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Master's Degree in

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FINAL DISSERTATION

REDUCING CYBERSICKNESS CAUSED BY WALKING IN VR ON AN OMNIDIRECTIONAL TREADMILL

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2 Acknowledgements

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3 Abbreviations

Abbreviation	Meaning
VR	Virtual Reality
VIMS	Visually Induced Motion Sickness
VRISE	VR Induced Symptoms and Effects
ECG	Electrocardiagraphy
SSQ	Simulator Sickness Questionnaire
CSQ	Cybersickness Questionnaire
VRSQ	Virtual Reality Sickness Questionnaire
FMS	Fast Motion Sickness Scale
MISC	Misery Scale
VIMSSQ	Visually Induced Motion Sickness Susceptibility Questionnaire
MSSQ	Motion Sickness Susceptibility Questionnaire
FOV	Field of View
SPES	Spatial Presence Experience Scale
VE	Virtual Environment
CVF	Central Visual Field
PVF	Peripheral Visual Field
HMD	Head Mounted Display
IPD	Interpupillary Distance
GCS	Galvanic Cutaneous Stimulation
DLL	Dynamic Linked Library

4 Summary

One of the issues still plaguing users of virtual reality (VR) is that some can experience motion sickness symptoms like nausea, dizziness, and headache as a result of using VR. This phenomenon is called cybersickness [1] but has also been researched under the names VIMS (visually induced motion sickness), VR sickness, simulator sickness, (classic) motion sickness and VRISE (VR induced symptoms and effects). Research has been generally focused on VR experiences in which movement is done either with a controller, following a predefined track or walking within the bounds of a room. However, cybersickness can also occur with other methods of locomotion, such as walking on a treadmill.

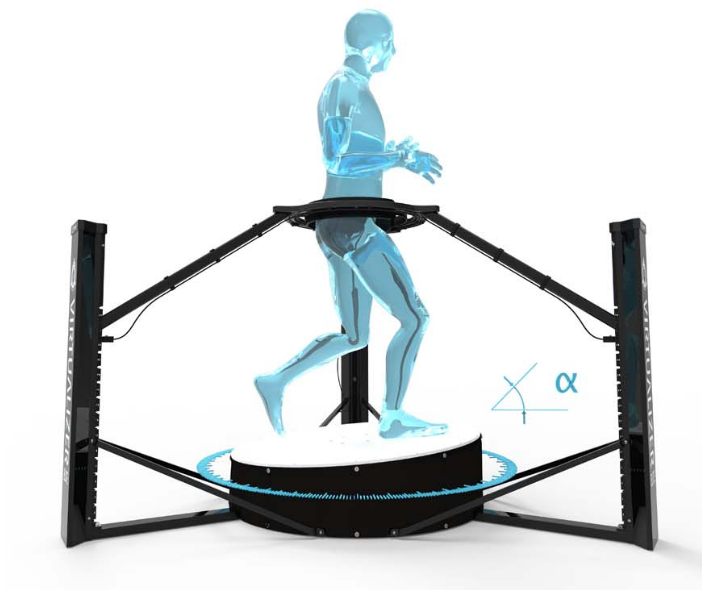

Figure 1: Cyberith Virtualizer ELITE 2

This thesis researched one specific form of locomotion: the omnidirectional treadmill. The Virtualizer developed by Cyberith[1] allows users to walk in any direction without being limited by distance (see Figure 1). The main purpose was to find what factors influence cybersickness when using the Virtualizer and how could a system assist in reducing sickness. To outline what needs to be researched, I defined the following research question and its sub-questions:

- *How can a system reduce cybersickness for users of Cyberith's Virtualizer while they are in a VR experience?*
    - *What are the causes of cybersickness?*
    - *What are solutions that can reduce cybersickness when using the Cyberith Virtualizer?*
    - *How can the level of experienced cybersickness, as well as the susceptibility to it, be measured before, during or after a session?*
    - *How could a system be adjusted to a user's specific cybersickness needs?*

Before performing a user study, I reviewed existing academic literature for theories on cybersickness, ways to measure it and solutions that could reduce sickness. The main theory on cybersickness is the Sensory Conflict Theory [2]. The basis of the theory is that during the VR experience, users receive conflicting sensory stimuli, which results in motion sickness. In the case of the Virtualizer, users perceive to be visually moving forwards as they walk, but physically they are walking on the spot. Although their vestibular system perceives accelerations while walking and physical, kinesthetic feedback from their feet and legs, they do not receive horizontal accelerations when starting to walk or stopping. Even though the Virtualizer provides better matching vestibular feedback than systems that use a joystick or artificial walking by swinging the arms, users may still become sick when walking.

Two other commonly discussed causes are the lack of a rest-frame and postural instability. A rest-frame is a consistent and stationary object in VR that can be used as a reference frame to understand self-motion and

[1] https://www.cyberith.com

motion of other objects. The Rest-Frame Hypothesis of Prothero postulates that it is harder to find or choose a solid reference frame in VR, thus a rest-frame is required to reduce cybersickness [3]. Postural instability was proposed as a source of sickness by Riccio and Stoffregen [4], but several studies have also found it to be a consequence of cybersickness [5], [6].

As postural instability was found to be a result of sickness as well, some researchers have used it to measure cybersickness. Rebenitsch and Quinby found that cybersickness could be measured by taking the head dispersion data from the VR headset [7]. This opens up the opportunity to measure cybersickness during the VR experience and take immediate action based on the data. Measuring cybersickness during a VR session is also possible by measuring the physiological state. The data I found successfully used for measuring cybersickness in other studies were electrocardiography (ECG), blood pressure, galvanic skin response, eye-tracking, heart rate, respiration, and cutaneous thermoregulatory vascular tone [8]–[12]. These often require extra hardware, however. Furthermore, some data might be distorted by the exercising nature of walking on the Virtualizer.

Researching the literature, I observed that the most used method of measuring cybersickness was the Simulator Sickness Questionnaire (SSQ) [13]. The SSQ consists of 16 symptoms that need to be rated on severity by participants. Two more recent questionnaires were the Cybersickness Questionnaire (CSQ) [14] and the Virtual Reality Sickness Questionnaire (VRSQ) [15]. According to the research of Sevinc and Berkman, the CSQ and VRSQ show better validity than the SSQ for VR experiments [16]. To measure cybersickness during the VR experience, I found that the Fast Motion Sickness Scale (FMS) [17] or the Misery Scale (MISC) [18] can be used. Susceptibility to cybersickness could be measured with the Visually Induced Motion Sickness Susceptibility Questionnaire (VIMSSQ) [19] or for a more general focus the revised Motion Sickness Susceptibility Questionnaire (MSSQ) [20].

