support the user and limit his motions to the specified platform. They mention that locomotion is necessary because the physical play space is limited by the sensing range of the trackers and by the wire length of the devices. For exploring a virtual space, haptics is essential. But the current methods to that time, like pointing, didn't have any. They wanted to develop an interface, where the user stays at a fixed place, while not being restricted. For that reason, they used a hoop. The movement is recognised via special shoes that can slide on the platform and are tracked by a magnet sensor.

They mention other devices, like a treadmill with steering bars, pedalling devices, WIP, and their own first prototypes with roller skates. Almost all these methods were also mentioned in the previous study. Their first roller-skate prototype had omni-directional roller skates with special wheels that allows 2d movement. The users were fixed by the trunk to a harness. The motion of the feet was measured by ultrasonic range detectors. The direction was determined by the walker's step direction. They also tried staircase simulation by pulling the feet with strings. Because the first prototype felt uncomfortable with the harness, they replaced the harness with a belt around the waist. They also added a brake pad to the tows of the shoes for stability. The breaks are used while the foot moves backward from the forward position. The problems for the second prototype were restriction of up-down and turn around motion. The roller-skates also felt unnatural with their weight and height. The proposed solution was a custom sliding mechanism for the feet with a hoop around the player, that restricts movement but still allows free turning and up-down movement. New users can now hold on to the hoop for stability. The sliding device consists of rubber sandals with low friction film at the middle of the sole and again a rubber pad on the toes for braking backwards movement. Head and feet are motion tracked via magnetic sensor and sandals with touch sensor.

Their setup uses a graphic computer and an I/O computer. They use the I-glasses HMD with an 18000-pixel LCD display and 30°FOV, clearly an older model of VR HMD.

Usability was tested by means of novice users. Their data for feet and head position was recorded. While the experiment was conducted the participants were observed to see, if the process was rhythmically alternating and if turning and changing direction was a smooth motion. Of 235 people 3% failed in rhythmical walking and another 3% failed the smooth turning. The data should have been an alternating position for left and right foot in a rythmic fashion contrary to what was actually seen in the data. 8% of the users could run inside the simulation. None of the users complained about uncomfortableness or fatigue.

This technique is one of the older techniques for locomotion and is the inspiration for many similar omnidirectional treadmills. Today many omnidirectional treadmills (ODT) rely on the sliding surfaces used here. Some use hoops, but other use harnesses, that are similar but more comfortable than the first prototype.

This study is also referenced by many other studies in this field, for example Virtual locomotion - Walking in Place through Virtual Environments.

3.7 A Walking-in-Place Method for Virtual Reality Using Position and Orientation Tracking

This study [LCH18] discusses a novel implementation of a WIP method with usage of the HTC VIVE and its internal measurement unit (IMU). Attaching the body sensors for WIP is troublesome, therefore a different solution is approached. The paper first reiterates a previous study, which uses a WIP method using an IMU, but has problems with recognizing not intended steps. The new WIP method should improve on the previous one and additionally use the current orientation to calculate the correct step size for the Jogging in Place movement. With this approach the error rate of wrong squatting moves dropped to 0%, while the recognizing rate of wrong steps decreases to 0,68%, regardless of head tilting.

The method from the study uses the position and rotation of the VIVE. It detects the default eyeline through the y value and calculates a WIP recognition range around that value. For this reason, it recognises WIP only originating from the original posture. The default eyeline is used to calculate an initial eyeline H, which changes depending on the head tilt. For that the pitch has to be calculated out of the equation to get the correct vector. Constants for down and up rotation are used, which are similar amongst the probands and seemingly depend on the structure of the neck. With H and the Y position of the headset you can calculate the sinus form of WIP values. The method recognises Jogging in Place when a difference between H and Y is clearly measurable. For that reason, marching in place movement, where the difference is quite small, won't be recognised. Also, bigger movements than the specified value aren't recognised. Similar to biomechanics the movement is recognised from the corresponding real repeating walking cycle of "foot off", "maximum step height", "foot strike", "opposite foot off", "maximum step height" and "opposite foot strike". With the walk cycle and the y position of the headset you can recognise movement. Step recognition begins at the bottom peak, which is calculated from recorded step data. In this method if there is a high variance between n data entries the accuracy is high, but latency is low and vice versa with using similar values. To filter noise an averaging method is used.

The velocity for the step uses a virtual initial velocity at first, determined by the difference of the Y position between the different steps and obtained via interpolation. A min and max value are calculated for distinguishing from unintentional and intentional movement values, where the min value is the smallest recognisable step, while the max is determined by the maximal step the user has taken for intentional movement. These values are used to determine max and min virtual initial velocity. Too slow and too fast movements won't be recognised.

Virtual velocity is not constant and can affect immersion and motion sickness. The best function for making the movement natural is believed to be the saw-tooth function. The saw-tooth function should be applied when the WIP movement is recognised to decrease the velocity until the next step is detected. The virtual movement should stop immediately after WIP is stopped to diminish CyS. In the study you can walk backwards by tilting your head upwards.

The user studies used the HTC VIVE and a textured hallway inside a Unity scene without any obstacles. The 9 subjects were informed about the possibility of motion sickness and were advised to stop immediately after high level of motion sickness was experienced. They were also made aware that they were recorded. Sandals were prepared, if their shoes would be uncomfortable. The setup would be checked for fitting and comfort. In the case of falling something to hold was prepared. They were asked about previous VR experiences and if they wear glasses. Afterwards questions for motion sickness and natural feel of the method were asked. The users were told what movements they should do in what order. Users should test 100 steps for and backwards and 10 squats. The accuracy for step recognition was 99.32%. Backwards walking gave dizziness and one subject didn't think of the movement as very natural. A possible solution would be a rear-view. The saw-method for virtual velocity felt natural for the subjects. Problems appeared through fatigue of the subjects and that the first step sometimes wasn't recognised and didn't match the virtual velocity.

Because of fatigue the method is more useful for military training and running exercises. So I won't be able to employ the same technique in my application. But there are still many things I can use from this study. For example, the user studies for WIP will be a blueprint for the user studies I will conduct as well. Additionally, I'll use initial calibration and the saw tooth function with virtual velocity for a more immersive and less CyS inducing experience. I can use the up vector of the hip tracker, which also needs to be calibrated correctly, to find the correct direction. With that method you can easily determine back, front and sideways moving in place by a slight leaning in the corresponding direction.

3.8 Virtual locomotion - Walking in Place through Virtual Environments

The next study [TDS99] predicts that VR will become an established practice in the near feature and therefore especially in health application sees CyS as a critical problem. This paper presents design guidelines to diminish CyS.

VR has a big influence in the future of entertainment but it especially increases in importance within the serious application area. The main cause for discomfort was latency, which is almost eliminated with newer headset, but they still induce discomfort through the separation of the eyes, poor focus and the convergence accommodation conflict. There are already attempts for simulating depth of field and focus selection, but to make these areas work more effectively, eye tracking is needed. In the study a prototype along the guidelines developed in this paper was created.

They listed some studies and their results. The first study found that complex scenes could induce motion sickness and HMD games generate more discomfort than desktop games. One study developed a dynamic real time depth of field (DoF) solution that depends on the head position and introduces a refocus time, which differs between age and lighting. The next study found that 30% couldn't use the system for more than 30 minutes. The approach therefore used also a similar refocus delay but used empirical observations for setting the time. Another study, from the authors of this study, used a dynamic region of interest (ROI) in a 3D environment to calculate a DoF. CyS is still a big problem, therefore this studies guideline will not be complete.

Guidelines from current literature already include some solutions for CyS. Acceleration over an extended time contributes to discomfort. Instant accelerations is therefore better. Degree of control is a similar issue to accelerations. The solution for unexpected movement is to foreshadow it. CyS increases proportionally to the device usage time, so hints for taking breaks is another part of the guideline. Reducing the FOV of the display is advantageous but hinders immersion. But reducing the FOV of the virtual camera leads to discomfort. Jumping movements are better than continuous because of the discrepancy between real and virtual moves. It's also quite important to reduce latency and frame drops. VR devices usually have an infinite focus, which leads every object to be focused and generates discomfort. The studies proposed five guidelines. First, the blur level should be subtle. If it is too high it induces CyS. Use a standard refocus time for about 500 ms and adjust it for the need of the user. Be aware that other points than the display centre can be focused. Simulate the effect of focusing on different depths. Let an object be able to maintain focus, even after it reaches the focal point.

Dynamic focus is discussed especially. They use a virtual camera at the midpoint between the two different eye cameras. An ROI is calculated with a weighted heuristic to exclude objects outside the visual field. The remaining objects are focused. The heuristic evaluates the number of metric rays (rays from a cone at the centre) hitting scene objects. They are evaluated with an alpha value, corresponding to the centre of the cone. The heuristic uses as second parameter, the distance between object and user, which assumes objects closer to the user get focused more often. The third parameter is the importance in the game context. Designers should choose the weight for this context value.

For the user study a game was played where the dynamic focus could be activated and deactivated. For the test an SSQ and a profile questionnaire was used containing name, age, gender and academic background. The procedure sequence was profile questionnaire, SSQ, first test session, SSQ, second test, SSQ.

From this study I got the procedure sequence used in my study. Some of the guidelines are also interesting for my study.

3.9 Walking > Walking-in-Place > Flying, in Virtual Environments

The next study [Uso+99] I looked into more detailed wants to verify an earlier study, which was conducted by comparing presence by walking-in-place and flying with buttons. They additionally tested the two methods against real walking. Similar to the original study, they found a correlation of presence and degree of association with the avatar of the user. The result from this suggests that presence can gain significantly from full body tracking and avatar appearance customizing.

Virtual presence is strongly affected by the users' body, its virtual and its aural data. There are two possible solution for developing locomotion further. The first solution is building better trackers, and thus creating a bigger tracked area. The other solution is developing surrogates for walking, like treadmills, WIP, redirected walking and others. In a previous study it was indicated that virtual walking enhances presence more than flying does. If the users didn't associate with their avatars there was no significant difference between flying and WIP. The aims of the study were to verify the previous results with new technology and compare flying, WIP and real walking via presence and naturality of locomotion. They hoped that WIP is equivalent to real walking, so that wide area tracking isn't needed and WIP could be the new standard locomotion techniques.

The experiment using real walking lets the users walk the entire scene. Especial care was taken to prevent tripping by cables and colliding with objects. This was realised by an experimenter, who walked behind the subject to ensure their safety. The WIP method used neural networks to detect head motion, while walking in place and turn it into a virtual displacement. The method felt natural. This was verified by giving no explanation to the users in which direction they moved. The users still could navigate the scene. The neural network for recognizing steps was trained for standard virtual walking by the gait method of the main author from the previous study. Recognition errors typically appeared on motion starting and on stopping, by not moving when intended or moving without intent. Flying used gaze direction for navigation, because it felt more natural than hand pointing.

The virtual test environment were 3 rooms populated with furniture and opaque doors. The first room was for getting accustomed. The second room on the other hand consisted of a room with a 6m deep room beneath and only a ledge around the room and a chair at the other site. When the participant entered the door, they stood on the ledge above the room. Much consideration was put into the avatar appearance to make the experience more immersive.

The data for immersion was recorded not after the experiences, because users would have to remember everything, neither questioning during the experiment, because that would break immersion. Instead they let participants indicate a break in presence (BIP) by raising their hands. Many questions were used from an earlier study on presence. Example for these are the state of sense of visiting versus viewing, being there and additionally some own questions for effectiveness of locomotion and ease of use were used. Data recorded was the virtual and real view, audio, button pushes and the tracking data.

The participants were naive subjects and experts for comparing the two groups, but it hasn't yielded any result. The groups were separated into walkers, WIP users and flyers. They had to fill in a SSQ after and before the experiment, a presence questionnaire and a debriefing session. The users should first get immersed in the first room by interacting with the boxes. Afterwards they should proceed to the next room and walk to the chair over the pit or around the ledge. The independent variable in the experiment used was the locomotion technique.

The experiment confirmed the previous study, where real walking is more immersive than WIP, which in turn is more immersive than flying. CyS diminished the difference between WIP and Flying. Real walking was the most natural and easy to use locomotion. 30% of users had BIP through cables and 15% got more immersed after instructions ceased. The result of the locomotion techniques where clustered together. Behavioural presences, measured by the subject's interaction with the VE and the real world, was not affected by the locomotion technique. Higher discomfort didn't break behavioural presence for WIP or real walkers, but for flyers. They conducted that longer playing of games is associated with lower subjective presence and no real difference was found between the three groups of locomotion types. With the new questionnaires they found a significant difference between flying, which was much less immersive, and WIP together with real walkers. There was no real difference of oculomotor value between WIP and real walking.

A big unexpected result was the effectiveness of the cliff visuals, which led many participants to quit the experiment.

Observations were that cables are a quite distracting element. Real walking is the best method and WIP seems clearly better than flying. Avatar realism is worth a lot of investment, surprisingly even for clothing. Investigator voices should only be present from within game, not from outside, to increase immersion. These are all factors which I considered in my user studies, but especially the realistic customizable avatar is difficult to create in the limited time frame.

3.10 Quantifying Immersion in Virtual Reality

The next study [PPW97] talks about a proof for the usefulness of VR. Virtual reality is defined by the study as a system with 360°field of regard and passive headtracking for view synchronization. To not waste money on a protentional inefficient method, a scientific grounding for VR should be found. In the user study, a virtual room had to be searched from a VR HMD and a desktop environment. Symbols should be found, which were present for 50% of the time and otherwise missing. The time for both user groups to find the correct symbol was about equal. But the VR users were substantially faster at determining missing symbols. This result lead to the conclusion that VR users generate a better mental frame-of-reference. Additionally, the users were equal or better after switching from VR to desktop and the other user group, who switched to VR, was worse. The goal now is to demonstrate that you can transfer simple tasks from VR to reality. There is almost no literature which already analysed the advantage of VR over Desktop applications.

Users were tested if they could control the environment better with their heads. A quite old model of HMD was used, hanging from the ceiling to make it stationary. The desktop users, while sitting in a chair, used a device with 6DOF trackers attached to rotate the virtual position of the display. The pilot test already had some problems. Because the symbols to find were not camouflaged, the test was dependent on the speed of turning the camera and how fast the user could serially examine items, instead of immersion. But they discovered with that first test that VR users were much better at systematic searches. The final study used a room with doors and windows as an orientation point in which camouflaged characters had to be found. The character to search for appeared above the door. Then the users had to show the symbol inside the VR HMD, which simultaneously could be observe red and rectified externally, or decide, that the symbol wasn't present.

The difference between speed of VR and desktop users was statistically insignificant. The cognitive portion mainly slowed down the search task. The users never turned the camera as fast as they could have. Fatigue and practice had no influence on the result. Almost every user had no experience in VR and was aged from 18-25. From 51 users 3 felt CyS and couldn't continue the study. The average time for finding the target can be estimated. You can measure the time for searching the whole room, when the users make sure the target isn't present. The average time for finding the target should therefore be half the time of a complete search. From this result it was discovered, that VR users didn't search part of the room twice. Desktop users however spent 41% more for a complete search than the perfect predicted time due to rescanning of previous searched areas. When switching to desktop from VR the reference built can be transferred, and therefore the users were better with a statistically significant result. On the other hand, changing from desktop to VR decreases the performances statistically significant.

For future studies, instead of finding characters, real objects could be used instead, but probably wouldn't affect the perfect search time.

This study showed advantages of VR over desktop use. Searching inside the virtual environment is also important for the application. And it also gives some confidence for the effectiveness of immersion.

4 Solution Approach

4.1 Introduction

4.1.1 Analysis of the Requirements

At first, I looked for ideas and constraints for finding good locomotion techniques. I began with the constraints, therefore I had to think about the application itself.

The application itself is an application primarily for researchers. There the user will create a virtual environment to test robots with neural networks, before they are built. The environment consists of a room, which can be manipulated and populated with objects through a scene view, similar to the scene view of unity. There are some pre-sets for objects, ready to place inside the room. You can also use rooms, which were created and uploaded from different users, as a pre-set. The robot itself uses a neural network to navigate the scene. While the robot is driving inside the scene, it interacts with other objects through collision. You can view the scene either from a screen or an VR HMD(Head Mounted Display).

When you use the HMD you will also get a virtual avatar which mimics your real actions. This avatar is a dummy and therefore not configurable at the moment of writing this thesis. The avatar's hands are tracked by the hand controllers, while the head and body are tracked with the HMD. Inverse kinematics (IK) is used for matching the tracked object to the avatar and constraining the range of movement. With the VIVE trackers together the IK not only uses HMD and the VIVE Wands for head and hands, but also the hip tracker for the hip and the feet tracker for the feet. With these trackers and the IK full body tracking is realized.

Full body tracking is not only for increased immersion but also to be able to test the robot more efficiently. The robot should not only interact with other objects but should also react to collision with the avatar. With full body tracking you can now closely simulate real actions to test the robot, like kicking the robot from its path or simply blocking him with your feet. The topic of collision and full body tracking will not be discussed further in this paper, because it lies outside the field of locomotion.