Using the studies I found, I reviewed 15 different methods that might reduce cybersickness. Reducing the FOV (Field of View), correcting the interpupillary distance and adding a rest-frame were the solutions that were proven on the largest number of participants. From the 15 methods, I selected three, that were business-wise and academically interesting, for the user study: movement speed, movement smoothing and a virtual body representation (avatar). The solutions were tested on 39 participants, using a within-subject setup with four conditions. 34 participants completed all sessions, which totalled to 32 minutes of walking in VR. The conditions were the control, no avatar, high speed and no smoothing. The control had an avatar, a speed I defined as realistic in relation to the speed of the feet, and smoothing applied, whereas every other condition had one parameter changed.

The main method of measurement was the CSQ. The FMS, participant comments, Spatial Presence Experience Scale (SPES) [21], participant characteristics, and VR headset motion variance and max data were also collected and analysed. Data were collected before, during and after each VR session in which participants walked in a maze, the virtual environment used for the test. The results showed that the high speed condition made participants report significantly higher dizziness scores compared to the control condition, whereas the avatar and smoothing were not statistically significant in their difference to the control. This conclusion was also supported by the FMS data and the thematic analysis of the participant comments. The comments did suggest that smoothing might have influenced the occurrence of shifting and stuttering movements, which might affect cybersickness. Stuttering steps and shifting happened due to incorrect movements of participants, which movement smoothing could reduce. The cause of the shifting issue was found in the Virtualizer being too sensitive and quick in measuring the feet sliding when a user stopped. With this knowledge, development has started for a Virtualize firmware update that can resolve this issue. The headset data did not exhibit any significant difference between the conditions. In contrast with these results, participants did favour the faster speed more often than the slower speed.

From the thematic analysis, several other cybersickness factors emerged. A major aspect that was not affected by the conditions was the turning. Participants reported having difficulties with turning, and some mentioned it made them sick. The issue of turning might have been related to the visual rotating, which was not affected by the Virtualizer. The virtual environment might have intensified the issue, due to narrow pathways. Lastly, for some, the moving Virtualizer platform might have resulted in instability. As an immediate way to solve this problem was not clear, a closer investigation into what can make turning less or more sickness-inducing is required. Nevertheless, the comments also suggested that participants got used to turning and walking and started to adapt their walking style. Other smaller factors included looking at the minimap on their controller as a cause of sickness and cognitive distractions as a way to reduce it.

As the user study proved that changing the movement speed can affect the level of reported cybersickness of Virtualizer users, I decided to develop my implementation around that. The thematic analysis showed signs of smoothing also being a factor in the comfort of walking, so I included that parameter as well. The result was an app (Figure 2) that allows operators and VR users to adjust the movement speed and smoothing factors either from the PC or while they are in VR. The app can communicate with the Cyberith software, without being dependent on the VR app that is using the Virtualizer. The effects of the factors are visually explained, to increase clarity. More information on smoothing is provided when clicking the info button above the smoothing slider. Users can also read more on cybersickness by clicking the link.

In conclusion, users that are susceptible to cybersickness can reduce the movement speed and increase the smoothing factor with the configuration app I designed. This can be done before getting into VR, but also while the user is in VR. Adjustments can then be made to fit the user's (cybersickness) needs and alterations can be made as they get more used to VR and the Virtualizer.

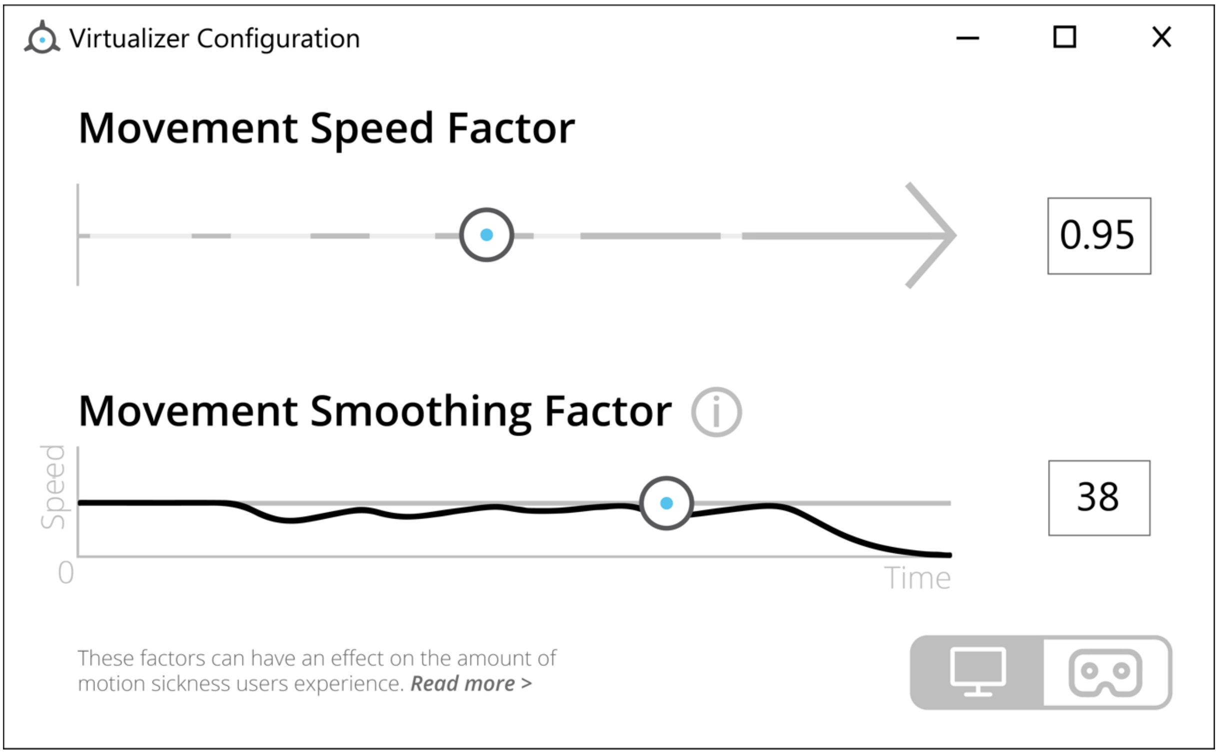

Figure 2: Implementation Result

5 Introduction

Experiencing virtual reality (VR) for the first time can be an exciting and enjoyable experience, but for some, this can quickly turn to discomfort. Certain users can experience cybersickness from VR, which is a kind of motion sickness similar to getting sick in the car or on a boat [1]. Whereas some participants do not experience any sickness at all, for others the symptoms can last even up to the next day [22]. Symptoms like nausea, dizziness and headache can take away the satisfaction of the experience.