Because the target group of the project are researches and industry and will be used in a working environment the most important point is to reduce CyS. With CyS you will not be able to work efficiently and may have to take many breaks. Some people will not be able to use the system at all. Therefore, the level of CyS should be reduced as much as possible. A locomotion technique should be found to minimize CyS. Another constraint is low exhaustion by using the system. You can't work for an extended time if you are exhausted fast. A locomotion technique that needs excessive movement, like running and swinging arms, are consequently not practicable. Because working while being immersed also increases productivity another focus should lay on keeping the immersion high. This already eliminates something like teleporting locomotion. Another constraint is the price. The target audience will rarely have high-tech equipment like omnidirectional treadmills, and we can't expect the users to buy such pricey equipment. But we can expect them to buy much cheaper alternatives, like the VIVE trackers, which cost in total about 350 Euro for full body tracking.

Apart from the application itself, another constraint is the availability of equipment. In the university we don't have access to expensive treadmills. What is available however are the ART tracking system and VIVE trackers. The ART system will not be used, because it needs additional setup and equipment with not that great of an advantage. But the VIVE tracker work with the lighthouse system, which is already setup for the wands and the VR HMD. The trackers are additionally not only used for the locomotion, but for full body tracking as well, so they are already available inside the application and an obvious choice to use for the locomotion techniques.

4.1.2 The Locomotion Methods

With all these constraints the first method I chose was Walking in Place. This method uses all VIVE trackers. Through empirical evidence I already discovered for myself that this method is effective against motion sickness, so it will likely be similar for CyS [Maz+18]. Additionally, there are already studies which show that this approach indeed reduces CyS. This approach is a physiological approach. WIP wants to negate the problem by introducing movement, which should simulate the real movement as accurate as possible and convince the vestibular system, that you are currently moving. With the vestibular system now matching the visuals CyS should be reduced. To make this approach work the virtual movement has to feel as natural as possible and hast to match the corresponding real movement as close as possible. Other projects, which already use this kind of movement, use automatic step detection. The detection is great for natural interaction, but to implement it you need machine learning and a lot of movement pattern data. Additionally, there will be false positives. You especially don't want those, if you move in the physical space. Additional detected steps will double the speed and therefore surprise the player, which generates CyS. Consequently, I decided to make movement dependent on button presses. Walking in Place is one of the most natural locomotion techniques, apart from real walking and some omnidirectional treadmills.

The second locomotion technique used is Hovering. This method uses AL where the direction of movement is not controlled by a joystick, but by the direction you are leaning in. You now necessarily need the press of a button for registering movement. This technique uses a psychological approach to diminishing CyS. The player should think he is not moving but moved by another system. This technique works better the higher the level of immersion is. It also should distract with immersion from eventually appearing CyS. But it's also more likely to produce CyS, because it's difficult to convince the player effectively and the vestibular system still gets differing signals. You only compensate for the different signals via a psychological effect. For this method the first idea was from my supervisor. The user should fly around the scene via a superman metaphor. The difficulty to make this metaphor convincing is quite high, therefore I thought about a different approach. This approach used jet shoes on your feet instead of the superman metaphor and conveys the feeling of Hovering above the ground. This matches quite well with the natural movement of leaning in the correct direction, therefore I decided to use it. To further increase the immersion the virtual avatar got hover shoes with a fire effect and a sound effect. This technique for reducing CyS is less documented than the Walking in Place techniques.

At first a third locomotion technique was suggested. This method was an AL technique with ghost movement, which just added some additional function of not colliding with objects to the existing Hovering method. This additionally should have used another metaphor of conveying movement, which would have been quite difficult. We finally decided against this third locomotion method because of time constraints and the exponential increase for difficulty of the user studies. Instead of two different groups, there should have now been 4 different ones, which not only doubles the required participants, but also increases the time per participant more than 25%.

4.2 Searching for Existing Solutions

4.2.1 Walking In Place

Some motivation for the WIP technique came from an available tech demo by smirkingcat titled ripmotion [smi]. This application uses a WIP technique for moving through a desert camp. You move by putting the hand controllers to your side, pressing the touchpads and start running in place. You move in the direction the controllers are pointing, so you are free to look around while walking. The movement of your headset plays a role in how you move. You can trick the system by emulating walking through moving the controllers up and down in sync or out of sync, but you also have to slightly move your head vertically, otherwise there won't be any movement. This technique is also used by many other applications. In the related work section, you could see [LCH18] and [TDS99], which implemented that technique in a similar manner. But the studies used machine learning to detect motion, while ripmotion needs the gesture of holding controllers to your side and additionally a button press.

The difference between artificial motion and the ripmotion solution is immediately noticeable. If you turn on lazy mode, you don't have to move your feet and can just press the touchpads to walk in the direction your controllers are aiming at. But while I have not experienced any CyS while walking in place, with the artificial movement I almost immediately got sick. It would be interesting to see, if switching from better to worse locomotion techniques in terms of CyS depends more on psychology and placebo effect or more on the previous method.

Another method for WIP locomotion is "Natural Locomotion" [Sof18]. This method is an application useable with hand swinging and feet tracking, like with the VIVE trackers. The method is a commercial product, consequently no source code is available and there is nothing to port to our application.

4.2.2 Hovering

Hovering is a kind of AL. AL is already widely in use as a commercial solution [Psy16]. But it generates high level of CyS [Uso+99]. Therefore, I took AL as ground work to get a different method.

The main difference between AL and Hovering is the availability of the three trackers. I used this additional equipment to find a better locomotion technique. Currently many AL techniques use the looking direction of your VR HMD or alternatively your hands as the movement direction. The natural movement however is mostly indicated by the heading direction of your body, in our case the hip tracker. I used the hip tracker to determine movement direction. This makes your hands and your head free to move around.

I haven't found any already existing technique who uses the exact mechanism I'm using, so I had to implement the movement without reference.

4.2.3 Result of Research

After I played the demos and tested the different available methods, I began thinking about the implementation. My first idea was to recognise movement by up and down movement from the VIVE trackers on your feet to move forward. The problem was, while the VIVE controllers had a clear pointing direction and a hand assigned, the trackers don't have a clear side, rotation or position. They can be located on different parts of the feet in different orientations. For the heading direction you could calculate a perpendicular line at the centre between the two feet trackers. Because you usually move your feet slightly in front of the other while doing WIP, the movement direction would constantly sway. This is not only contrary to what the user wants to achieve, but also will result in a high level of CyS. To get the direction the person actually wants to walk in, you need additional information. Thankfully I have three additional sensors I can use to make the result more viable. The hip sensor is a great sensor for this. It is the first sensor, which points in the direction you want to go in. The head and the hands are in general not the best indication. If you think about a VR shooter, the movement of your arms aligns most of the time with the direction your looking at, and not necessarily the direction you are moving in.

For additional certainty, it's also worth thinking about a button to press, if you want to start walking. This eliminates duplicated movement problem, which would occur if you move in your physical play area and the software also respond to the movement of the trackers.

Another important factor, which is especially noticeable in the ripmotion demo is the speed of your movement. In ripmotion you can run in place instead of walking to move faster or tweak the default speed. While running is a great addition for a more immersive experience, it wouldn't be appropriate in a more serious, business focused setting. You still want immersion, but convenience and comfort are more important. Sweating and being out of breath or walking for 5 minutes before reaching your destination just for testing your bot is not necessary and a hindrance to productivity. On the other hand, you don't want to be too fast and overshoot your target. For that reason, some mechanism should be developed to dynamically adjust the movement speed when needed.

4.3 Implementation

4.3.1 Technical Fundamentals

The VIVE trackers use the SteamVR tracking system. They have a similar shape to the VIVE controllers, but don't have a handle. They use the same sensors, which capture light from the lighthouses, and have the same tracking efficiency as the wand controllers. A VIVE tracker can also be used as a primary controller by connecting them before the actual controllers. The VIVE trackers are able to be a surrogate for a controller by using the input pins at the backside of the trackers and connecting them with wires. One of the reasons for buying VIVE trackers is to have a highly mod-able device, which is much easier to modify than the VIVE wands. The VIVE trackers position inside the global coordinate system may be counterintuitive. Inside Unity the forward vector points upward instead of the upward vector, when the tracker lays on its back. For that reason, the up vector is on the side and doesn't have to point upward globally. Therefore, you either have to rotate the tracker until it matches, which is not practicable for frequent usage. Or you have to calibrate the vector beforehand, which is the method I chose for the project.

Unity uses two different kinds of "main threads", which are update and fixed update. Fixed update should be used if you want to simulate physics, because it has a stable rate of 60 fps, while the fps in update usually varies. Therefore, the movement is calculated inside fixed update. A problem occurred while getting input for the controllers inside the fixed update. For some reason the input got recognized more often than once, which made the toggable locomotion button not reliable. After the input was placed inside the update loop, it was recognized correctly again.