Although repeated exposure to VR can decrease the susceptibility to cybersickness [22]–[27], a bad first experience can leave users never wanting to do VR again. This can act as a barrier to new users. It is hard to sell your VR product or perform VR experiments if a significant portion of the people gets sick while experiencing VR. Thus, it is important to find ways to reduce cybersickness.

As VR gained popularity in the previous decade, the subject of motion sickness in VR also found its way into academic literature. Several solutions have been proposed, from putting a virtual nose on the user's face [28] to decreasing the FOV (Field of View) [29]–[35]. Most research is focused on moving either while being physically stationary or being confined within the space of the physical room. This thesis focused on a different method of VR locomotion. An omnidirectional treadmill, the Virtualizer developed by Cyberith[2] (Figure 3), was utilised for my research.

As the Virtualizer is a different way of experiencing movement, the cybersickness reduction methods discussed in other studies might not have the same effect. To the best of my knowledge this is the first study that investigates cybersickness on an omnidirectional treadmill. The main theory on cybersickness, the Sensory Conflict Theory, puts the source of sickness in the sensory mismatch, mainly the visual-vestibular conflict, that users are experiencing [2]. Walking on the Virtualizer might lead to a different sensory mismatch that could cause motion sickness as compared to the sensory mismatch that comes from using a controller for walking. Testing these solutions on the Virtualizer will broaden the view on how applicable these solutions are to a different context than those used in previous studies. Also, this thesis might bring attention to potential new solutions and factors in cybersickness.

Some users may be hesitant when first using the Virtualizer. This can happen due to them having to get used to walking in the Virtualizer but also because they could be experiencing cybersickness. This can cause them to use the device incorrectly and can lower the quality and satisfaction of the experience. It is important to Cyberith that users feel comfortable in VR and that using the Virtualizer does not result in any negative experiences. Reducing the sickness and making it easy to adjust the system to the user's specific needs can make the Virtualizer a more attractive product to potential customers. Thus, this research provides value to Cyberith.

The purpose of this research was to test several methods that could reduce cybersickness for (new) users of Cyberith's Virtualizer and develop an implementation that allows Virtualizer operators or users to quickly make adjustments that could reduce sickness. Academic literature was reviewed to collect and discuss the current body of knowledge regarding cybersickness. A user study tested movement speed, movement smoothing and a virtual body representation on their effect on cybersickness. Finally, the results of the experiment were used to develop a small app that made it possible to adjust movement speed and smoothing while users are in the VR experience.

5.1 Research Questions

There are several research questions that this thesis aimed to answer with the literature review, user study, and implementation. The main question and sub-questions are as follows:

- *How can a system reduce cybersickness for users of Cyberith's Virtualizer while they are in a VR experience?*

  - *What are the causes of cybersickness?*
    To reduce cybersickness, it is needed to understand what are the known causes and theories behind it. Having gathered the causes, made it easier to find and come up with matching solutions. Academic literature was investigated to answer this question. The user study also gave insights on specific factors in the experiment experience which induced cybersickness.

[2] https://www.cyberith.com

- *What are solutions that can effectively reduce cybersickness when using the Cyberith Virtualizer?*
  Finding effective solutions that can reduce motion sickness is the core of this thesis. As this is not a new topic, most of the reduction methods were taken from already existing literature or comparable products. The ideation of other solutions was done using the causes, found in the previous research question, as the starting ground. A user test led to the final list of suitable and effective solutions.

- *How can the level of experienced cybersickness, as well as the susceptibility to it, be measured before, during or after a session?*
  To be able to measure the effectiveness of the proposed solutions, there needs to be a method of measuring the motion sickness that is experienced. Also, if it is possible to measure or even predict the motion sickness in real-time, the system could potentially dynamically adjust itself. If the susceptibility could be measured beforehand, then the system could be adjusted accordingly before any symptoms show up. This thesis discusses the different methods of measurement in the literature review. The user study employed several questionnaires and headset tracking as measurement methods.

- *How could a system be adjusted to a user's specific cybersickness needs?*
  For the final product of the research, it was important to consider how the configuration of the system can easily be changed based on the user's preferences. Taking the results of the user study, a small implementation was developed that allows users or operators to change certain parameters that can affect cybersickness.

5.2 Business Background

Cyberith GmbH is an Australia tech company that develops locomotion hardware for VR experiences. Their product, the Virtualizer (Figure 3), is an omnidirectional treadmill that can be used by VR users to physically walk in place in any direction. On the Virtualizer, users can walk in-place by sliding down with their feet and taking steps forward. The forward direction is defined by the ring around the waist of the user. So, to turn users need to turn their whole bodies. Walking backwards is also possible by sliding the feet forwards. The platform underneath the user can also provide haptic feedback. For example, the platform can vibrate when a user hits a wall in VR, to provide them with a sense of spatial limits.

The Virtualizer is mainly sold to other companies and institutions that utilise it for a variety of use-cases, e.g., gaming, training, rehabilitation, and research. The customer is generally not the one experiencing the VR, but the Virtualizer users can be employees, trainees, patients, experiment participants or customers of the company who bought the Virtualizer. This also means that a lot of the VR users are incidental and/or first-time users. Also, they tend to be assisted by an operator. The operator can instruct the user, operate the PC connected to the VR system, and keep track of the user.

Recently, Cyberith has also developed a system that with inverse kinematics and two extra sensors, one on each foot, can realistically portray the body of the user and the position of all its limbs in VR.

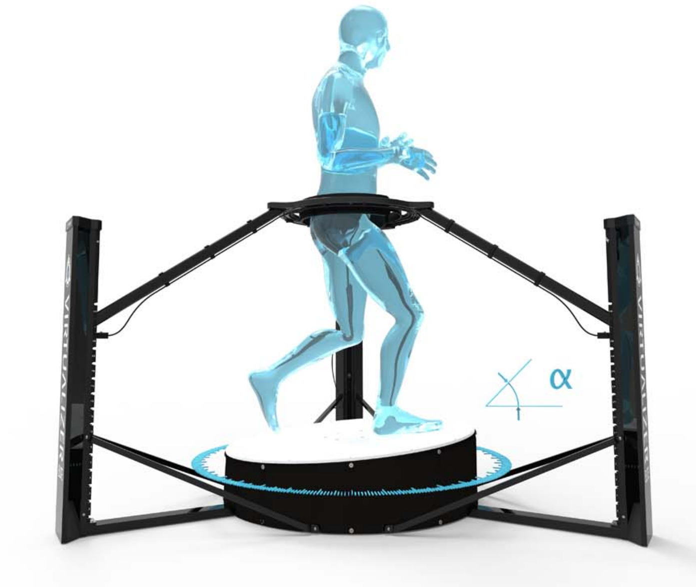

Figure 3: Virtualizer ELITE 2

6 Literature Review

In this chapter, I will discuss the literature that I found relevant for answering the first three research sub-questions. First, I will talk about the current theories surrounding cybersickness and its causes. Following that is an overview of different objective and subjective ways of measuring cybersickness. Lastly, I will compare the cybersickness reduction methods that are proposed in the reviewed literature. Articles were found through the Scopus search engine or through references of other articles. The initial search on Scopus focused on articles from 2015 or later. Older studies were included if they were referenced in the articles that I found on Scopus.

6.1 Cybersickness Theories

In this thesis, I will mainly use the term cybersickness, coined by McCauley and Sharkey [1], to talk about the phenomenon of suffering from nausea, eye fatigue and/or dizziness induced by experiencing VR or other types of virtual environments (VE). However, in academic literature, several different terms are used for the same or similar phenomena. The list of terms includes the more general VIMS (visually induced motion sickness), VR sickness, simulator sickness, (classic) motion sickness and VRISE (VR induced symptoms and effects). Those articles were included in the review as well, as the causes and symptoms are the same or at least similar.

6.1.1 Sensory Conflict Theory

Cybersickness is not a clearly defined sickness as there are many symptoms, its effects are different per individual and there are different theories on the source of the sickness [12], [36]. From the theories that I found in the literature, the most discussed one was the Sensory Conflict Theory. It postulates that cybersickness is induced when there is a conflict between the input of different senses. In the Virtualizer this conflict occurs when you move in the VE. The visual stimuli are telling the brain you are moving forward, but the vestibular sense is not detecting any horizontal acceleration as you are walking on the spot within the Virtualizer. Thus, this creates a sensory mismatch.

Regular motion sickness (e.g., car or sea sickness) was found to be relatively similar in its symptoms and physiological changes with cybersickness [37]. Also, sensory conflict seems to be at play for both. There is, however, a significant difference in the sensory conflict in a car compared to being in VR. In the car, motion sickness is induced because one can experience acceleration, but their visual environment, the interior of the car, remains stationary. Following the Sensory Conflict Theory, you can reduce the conflict by looking out of the window, so the visual information is in line again with the vestibular information. In VR the direction of conflict is the opposite. Users of VR experience motion and accelerations through visual stimuli, whereas the vestibular sense either recognizes no motion or it is not in sync with the visuals. This also has an impact on the method of reduction for cybersickness as compared to reducing normal motion sickness. The resulting reduction methods I will discuss more extensively later.

6.1.2 Vection

The experiencing of motion through visual stimuli is called vection and many articles have related it to cybersickness or VIMS [38]–[47]. However, other studies have found that vection can occur without inducing sickness [48]–[50]. This suggests that the relation between vection and cybersickness is more complex than just a simple causal relation. Bonato et al. sought to further investigate this relationship and found in their study that rather the change in vection causes sickness [51]. It does make sense from the sensory conflict perspective that it is rather the perceived visual acceleration than the constant visual motion that causes cybersickness. The vestibular system can only perceive accelerations, so conflict arises when one sense perceives acceleration and the other does not. The results of the study of Kuiper et al. [52] contradicts the study of Bonato et al. [51], however. Neither the strength nor the variability of the vection significantly affected VIMS. I consider a possible explanation of these opposing results that Kuiper et al. did not manage to induce a high level of motion sickness. Therefore, any possible difference between constant and changing vection in motion sickness inducement might not have been able to reach statistical significance.

Humans do not solely rely on visual input to determine bodily motion, but also receive input from their vestibular system which senses rotational and translational accelerations of the head. Thus, the vestibular system is an important tool for us to recognize when our own body is moving and to differentiate object motion from self-motion when integrated with the visual system [53], [54]. This multisensory integration can fail when you start moving in VR with for example a joystick. You can experience vection, whereas the vestibular system does not provide any self-motion signals, which results then in a sensory conflict. Gallagher and Ferrè take another perspective on the Sensory Conflict Theory and explain it as a problem of dynamic sensory reweighting [55]. They argue that generally the vestibular input is weighed higher than the visual input, but when you experience VR more often, the weight will shift more to the visual side as multisensory integration favours the most reliable signals. This could then explain why cybersickness symptoms lessen after repeated exposure to VR [22]–[27]. At the start, sensory conflict is large as the vestibular cues are weighted higher than the more salient visual cues, but after a while, this sensory weighting is shifted and the vestibular system is ignored, reducing the conflict.

Whereas the central visual field (CVF) is mainly responsible for recognizing and identifying objects with the higher density of cones ("what"), the peripheral visual field (PVF) is responsible for perceiving motion ("where"), including vection [56], [57]. Motion that occurs in the perceived background results in more vection as compared to the foreground according to Delorme and Martin [58]. Howard and Heckman observed that the peripheral stimuli tend to be interpreted more as the background, whereas the focus is in the CVF on the foreground [59]. So, motion in the PVF is more likely to lead to the feeling of self-motion. Pöhlmann et al. found in their experiments that the amount of VR sickness was dependent on the eccentricity and the direction of the motion [60]. Motion that moved laterally caused more sickness but not more vection when it was placed in the CVF, longitudinal (forwards or backwards) motion resulted in more cybersickness and vection when it was situated in the PVF. In the case of the Virtualizer, it could be expected then that motion perceived in the PVF causes the most cybersickness because while you are walking motion will be mainly forwards or backwards.

6.1.3 Postural Instability

Another frequently mentioned theory is that of postural instability introduced by Riccio and Stoggregen [4]. They proposed that symptoms occur when you are experiencing postural instability and have not learnt yet how to stabilize yourself in that specific environment. You might recognize this feeling of instability when experiencing a rollercoaster ride in VR while standing. On the Virtualizer this postural instability might come from the fact that users are sliding down with their feet while doing a walking motion. This is different from normal walking and thus creates postural instability. It is still unclear what is the exact relation with cybersickness as different studies seem to contradict each other with some providing evidence for the theory [43], [46], [61]–[63] and others either only finding postural instability as a consequence of cybersickness [5], [6] or finding no causal relation at all [64]–[69]. Nevertheless, this theory provides the basis for objective measurements of cybersickness. The use of postural sway as a method of measurement will be further elaborated on in the next subchapter.

6.1.4 Rest-Frame Hypothesis

An additional theory that has inspired a common cybersickness reduction method is the Rest-Frame Hypothesis proposed by Prothero [3]. It posits that cybersickness comes from the lack of finding or choosing a consistent stationary reference frame, the rest-frame, from which one can judge motions, positions and orientations to be relative to. The rest-frame is selected from several available reference frames by the nervous system and provides it with spatial-perceptual information [70]. The hypothesis suggests that it is not the sensory conflict that directly causes cybersickness, but it is the cognitive conflict coming from not being able to find a single rest-frame that is consistent with somebody's inertial and visual motion signals [58]. In other words, sickness is not necessarily bound by the degree of conflicting cues, but rather how the user perceives what is moving and what is not, based on those cues.