4.3.2 Calibration and Initialization

Because the VIVE tracker registration and the tracker ID depend on the activation sequence, especial care has to be taken. At the current moment you have to activate first the left, then the right and lastly the hip tracker, for registering the tracker correctly. Another problem is the activation of the controllers. If you don't have your controllers connected, before you connect the trackers, they will be not registered correctly. Sometimes a tracker replaces one of the controllers, which is wanted if you use it as a primary controller. But because we don't have any wiring, you can't input anything. Even after you change the registration ID to make the controller match with your hand, the controller still will be seen as a tracker by the application and no input is registered. The easiest solution at the moment is to first connect the controller and afterwards the trackers in the correct sequence. Another problem is that sometimes the lighthouses get recognized as a tracker. This is another problem, which can't be solved manually by changing the ID. The only way to fix this rarely occurring problem is to restart the application. Later a solution has to be found to reliably access the registration algorithm and set them correctly.

The trackers are fixed to the body with 3 straps. One strap is a belt and the other two are foot collars. Each one has an area, where you can screw on a VIVE tracker and make it stable via a nonslip surface. The trackers on the feet should look outwards and the hip tracker should face forward. The first problem is that the orientation of the trackers is not always the same, so your feet and body of your avatar will be rotated incorrectly. For that reason, a calibration algorithm was implemented. This algorithm rotates the upward axis of the trackers until it matches the upward axis of the world coordinate system closely. This works for all trackers simultaneously. The user can calibrate the tracker orientation by first standing upright with the controllers to their side and then pressing the left application menu button. The algorithm will rotate all trackers towards the upward vector.

A problem, which still exist, is that the hip tracker can also be angled downwards or upward, depending on positioning and circumference of your belly. For that reason, some additional initialization has to be implemented. This time you rotate around the global x-axis to match the forward vector. The initialization uses the same function as the first initialization to eliminate duplication after the DRY design principle. You initialize the heading with the other application button.

The best procedure for activating the devices is to first initialize the orientation and afterwards the heading. For one its more stable and secondly the function also initializes the height of the trackers. To calculate the difference between the trackers on the tracking plane you need a point where the distance is zero. The tracking plane is generated from the vector between the two trackers. If the trackers have different heights on your feet your tracking plane is crooked, and movement will not be tracked correctly. With a crooked tracking plane, the movement of one foot usually requires more height than the other foot to register movement. To fight this problem the tracking plane will be initialized by moving the higher tracker default position downwards until both trackers lie on the xz-plane.

The size of the avatar is another problem. At the moment the avatar size is static, but taller people should have a different avatar size. The avatar size has to dynamically recognise the height of the character and initialize it correctly. Additionally, it has to be considered, that the body parts from different people have different lengths, independent from the size. Therefore, the avatar of small people with long arms appears with the hand controllers further away then the virtual avatar hands. But this is not part of my thesis and can be further researched and implemented in another thesis.

4.3.3 Walking In Place Implementation

The implementation of walking in place uses a tracking plane. The tracking plane is generated by first projecting the trackers on the xz-plane and use the two two-dimensional position to get a vector between the two foot trackers. This vector is used to get the normal of the tracking plane. The plane is generated each frame. With the tracking plane in place you can easily calculate the distance between the foot trackers in respect to the y value by projecting the trackers onto the tracking plane and calculating the distance. You only need to detect movement. Therefore, a threshold is integrated, which registers steps only after this initial threshold is reached. Movement stops if the distance is below the threshold. To diminish unintentional movement, you have to press both trackpads to be able to use the walking in place method. The direction of the movement is determined by the normalized forward vector of the hip sensor, after projecting its forward vector onto the xz-Plane.

The movement speed while taking a step is not dependent on the distance. The initial movement speed is set via the editor in m/s. Afterwards the movement speed is calculated by dividing it by the refresh rate of fixed update. An additional value for walking in place is the speed falloff. A technique to reduce CyS is to make the movement speed not constant, but let it fall off at a saw wave rate. This method was introduced by [LCH18] and implemented here by reducing the current movement speed each frame by a saw wave reduction constant, which was found through trying different values.

To the reduction of movement speed via the saw wave, a maximal step width is defined, so that unrealistic large movement can be stopped. This uses a similar method as the movement speed, by subtracting the travelled distance between frames from a current step width.

After the feet are again inside the threshold, the current movement speed is set to the max value, as is the current step distance. To make the experience a bit more immersive you get a step sound each time you re-enter the threshold.

4.3.4 Hovering Implementation

Hovering also uses a binary movement detection but it solely depends on the button input. You only move while pressing both touchpads together. The more interesting value to consider is the movement direction. This is again dependent on the hip tracker, but this time it uses the up vector of the hip tracker to get the direction of movement. By taking the up vector you can simply lean in the direction you want to go. Additionally, backwards movement and strafing is easily achievable by leaning backwards or sideways respectively. This is achieved by projecting the up vector onto the xz-plane and normalizing it. This way you always have a constant movement speed.

The movement speed is calculated like the max movement speed of the Walking in Place method, but a falloff for the speed doesn't work in this context, because the movement is continuous.

For making this experience especially immersive additional measures are taken. Two jet shoes are attached on your avatar feet, which emit fire while you are moving. Additionally, you hear a jetpack sound.

4.3.5 Further CyS Reduction Techniques

To reduce CyS further, another technique was implemented. This works for both locomotion methods. This technique is tunnelling, implemented through the "VR Tunnelling Pro" asset pack [Sig]. This technique only depends on the current movement speed to reduce the FOV dynamically, which in turn reduces the level of CyS.

4.3.6 Switching Locomotion Methods

The two locomotion techniques are implemented with the strategy pattern [Gam+95]. Therefore, you can dynamically switch between them at runtime. When you switch the locomotion behaviour, every value is reset, the jet shoes with its particles disappear or reappear and the audio switches to the correct sound file.

4.3.7 Implementation of Suggestions for the User Studies

It was immediately noticeable that the input method wasn't ideal. Especially for the WIP method it was distracting, tiring and unnecessary. The reason could have been the extended movement time, but a better version was implemented anyway. At first a method was introduced where you had to press the button only once. After you pressed the button you would walk until you stopped moving for a certain time frame. For Hovering it would be much more difficult to implement this kind of dynamic movement, because you can't really stop the movement, or you would have to stand exactly straight to stop it. Therefore, a second approach was implemented. This time the movement was toggable. This is a much easier implementation but had its own problem (see 4.3.1).

Another point of frustration for a smaller group of people was the movement speed while Hovering. Some expected the movement speed to increase while leaning further, but the speed was constant instead. They expected it to have a more Segway like dynamic movement speed. To increase immersion and naturality of the Hovering method this technique was implemented. Instead of normalizing the upward vector, the raw value was projected onto the xz-plane.

5 Evaluation

5.1 User Studies General

5.1.1 Introduction

The user studies I conducted consisted of 8 participants, which tried the two different locomotion methods in succession. The group was separated in two groups, equal in motion sickness affectedness and VR experience. Because of some quite late adjustments to the participant count the groups weren't as similar as they could have been. The participant consisted of 6 males and two females. The age ranged from 18-29. 2/3 of the participants rarely to never used a VR headset (Figure 5.1). The motion sickness and CyS mapped quite nicely on each other (Figure 5.2 and Figure 5.3) with 55.6% never having motion sickness. With a closer look at the individuals some people get motion sickness, but not CyS and vis versa. Therefore, you couldn't conclude that having motion sickness easily also leads to low threshold for CyS. Although the participants were allowed to leave the experiment at any time, none of the participants had to quit the application early because of CyS.

The user studies used a scene (Figure 5.4) of 4 long corridors, which were arranged in a square for one to get a long enough corridor for walking 10 minutes and have more varied movement. The corridor was textured convincingly and was approximately 5 m wide. A skybox of a sunny day with many clouds were used to further enhance immersion. It was also used to reduce CyS by giving a more natural environment and give the participant something to focus.

The room used a tracking setup with a high ceiling and the lighthouses of the lighthouse tracking system version 1 were fixed at about 3m above ground, looking down at about a 30°. The VIVE itself had a zed mini attached to the front. The play area was about 2.4 m x 1.8 m. The trackers used were two VIVE trackers 2.0 and 1 VIVE tracker 1.0 for the waist. The mixing of trackers had no special reason but was dependent on the availability of the devices. Another VIVE tracker 1.0 was held for reserve. The controllers were VIVE 1.0 wand controllers. A wireless module was not used, because it would be more difficult to keep the system running and it could result in more latency. Because latency is one of the main factors for CyS and CyS reduction is one of the most important factors for the application, this decision was felled.