People are generally not consciously aware of the process of choosing a reference frame. However, you might be familiar with the feeling of not having a suitable rest-frame when you are on a train waiting at a station, next to another train. When the other train starts driving, there can be, for a short while, some confusion as to which train is actually moving. This lasts until you spot a rest-frame outside of the trains, for example, the ground underneath the trains or other buildings. Your brain can then finally come to the conclusion; it was the other train that was moving, not yours.

6.2 Measurement Methods

As I discussed in the previous section, there is not one single and established theory on cybersickness. Similarly, there are a wide variety of ways to measure cybersickness subjectively or objectively. I have divided them into three categories: questionnaires, physiological state and postural sway.

6.2.1 Questionnaires

Most papers use the Simulator Sickness Questionnaire (SSQ) proposed by Kennedy et al. [13]. Although this questionnaire was originally meant for the use of simulators in the military (for example, flight simulators), it is still the most established questionnaire for cybersickness in VR research. Participants rate the severity of 16 symptoms on a 4-point scale from none to severe. The results are then calculated in four scores: nausea, oculomotor, disorientation and total score.

As the SSQ's original purpose is not VR and it was tested on highly trained professionals, some researchers have proposed alternatives [14]–[16]. The virtual reality sickness questionnaire (VRSQ) presented by Kim et al. and the CyberSickness Questionnaire (CSQ) introduced by Stone can be seen as subsets of the SSQ [14], [15]. In the VRSQ the symptoms that are related to nausea are left out, which only leaves nine symptoms. Kim et al. argue that the disorientation and oculomotor components contribute more to sickness in VR than the nausea component. They are reasoning that in simulators users experience inertial motion, whereas this is not the case in VR, which causes the difference in nausea inducement. I suspect, however, that in the Virtualizer it might still be possible to experience inertial motion as the user is making in-place walking movements and the platform underneath them is moving. Therefore, the SSQ might still be more suitable. The CSQ also kept only nine out of the 16 symptoms from the original SSQ. Five of these are the same as used in the VRSQ. The CSQ does not have a total score, but the calculations result in two factors: dizziness and difficulty in focusing. Sevinc and Berkman performed a psychometric evaluation on the SSQ, a French version of the SSQ, VRSQ and CSQ [16]. They found that the VRSQ and CSQ showed better validity compared to the SSQ and its French version. As the VRSQ and CSQ are subsets of SSQ, it is possible to let participants fill out an SSQ but analyse the data as a VRSQ or CSQ.

A major disadvantage of the previously mentioned questionnaires is that due to their size you can only utilise them before or after a VR session. Thus, it is not possible to get real-time data with the SSQ, VRSQ or CSQ. To get around this, Keshavarz and Hecht proposed and validated the Fast Motion Sickness Scale (FMS), a one-dimensional scale that goes from zero, no sickness, to 20, frank sickness [17]. As participants give a score verbally every minute, it is possible to evaluate the timing of the motion sickness. Other studies found as well that the FMS correlates strongly with the SSQ score and its subscores [72], [73]. An alternative to the FMS is the misery scale (MISC) introduced by Wertheim et al. which ranges from zero, no symptoms, to 10, vomiting [18]. The study of McHugh et al. demonstrated that it is also possible to use a physical dial instead of a verbal response to capture answers on a one-dimensional sickness scale [74].

Not only is it of interest to measure cybersickness during or after a VR session, but it can also be relevant to know a participant's susceptibility to motion sickness. Susceptibility to cybersickness can differ between participants, so to measure that there is the revised motion sickness susceptibility questionnaire (MSSQ) by Golding [20]. The MSSQ looks at a participant's history with motion sickness. This questionnaire was not developed for cybersickness (or VIMS), so Keshavarz et al. introduced the Visually Induced Motion Sickness Susceptibility Questionnaire (VIMSSQ) that rather looks at past experiences with symptoms than motion sickness in general [19]. Due to its length, Golding et al. also proposed and tested a shorter version of the VIMSSQ in another paper [75].

6.2.2 Physiological State

While questionnaires are the most often used method of measurement for Cybersickness, they do have several disadvantages. First of all, questionnaires interrupt the experience of the user, so they cannot measure their sickness in real-time. Although the FMS does allow researchers to get sickness data during their experience, there is still a slight interruption and pulls the attention of the user away from what they were experiencing. Another drawback is that questionnaires are subjective in their nature. Thus, they do not always reliably measure what they are trying to measure. To get around these problems, researchers can measure the physiological state of the users. This can be done in real-time and can provide a source of objective data.

There is not one specific physiological signal that is used throughout most of the literature. In their review, Rebenitsch and Owen advocate for using electrocardiogram (ECG) and blood pressure [12], whereas in the review of Caserman et al. galvanic skin response is put forward as the most reliable method of measurement [76]. Other possible methods include eye-tracking, heart rate, respiration and cutaneous thermoregulatory vascular tone [8]–[11]. However, Gavgani et al. found changes in heart rate and respiration mostly related to autonomic arousal [77].

A major benefit of measuring the physiological state is that it becomes possible to develop a closed-loop system. Sensors could measure the user's current state and then apply cybersickness reduction methods accordingly. Several studies used machine learning to establish a system that can measure cybersickness in real-time from physiological signals [78], [79]. Islam et al. developed a full closed-loop system with a pre-trained neural network that was based on physiological data (heart rate, breath rate, heart rate variability and galvanic skin response) [79]. It applied Field of View (FOV) reduction or Gaussian blurring based on the calculated level of sickness, which then could reduce the level of sickness. The level of cybersickness was calculated by measuring the physiological data of the user on an interval. The effectiveness of the system in reducing cybersickness was not tested.

To measure the physiological state users will often need to wear extra hardware. Some headsets include extra measurement options like the eye tracker and heart rate sensor in the HP Reverb G2 Omnicept Edition, but most HMDs do not include any physiological sensors. It could be acceptable for a scientific experiment to have to wear extra hardware, but in my opinion, it is not desirable from a user experience and product perspective. Wearing sensors might feel intrusive and uncomfortable, and having to put them on creates an extra barrier for users. Additionally, it adds complexity to the Virtualizer system, which might make it harder to implement in different business scenarios.

Although physiological data is objective, it has not been able to replace SSQ as the golden standard for measuring cybersickness. Generally, studies have used physiological results as a way to support their findings, but not as the main method of measurement. Additionally, physiological measurements are often validated using the SSQ or other questionnaires. Thus, their validation is based on subjective data.