The user studies will be conducted for mainly two reasons. First as an evaluation of the locomotion techniques for finding the better method. Secondly, getting some input for improving the application. There are many different values and techniques, which can be changed as needed. The values to change are speed of the movement,

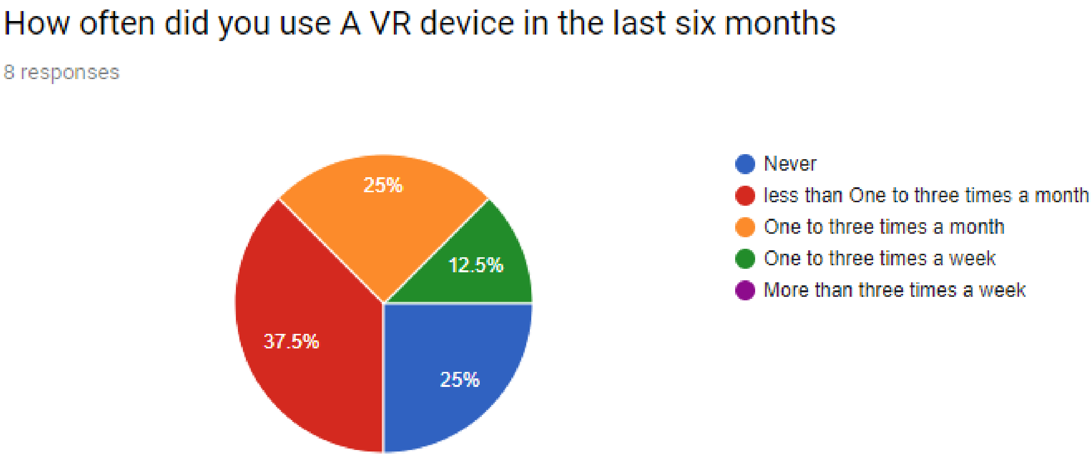

Figure 5.1: VR Usage rate

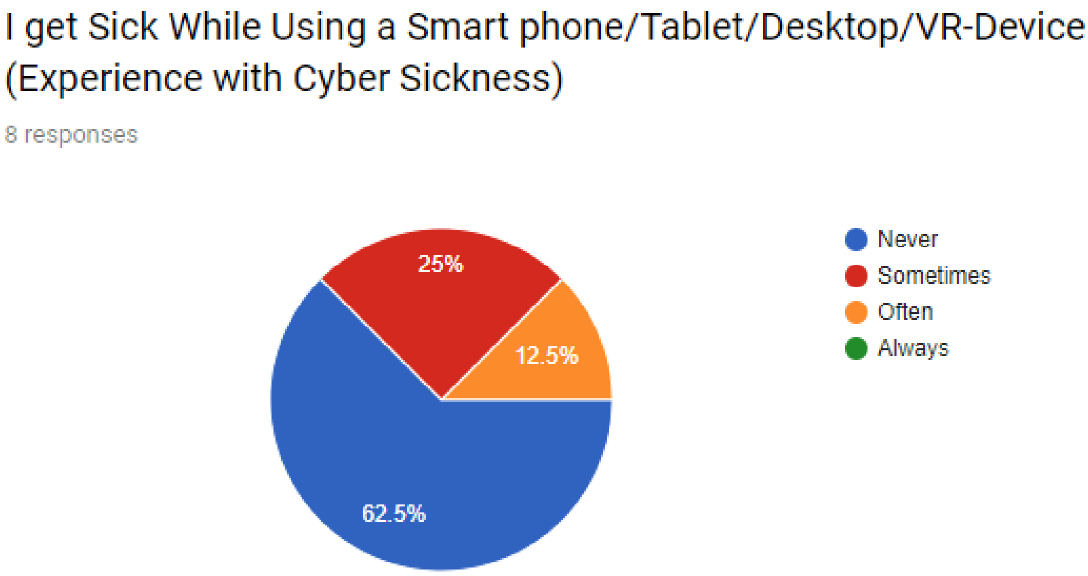

Figure 5.2: Frequency of CyS in general

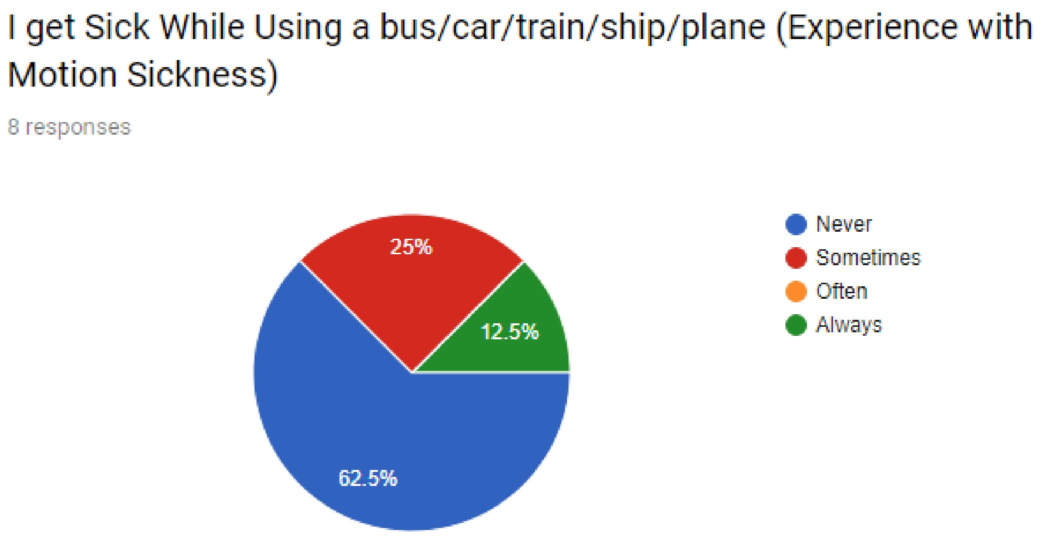

Figure 5.3: Frequency of Motion Sickness in general

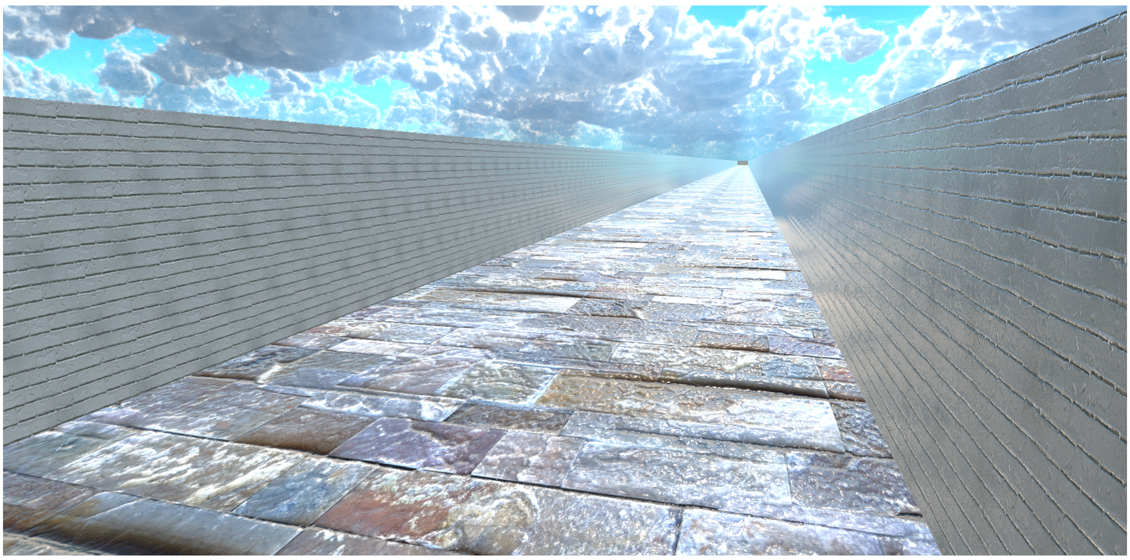

Figure 5.4: User Study Scene

level of tunnelling, sound loudness, distance for steps and falloff of the step movement. Techniques to change are input mapping, if hover speed should be constant or dependent on the extent of leaning and if the tunnelling is enough or another technique should be used.

The experiment used a much longer consecutive usage time than there will be in the actual application. But the time still was necessary to give the participants a chance of feeling CyS. It additionally should simulate a longer usage time, but more an endurance walks than the usual smaller short-lasting movement blocks.