6.2.3 Body movement

Even though the link between postural instability and cybersickness is not completely clear yet, postural sway has still been used in many studies as an objective method of measurement [80]. Feigl et al. demonstrated that it is also possible to measure gait parameters to identify cybersickness [81]. They used an inertial measurement unit on both feet to record the required data and then applied a support vector machine to build a cybersickness classifier.

One way to record postural instability is to use a balance board from which you can get the movements around the centre of gravity [62], [82], [83]. Chardonnet et al. analysed their data and found the specific postural sway features that can predict VIMS [82]. The results showed that participants that reported higher levels of sickness had a postural with a larger area, in a more circular shape (as opposed to elliptical) and a higher frequency of forwards/backwards oscillations. Wang et al. trained a deep long short term memory model for each participant that can predict the cybersickness based on their postural sway [83].

Unfortunately, a balance board is not compatible with the Virtualizer. The feet of users are sliding on the Virtualizer, so they cannot stand still on a balance board while in the Virtualizer. So, they will have to exit the Virtualizer first, to measure their current level of cybersickness. This will make it impossible to continuously monitor the cybersickness. There are, however, also sensors in the Head Mounted Display (HMD) users are wearing, which have the potential for recording postural sway. Lim et al. tested and confirmed that head dispersion, the change in roll and pitch, is highly correlated to the changes on the x- and y-axis around the centre of gravity [31]. To measure head dispersion, participants had to look straight ahead or hold their heads still. Rebenitsch and Quinby also looked at the link between the positional data from the HMD and cybersickness [7]. Although the data was quite noisy, they still observed significant correlations between certain position parameters and the SSQ scores. These results suggest that it could be possible to develop a system that records the position data from the HMD, then calculate in real-time the level of cybersickness of the user and uses that as feedback to adjust the sickness reduction techniques. It might not be an attainable goal to build that system within this thesis, but it would still be beneficial to record the HMD data anyway for future steps.

6.3 Reduction Methods

When reviewing the academic literature, I focused on finding methods that can be implemented in the Virtualizer experience and do not include taking medication. This meant for example that techniques that involved somebody sitting on something specific were not included in this review. An overview of all methods, the studies that tested them and the total number of participants can be found in Table 1. The methods that I tested in an experiment are in bold text. The explanation for the choice of those methods can be found in the next chapter. This overview also consists of studies that did not involve VR but did still concern VIMS.

Table 1: Overview Cybersickness Reduction Methods

Method	**Proven**	**Total N**	**Failed to proof**	**Total N**
FOV reduction	[29]–[35]	284	[84]	18
Correct IPD	[85], [86]	220	-	-
Rest-frame	[28], [70], [71], [87], [88]	137	-	-
Movement speed	[38], [89]	133	[90], [91]	49
Olfactory stimulus	[92], [93]	76	-	-
Galvanic cutaneous stimulation	[94]–[97]	69	-	-
Texture complexity reduction	[98], [99]	52	[100]	25
Slow deliberate breathing	[100]	43	-	-
Airflow	[101]	41	[102]	12
White noise	[93], [94]	39	-	-
Head-worn haptic feedback	[104]	30	-	-
Movement speed smoothing	[105]	15	[106]	24
Virtual body representation	[107]	15	-	-
Cognitive distraction	-	-	[108]	14
Artificial speed reduction near collision	-	-	-	-

6.3.1 Field of View Reduction

Reducing the FOV, also known as vignetting, is one of the most popular methods of lowering cybersickness symptoms or delaying its onset. It has also found its way on the VR market by being included in the VR game Eagle Flight [109]. Many studies found that FOV is related to cybersickness or VIMS and that vignetting works as a solution against sickness [29]–[35]. In contrast, in the study of Norouzi et al. vignetting lead to an increase in cybersickness [84]. It seems like this might have been caused by their utilisation of amplified head rotations.

An issue with using a FOV restrictor is that it does not consider the eye’s gaze direction, so users are always forced to gaze in the direction of their head. Adhanom et al. developed a foveated restrictor, a vignette that follows the eye’s gaze position [110]. Although they did not find any significant effect on cybersickness, they did report that users had more eye gaze dispersion in the foveated FOV restrictor condition. So, a foveated restrictor could improve user experience by providing more gaze dispersion flexibility.

Looking at sensory conflict and vection it makes sense that reducing the FOV helps as it also reduces the number of motion cues in the periphery, which is the most sensitive area to vection from longitudinal motion [60]. By reducing the FOV, the visual cues in the periphery are in line with the vestibular cues. Both suggest no longitudinal motion, thus decreasing sensory conflict.

6.3.2 Correct Interpupillary Distance

Many studies have reported differences between sexes in the level of cybersickness [102], [111]–[113] or other kinds of motion sicknesses [114]–[116]. There might be an explanation, however, for these differences in VR. Stanney et al. found in their first experiment when the interpupillary distance (IPD) of the headset did not match, participants reported more sickness and that this was causing sex differences [85]. In a second experiment, they confirmed the hypothesis that IPD non-fit leads to a higher degree of cybersickness and if the IPD is made to fit there are no sex differences anymore. The study of Fulvio et al. adds support to this hypothesis [86]. They made sure to measure the IPD of every participant and adjust the headset settings accordingly. In the results, they did not find any differences between male or female participants.

6.3.3 Rest-Frame

Using a “rest-frame” is a strategy that is suggested by the Rest-Frame Hypothesis discussed earlier [3]. A rest-frame is a stationary frame of reference that somebody can use to perceive the motion of other objects and self-motion. In other words, people can understand the motion of other objects or themselves by relating it to a stationary and stable object that then functions as a frame of reference. Although there is quite some diversity in the designs of the rest-frames used by the different studies (e.g., cockpit, cap, glasses, grid, black metal net, physical nose) they all found success in reducing cybersickness with a static rest-frame [28], [70], [71], [87], [88]. In the study of Wienrich et al. half of the participants that had a virtual nose were told of the nose, but they found no effect of this awareness on cybersickness [28]. Cao et al. also tested a dynamic version of their rest-frame that changed the opacity based on the translational and rotational speed [85]. This resulted in worse comfort as opposed to using a static frame. McGill et al. combined the method of reducing the FOV and using a kind of peripheral rest-frame into one solution for VR in the car [117]. The periphery was filled with a rest-frame which was consistent with the motion of the car.

6.3.4 Movement speed

Changing the movement speed could have an impact on cybersickness, as it also affects the magnitude of the conflict between the visual and vestibular systems. At higher speeds in the VE, visual flow is intensified. Thus, the difference between the visual and vestibular cues increases, so I expect that a higher movement speed can amplify the level of cybersickness. Some studies found differences in speed causing a significant change in cybersickness [38], [89] whereas others did not reach the same conclusions and found no significant difference in overall cybersickness or VIMS [90], [91]. Keshavarz et al. argue that they cannot conclude whether the speed is a factor, as the VIMS ratings from their experiment were overall quite low [91]. So, there seems to be a correlation, but a higher speed might not automatically result in more cybersickness.

In the Virtualizer users might experience another sensory conflict as well. I think a higher movement speed might also cause a conflict between the proprioceptive and visual systems. From walking in real life, humans have developed a mental model on the distance they expect to cover per footstep. So, when setting a step, they expect to see a specific amount of visual motion that corresponds with their movement in space. In VR, however, the movement speed is defined programmatically and tends to be higher than real life walking speeds. So, there is a sensory mismatch between the distance a user traversed with one footstep and the distance they moved in the VE. In VR systems that use a joystick, or something similar, to move, this conflict does not exhibit itself as the legs are stationary and consequently do not send any proprioceptive cues. In conclusion, I expect cybersickness to be reduced in the Virtualizer when the movement speed matches the real-life walking speed compared to having a higher movement speed.

6.3.5 Olfactory Stimulus

Using a (pleasant) smell is an unconventional method, nonetheless, two papers report that olfactory stimuli can reduce cybersickness [92], [93]. They both discuss a variety of research that relates olfaction with nausea, but there is no clear explanation yet as to how and why pleasant smells help against cybersickness. Although there might be a link to research that shows that cognitive distractions reduce sickness. I will discuss this aspect more later in this chapter.

6.3.6 Galvanic Cutaneous Stimulation

According to Gálvez-Garcia, galvanic cutaneous stimulation (GCS) can improve balance which is one of the theorised factors of cybersickness [94]. Several studies found that tactile stimulation through GCS reduces sickness in a car or flight simulator [94]–[97].

6.3.7 Texture Complexity Reduction

Generally, as VR technology improves, cybersickness inducement is lowered [76]. However, this might not be the case for all technological advancements. The results of the study of Tsai et al. seem to suggest that a greater level of detail leads to a higher level of cybersickness [98]. They blurred textures depending on the importance of and the distance to the object and found that it improved sickness, albeit with only 12 participants. Nie et al. blurred non-salient content dynamically in real-time [98]. They used deep learning to develop a method for differentiating salient from non-salient content in real-time. Assuming that the eye's gaze is generally focused on salient content and thus the non-salient content is positioned in the PVF, the technique works similarly to reducing the FOV. The periphery will be blurred then, reducing motion signals that can cause sensory conflict.

Pouke et al. did not blur content but lowered the overall realism of the scene [100]. They found lower FMS scores for the low-realism condition compared to high-realism, but these results did not reach statistical significance.

6.3.8 Slow Deliberate Breathing

In their research, Stromberg et al. trained participants with a video to perform diaphragmatically (slow deliberate) breathing during their VR experience [101]. Participants that saw the training video were able to decrease their breathing pace significantly compared to the control group and reported a lower level of sickness.

6.3.9 Airflow

In the study of D'Amour et al. providing constant airflow using a fan helped in reducing cybersickness [102]. They explain that the airflow cools down the body, which helps against "real or apparent (i.e., motion sickness) poisoning" and it can provide more user comfort. Another theory they bring up is that airflow reduces sensory conflict by providing haptic/proprioceptive motion cues. They argue, however, that their experiment contradicts this as the airflow was constant no matter the visual motion and the perceived vection did not change because of the airflow. Thus, airflow seemed to not reduce sensory conflict. In another study, Paroz and Potter did not report a significant effect of the fan on cybersickness [103]. They argue, though, that this might have been a result of a low number of participants, weak fan, occasionally blocked airflow by the rotating chair, and including several participants who already had experience in VR.

6.3.10 White noise

Like GCS, white noise can improve balance as it amplifies the intensity of a weak signal, in this case, the vestibular signal [94]. Two separate experiments showed that white noise reduced sickness in a driving simulator [94], [95].

6.3.11 Head-Worn Haptic Feedback

Liu et al. developed a system with two motors, each with a little arm, that can give taps lightly on the user's head [104]. By giving taps that are synchronised with the virtual footsteps, cybersickness was reduced.

6.3.12 Movement Speed Smoothing

In the case of constant movement, there is no acceleration, thus no (expected) vestibular input. So, you could expect no sensory conflict either. It is rather during acceleration, for example when you start moving, that you could experience sensory conflict. Therefore, one could assume that experiences that include higher peaks of acceleration lead to more cybersickness than when movement is smoothened. Widdowson et al. put this assumption to the test by performing an experiment with three speed profiles (constant, ramp and polynomial), but they found no significant differences in cybersickness between the three profiles [106]. Conversely, Wang et al. managed to develop a system that provided smoothing that worked for reducing sickness [105]. Their system optimises the smoothing by reducing the total jerk (the rate at which the acceleration of the user changes).

Movement speed smoothing might provide additional benefits when used with the Virtualizer. First, when a person walks in real-life and they stop, their whole body does not come to a full-stop instantaneously. The inertia of the body causes the body to gradually come to a halt. Applying smoothing can simulate this physical behaviour that a user might also expect to happen in VR.

The other benefit is related to compensating incorrect walking movements. From personal experience and conversations with the team at Cyberith, I found that it can take some time to learn how to correctly walk in the Virtualizer. Consequently, the virtual movement can be in a stuttering manner. So, though the user might expect a constant forward motion, like normal walking, they experience rapid starting and stopping of the motion as shown by the upper graph in Figure 4. This could cause more cybersickness. By utilising smoothing, users do not come to a direct halt when the system does not correctly identify their walking pattern as can be seen in the lower graph of Figure 4. One downside of this smoothing is that motion might persist for a while after users have made a full, intended, stop. Therefore, it is important to adjust the smoothing to a factor that reduces stuttering significantly, but where the motion after a full stop matches expectations.