5.1.2 Ethics

Because the health of the participants could be affected, especial care had to be taken. Firstly, every participant was informed before the user study began, that they could be affected by CyS. When the participants reached the room for the user studies, they also had to fill in a consent form, which made them aware of the possibility of getting CyS with all its symptoms, having lasting symptoms even after the experiment ends and that they may not be able to drive until the symptoms die down. In case of sickness, water, vomit bags and a bucket were provided. Additionally, the room was kept cool and filled with fresh air.

Apart from sickness, data gathering was also an issue. For that reason, no name in the questionnaire were given, but an identifier. Additionally, the participants had to agree via the consent form, that data will be collected from the headset and that the questionnaires will be further analysed and used in the study.

5.1.3 Content of the Questionnaire

There were 7 parts to the questionnaire. The first questionnaire was conducted before the experiment began, for sorting the participants in groups. The other 8 parts were filled in while the user study took place. The first one was an SSQ, which was filled in before the experiment. After each experiment, a usability, immersion and SSQ had to be filled in. Finally, a comparison between the two techniques was asked from the participants.

The first questionnaire was a personal questionnaire with identification number, experience with motion sickness, CyS and VR, gender and age. Two different groups for the experiment were generated by matching two about equal people in their experience with VR and CyS and putting them in different groups.

The first, third and fifth part of the questionnaire were SSQs. The first questionnaire was taken to establish a baseline for the current level of the participant and be able to calculate only the difference. This SSQ was also taken to make the participants already aware of the possible symptoms. The SSQ had 16 different symptoms listed and for each 4 different degrees from no symptoms to extreme symptoms. These were later used for adding points together. The SSQ symptoms were taken from [BBI17].

The immersion questionnaire didn't establish a baseline. The question were parts redundant, to increase the accuracy of the questionnaire. This is necessary, because immersion is subjective. The questions were taken from [Igr]. For the usability questionnaire 5 questions were used. These were taken from [Usa]. There was no duplication, because it doesn't have the problem of high subjectivity.

The last part was to compare the two different methods in different context. The context was preferred, preferred for longer sessions, more natural and more reliable locomotion techniques. Additionally, some place was reserved for comments and suggestions. These were later taken to fine-tune the values of the application and exchange not working parts.

5.1.4 Predictions

For the user studies I first predicted that the WIP method would be more exhausting than the Hovering techniques. I also predicted that WIP feels more natural than Hovering, but less responsive. The Hovering method would probably be more immersive than WIP. Another prediction was, that the level of CyS would be much higher for the Hovering locomotion method then for the WIP technique. I thought that more people would prefer Hovering for working and walking elsewhere. I also predicted that people switching from WIP to Hovering will be having more motion sickness while Hovering, than the other way around.

5.1.5 Preparations

The participants were invited via Moodle and had to fill in the personal questionnaire. Another way to participate was just with the questionnaire. After the participants filled out the questionnaire, they should also put their identification number in the doodle time slot they wanted to take. This was needed for the non-Moodle users, because Moodle users had already signed in with a time and date. To not have double booking, Moodle users also needed to fill in their time slot in doodle. The identification also was used to prepare the questionnaire for each participant. After participants from non-Moodle courses filled in a time slot, the corresponding Moodle slot was deleted.

The participants were provided with controller friendly snacks and water. The vomit bags and the bucket were prepared as well. After each participant the room was ventilated. The participants got about 20 minutes for the whole questionnaire, but no one needed much more than 15 minutes. The first group would begin with the WIP method, while the second group first used Hovering. The separation of the group was used to minimize the transition effect. CyS can last even after the experiment ends and therefore affect the second method. The level of fatigue, boredom and the accustomedness to the virtual scene and the headset has to be considered as well. The questionnaires could also be filled in differently after the second experiment.

The whole user study had a script written in English and German at its basis. A script was necessary for not influencing the participants with different formulations. Because of some issues with the hardware and the software the script couldn't always be applied completely. Therefore, the text spoken differed from the script.

When the participants arrived, the controllers and trackers were turned on in the correct order. On a table a laptop was placed, where the participants were able to fill in the questionnaire. On this table the consent form with a pen was prepared as well.

5.1.6 Procedure

The participants had to first fill in a SSQ. This was conducted to take already occurring symptoms of the participant into consideration and to be able to calculate the difference. Another reason was to familiarise them with the later occurring questions.

Afterwards the participants put on the strap and the headset. The HMD didn't fit everyone correctly, so the straps had to be adjusted for the many different head sizes. The controllers were placed in each of their hands. Now they were instructed to stand still to calibrate the virtual body with the trackers. After the tracker's rotation and position were calculated, the participants were ready to conduct the experiment. After the movement was explained to the participants, they got the HMD to wear.

It was explained that they had to press both touchpads of the controller and start walking in place to move. They should move inside the virtual environment within the corridor, until they reached the end of the square or after 10 minutes. Nobody reached much further than the second corridor by walking. While they were walking, communication was kept to a minimum to increase immersion.

After they reached the finish or after the 10 minutes, they put off the headset, the HMD and the controller to answer the next questionnaire. This questionnaire first contained some question for the immersion and usability of the method. Afterwards they had to fill in another SSQ.

When they finished their questionnaire, the participants could begin with the second experiment. They again had to wear the equipment. Now they got the instructions to lean in the direction they wanted to go. After wards they got the headset again and continued the experiment. This time almost everyone reached the end of the square corridors.

After the second experiment ended they were instructed to fill in the last questionnaires. The first two parts were the same as before. But the last questionnaire was a comparison between the two different locomotion methods as a personal evaluation from the participant. Additionally they got some space to write down improvements and suggestions for the project. The participants also were asked questions individually to later Additionally the values and input methods for the locomotion technique.

Afterwards the participants could try different games with the knuckles/index controller for the remaining time as a reward.

5.1.7 Problems

While the user studies were conducted there were some issues, which decreased the accuracy of the experiment. This probably led to falsification in the questionnaires. Tracking was the biggest problem, especially for the feet, which didn't' always work correctly. This heavily affected the WIP technique. For the Hovering method it was troubling, because of the visual glitching of the leg.

The next issue was that only 2 of the 4 trackers worked. Both, the hip and the reserve tracker, were first really badly and then not at all tracked. Consequently, for the first few participants only 2 trackers could be used. As a workaround the hip tracker was fixed to the head at approximately hip height and wasn't a tracked object. This worked fine for walking in place, but the Hovering, which used the up vector of the hip tracker for movement direction, was more difficult to use. You had to look down to move in the correct direction, which made the experience less immersive and less natural. For that reason, the tracker was switched between the two experiments. One feet tracker was replaced with a broken one, to have the hip tracker working. The last few participants could use the correct methods, because it worked again over night.

On the second day no audio could be played, which also was fixed overnight. The immersion could be therefore diminished on that day. The audio is used to further immerse the player and shutout any environmental sounds.

Because some participants didn't arrive and others had a late entry, the participants couldn't be matched as equal as possible.

Another problem were the cables of the headset. They were quite distracting for the participants. I decided to hold the cable while the experiments were conducted, to ease the cable distraction for the users. While performing WIP the participants walked forward ever so slightly each time they took a step, wherefore they had to be interrupted and walked back, which decreased immersion.

5.2 User Studies Results

The questionnaires were sorted into the two groups. These were then first analysed separately, then in total, and afterwards compared with each other. Because the sample size was small, some conclusions could be wrong and just appear within the test group. None of the participants had to or did cancel the experiment. Some participants thought the experiment took too long or that it was too much walking.

5.2.1 Immersion

The immersion questionnaires (Figure 5.5) were taken from [Igr]. These are partially redundant questions to get better results. The questionnaires had 3 to 4 answers, which indicated degree of immersion. The WIP method was taken as a baseline and was compared with the differing values for the Hovering method. For each degree of difference 1 was added or subtracted to a total, depending on immersion level. If the

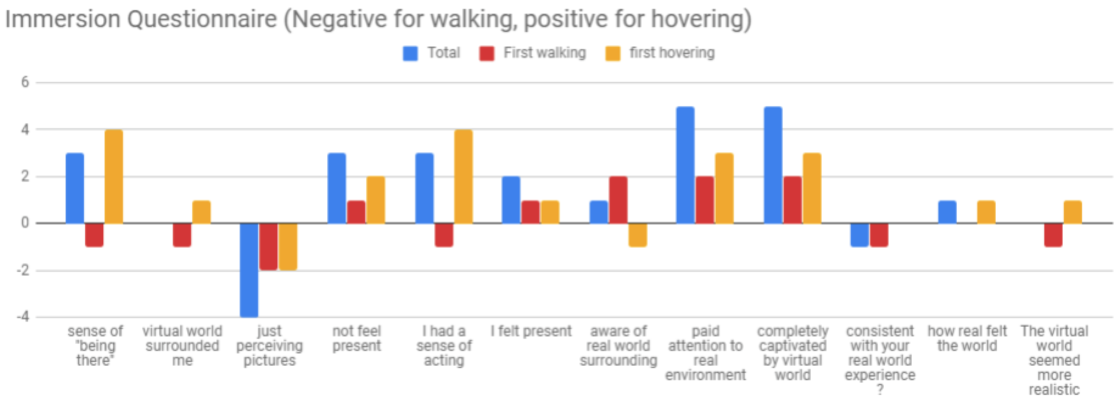

Figure 5.5: The Results of the Immersion Questionnaires. If the value is negative WIP was preferred, if it is positive, Hovering was preferred

Hovering method was more immersive, points were added and otherwise subtracted. With this method a total could be calculated for each group and finally a total for all participants. The result was that Hovering felt much more immersive in total with 18 points. With a closer look at the participants it was discovered that this high value in favour of Hovering mainly depended on the group, who used Hovering first. The group who used WIP first also thought of Hovering as more immersive, but to a much lesser degree with only 1 point, while the WIP group scored 17 points. This result clearly shows a bias for the first used method. It already made the separation into 2 groups worthwhile. People with more experience in VR in general thought of Hovering as the more immersive method.

Hovering clearly was seen as the more immersive method. As written in prediction I already expected immersion to be higher for Hovering, but not to that extreme of a degree.

5.2.2 Usability

Usability (Figure 5.6) had much fewer questions because usability is more objective that immersion and it's not part of the bachelor thesis. It's still interesting for the usage of the system and can also be an indicator for a more objective immersion result, therefore it was included. In this category Hovering also scored more points with again a bias for the first method. The total was 9 points, were the Hovering first group contributed 6, the walking first 3 points. Participants with more experience with VR in general thought of Hovering as more usable.

The prediction of WIP as more usable in this case was wrong. Hovering was the more usable method for the users.

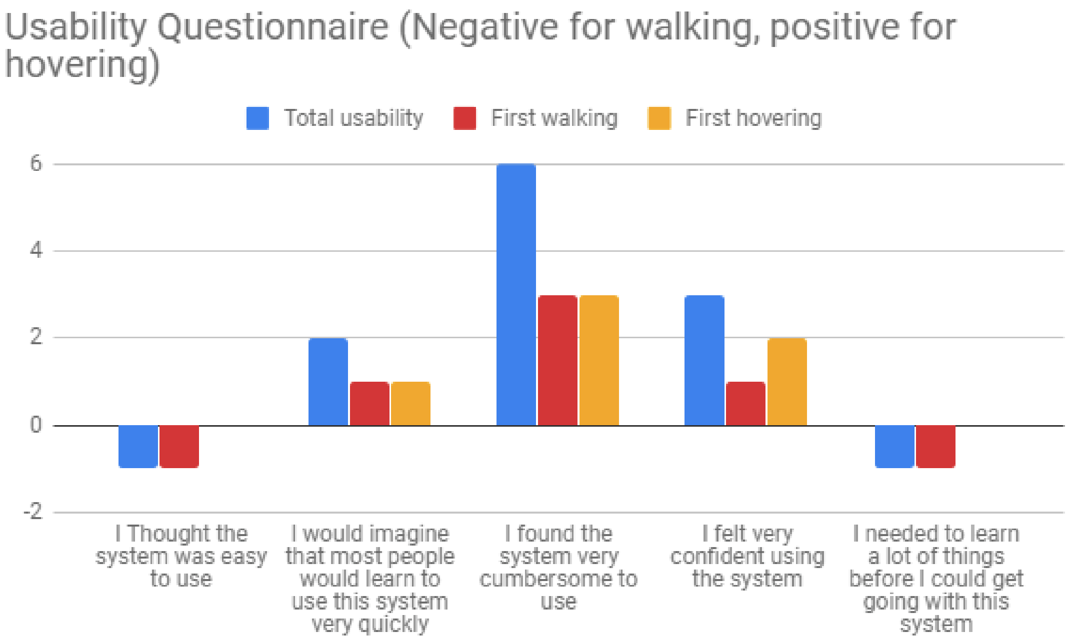

Figure 5.6: The Usability Questionnaires. Again negative values mean walking was preferred, and otherwise Hovering was preferred

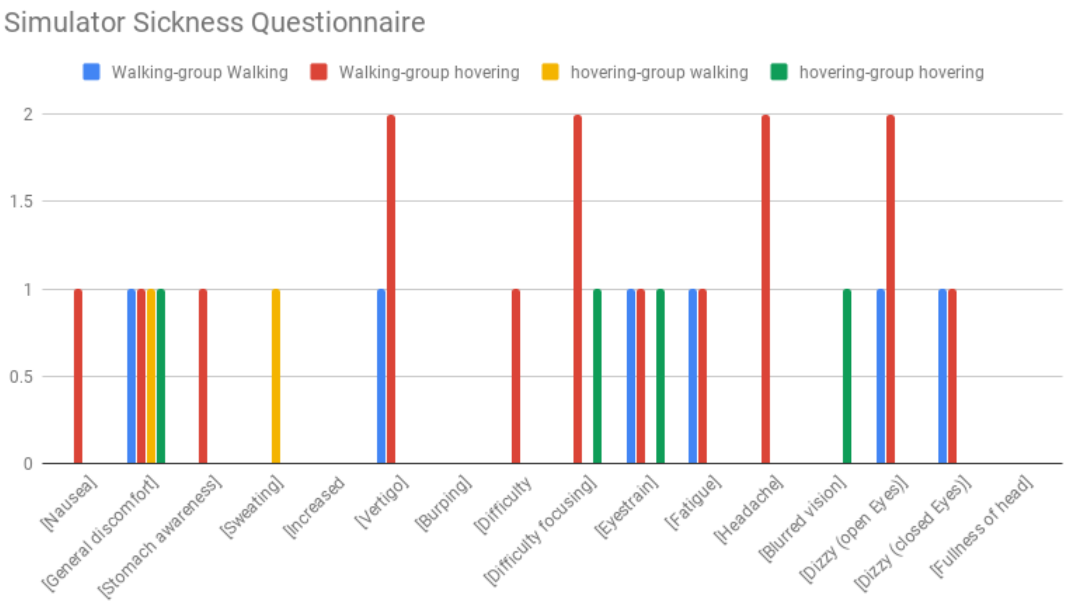

Figure 5.7: Results of the SSQ

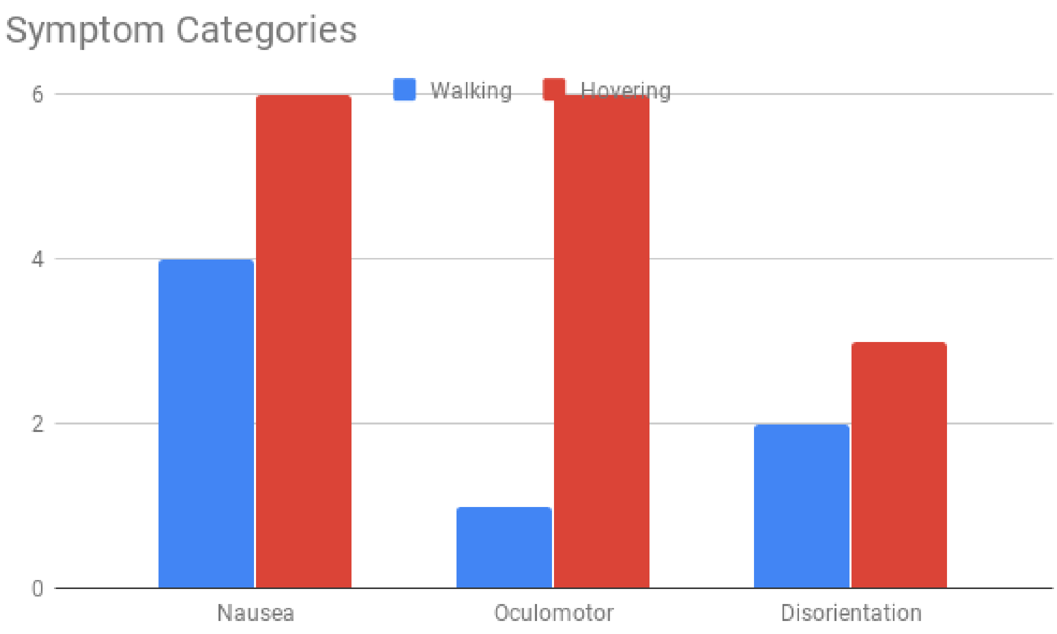

Figure 5.8: Categories of Symptoms for each Method

5.2.3 Cyber Sickness

The CyS questionnaire (Figure 5.7) was similarly conducted to the two questionnaires before by calculating a difference. But this time a neutral baseline was established before the experiment began, to filter out any symptoms beforehand. Only an increase in CyS symptoms is interesting for this experiment. Here a bias was not established. In both groups the points for Hovering were more than double the amount of the points of WIP. But the WIP first group had much more symptoms while Hovering than the Hovering first group. This was the result of some individuals with high level of CyS, which could already be seen from the profile questionnaire. The experience with CyS and motion sickness was a good predictor of experienced CyS in the experiment. With the weighting (Figure 5.8) of the 3 categories oculomotor, disorientation and nausea from [KDK10] the value for nausea was about equal and disorientation had no significant difference. But oculomotor had a strong difference with WIP one point and Hovering 6 Point in total. This result makes out oculomotor as the most important difference for the value of CyS for the locomotion method.

As predicted the Hovering method induced much more CyS than WIP.

5.2.4 Comparison of the two Techniques

The preferred locomotion technique (Figure 5.9) in general was dependent on the first used technique. Both groups preferred their first method to 75%. Therfore the methods

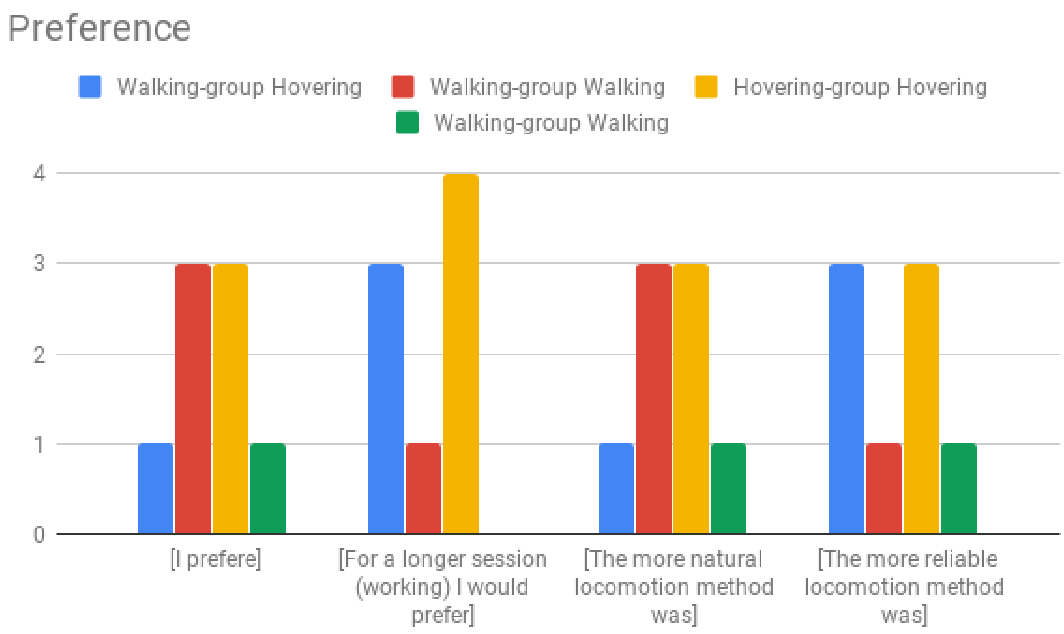

Figure 5.9: Preference of locomotion Method

were preferred to 50% in total. For a longer play session almost everyone preferred the Hovering method with 87.5%. The question for naturality was again dependent on the preferred method with again 75% each and 50% total. Lastly the more reliable techniques in total preferred the Hovering method with 75%.

5.3 Analyzing the Data and Evaluation of the Techniques

Now the user studies results will be analysed to see, which one the better locomotion method for the use case is. Additionally, any problems found with the application during the user studies will be fixed and the values will be fine-tuned from the results.

5.3.1 Analyzing of the Data

Some of the data could be a bit off. For one sweating is not only an effect of CyS, but also from the exertion through WIP and the hot HMD. For that reason, if sweating is the only symptom it will be evaluated as less important. Also, some participants had higher values for the symptoms before the experiment began than after. A decreasing in CyS symptoms through playing a possible CyS inducing experience is highly unlikely. Therefore, these improvements will also be not evaluated.

The main category for CyS was oculomotor. The symptoms of oculomotor can also be induced by low fps and the visual appearance. Because the oculomotor was much higher for Hovering, this however can be eliminated as the main effect. Disorientation had no statistical relevant difference, and nausea was also a bit stronger with Hovering.

Analysing the triple question for the immersion questionnaire resulted, that in most cases the answers were coherent and didn't contradict them self. This was also the case for usability, where the system was thought of usable or not over all 5 questions about equal for every individual.

5.3.2 Summarizing Thoughts and Results

With all the different data collected there can't be declared a clear better option at first. The Hovering method in general was more immersive and usable. Additionally, it was mostly preferred by the users over WIP. There was no clear indicator for which method was more natural, which went contrary to the original prediction, which held WIP as the more natural method. The most important advantage of WIP is the lower level of CyS generation. With further analysis you can see that for both methods about the same people got CyS. But the symptoms were more and greater for Hovering. For Hovering there was also one person who didn't have any CyS with WIP, but with Hovering. With these data the Hovering method seems to be superior, if immersion is more important or equally as important as CyS reduction. WIP should be chosen, if immersion and usability is not important, but reduction of CyS has a high priority. Because these reasons are subjective, the best approach is to make both available and easily interchangeable.

6 Future Work

I realized that finding the perfect values for the locomotion techniques can't depend solely on myself. Other user studies or testing would be necessary, where you vary the different values, to find the best option. The most important values are max movement speed, saw wave falloff and tunnelling sensitivity. Better cable management could also help the experiment.

As mentioned before, the dynamically adjustment of avatar height and limb size could also be a topic for further researching.

The results found in the evaluation part are far from a perfect sample size for finding conclusive results. Only 4 people per experiment were administered. With the low sample size and technical problems the results could vary in some parts. The correct results could have given more insight in the effectiveness of the locomotion methods. You are also able to filter some of the erroneous data, for having more accurate data.

Another helpful software technique, which could be implemented, is redirected walking. This technique relies on redirecting the users while walking little by little to make it seem that he is walking in a straight line when he is actually going in circles. This method however needs much more space than the other locomotion techniques, where you theoretically could use just standing VR, but it's still a viable alternative.

As mentioned before another interesting research theme would be to see if switching from better to worse locomotion techniques in terms of CyS depends more on psychology and placebo effect or more on the method used beforehand.

7 Conclusion

The goal of the thesis was to find a trade-off for getting the best possible locomotion method. The constraints were a low level of CyS, high immersion, price, setup and availability. The CyS level should be low to make efficient working with the technique usable for longer periods. High immersion was a criterion to make the work possibly more productive. After some searching two different kinds of locomotion methods were chosen, which closely matched the constraints. These were Hovering, an AL technique with additional help from sensors, and Walking in Place.

Implemented were both methods by using the VIVE trackers for either movement detection or movement direction. In both cases the hip tracker is used for the movement direction because of its naturality. With WIP the hip sensor is just used for direction, while the Hovering utilises the hip tracker additionally for dynamic movement speed. The feet trackers are not directly relevant for the Hovering locomotion method but are used for immersion instead, via full body tracking and hover shoes with particles. For the WIP technique they are used for determining when movement should occur. The avatar moves as long as the feet are above a certain threshold and until a max distance per step is reached.

The resulting locomotion techniques were evaluated by conducting user studies. Because of the small sample size and technical problems, the results aren't as accurate as they could have been, but effective enough for finding some consensus. The user studies were conducted by having two different but equal groups which used a different locomotion technique first. This was needed because a strong bias was found toward the first locomotion techniques the users experienced. The users had to fill in a SSQ beforehand and after each experiment. An immersion and usability questionnaire were taken only after each experiment. The result of the study was that users thought of the Hovering method as more immersive and usable, while having higher CyS. The WIP method was less immersive but had a much lower level of CyS. Especially the level of oculomotor was higher with Hovering than with WIP.

After the user studies were conducted some suggestions of the users were integrated into the application, especially the exhausting input method was changed from holding to toggling. Many values, like speed, also were tweaked after observing the users. Both methods in general had a low degree of CyS, so both methods are viable. If, however, the user has a strong sensitivity for CyS, WIP would be the better option. Both methods are implemented so that they can be switched easily and for both methods all necessary hardware should already be present. Therefore, it would be best to give an option for switching and letting the user decide which locomotion techniques would match best for them personally.

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