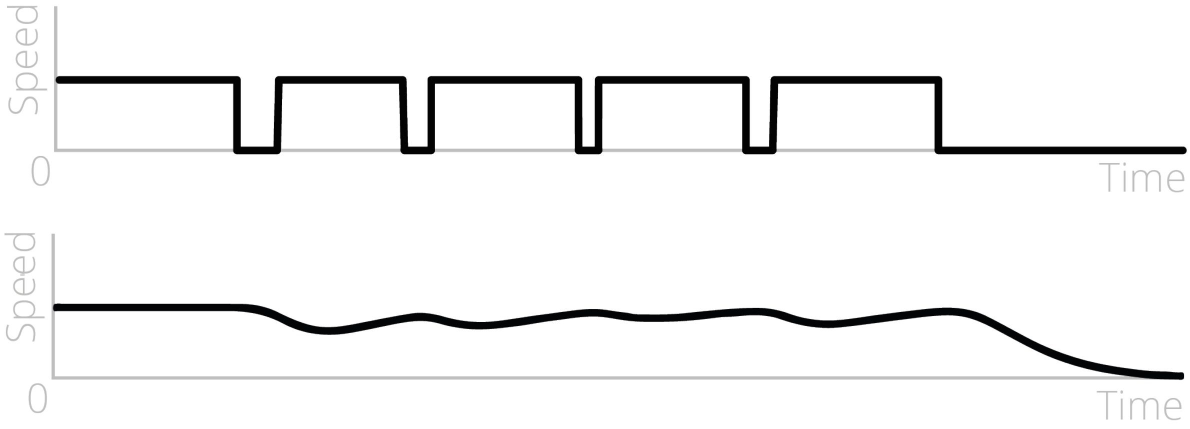

Figure 4: Walking Speed Without (upper graph) or With (lower graph) Smoothing

6.3.13 Virtual Body Representation

In the standard Virtualizer experience, your body is not visualised. So, when a user looks down or puts their arm in front of their face, they cannot see their body. This means that they can also not use their body to judge distances, positions and motions of the objects around them relative to their body. For children, the body is their tool to learn about the new world around them, also known as body-syntonic learning, which was introduced by Papert [118]. You could say VR is also kind of a new world and without a virtual body, users lose one of the tools to explore the rules of this new world. I hypothesize that the body can be used as a frame of reference and thus, like the rest-frame, decrease cybersickness. Wienrich et al. already found that only a virtual nose can work as a rest-frame and reduce cybersickness [28].

From the literature I reviewed, only the study of Zaidi and Male used a simulated body in one of the tested experiences [107]. They concluded that a virtual body helped to reduce cybersickness. They used a small sample size (N=15) and a non-psychometrically evaluated cybersickness questionnaire. Furthermore, every participant experienced all three conditions, but the simulated body condition was for every participant at the end as they did not shuffle the condition order. Thus, at least part of the reduction in cybersickness could have come from the adaptation effect which has exhibited itself in other studies as well [22]–[27]. The results are promising, but more research is required to see if a realistic avatar can reduce cybersickness.

6.3.14 Cognitive Distraction

For regular motion sickness, it has already been demonstrated by Bos that cognitively distracting participants can reduce sickness [119]. Consequently, it was posed as an explanation as to why pleasant music worked in reducing VIMS [120]. In a similar vein, it could also explain the results of the studies on olfactory stimuli [92], [93]. Zhou et al. sought to prove that cognitive distraction can mitigate cybersickness in VR [108]. They found a positive effect, but no statistical significance.

6.3.15 Artificial Speed Reduction Near Collision

In my personal experience, walking nearby a wall, without colliding, results in more sickness. This is in accordance with the study of Pouke et al. that found that participants reported high levels of discomfort when entering the building, thus when they are close to the walls [100]. Considering that being closer to the wall creates stronger visual cues, visual flow, I expect stronger vection. By reducing the speed near walls, the visual signals could decrease in intensity as well.

Another potential source of sickness could be the collision with walls or other virtual objects. When colliding with an object, the user is virtually immediately stopped, but physically they are still able to make walking movements on the Virtualizer. This creates a sensory conflict between the visual cues and the proprioceptive/haptic cues, possibly increasing cybersickness. A sudden stop also results in a large spike in visual deacceleration. This specific problem has not been covered in research yet, so there are also no suggested solutions as of now. The method I propose is to reduce the speed of the user in VR when they get closer to a collision. An artificial spring could increasingly reduce movement velocity as they get closer until they collide with the object and reach a speed of zero. This would be like smoothing the movement speed, but then dependent on the user's proximity to other objects. Slowing down near walls would then also reduce the visual flow.

6.4 Selection of the Reduction Methods to Evaluate

I have discussed 15 potential techniques to reduce cybersickness, but I could not test and/or implement them all within the scope of this thesis. Thus, I have had to choose what to include. In my opinion, it does not provide much academic or business value to test again certain methods which are already well established and/or have been tested successfully on many participants. The methods that I consider as sufficiently proven, due to the combined size of the samples that they have been successfully tested on, are FOV reduction, correct IPD and rest-frame.

Limiting the FOV is a flexible technique that could fit within all kinds of VR experiences, which makes it an attractive reduction technique. It would also be relatively easy to adjust to the user's specific preferences. Thus, it makes sense for VR experience developers to add FOV reduction as an option for users.

Correcting the IPD for every participant requires extra hardware to measure the IPD. This might be an extra hurdle for customers. Nevertheless, for my experiment, it was useful for limiting the effect of individual factors in the results. By measuring the IPD I made sure that the headset was set up correctly for every participant.

A rest-frame has been demonstrated to be a cheap and effective solution [28], [70], [71], [87], [88], but a major drawback is that subtle rest-frames should fit with the rest of the VE. For example, a cockpit makes sense for when you are flying, but not for when you are just walking around in the forest. It is not doable to design a rest-frame for every existing Virtualizer experience. So, I want to leave that to the developer of a specific experience. The one thing that is consistent with every experience is the presence of the human body. Cyberith has already developed a system with two extra sensors (one on every foot) that can realistically visualise the user's body. Using a virtual body representation to reduce cybersickness has not received much attention in research yet, so it is academically interesting as well to see if a virtual body can mitigate cybersickness.

Even though movement speed has been shown to affect cybersickness on a fair number of participants [38], [89], some studies did not find a significant effect [90], [91]. Thus, there is value in testing it on more participants. Furthermore, these studies did not test it with the Virtualizer or a similar locomotion device. So, the context is a bit different from the one I tested this method in. As I mentioned before, there might be an additional conflict between the proprioceptive and visual systems. Therefore, results in a new experiment with the Virtualizer could differ compared to the previous studies with movement speeds. In my own experience with the Virtualizer, the movement speed mattered significantly for the feeling of cybersickness. So, based on that my expectation is that in a user experiment making the movement speed realistic reduces cybersickness.

Movement speed smoothing is a solution for which it is still unclear if it can work or not, with two studies contradicting each other [105], [106]. Furthermore, it functions independently from the specific VE, which makes it flexible for implementation. Therefore, I chose to test this method. Assuming that smoothing successfully reduces cybersickness, it also provides a base for the method of reducing the speed when nearing collision. Both methods work similarly as they are trying to reduce the (de)acceleration spikes.

The outcomes of the study on non-salient content blurring are promising, but implementation is more complicated as it requires a saliency detection model using machine learning [99]. I lack the proper experience to implement that within the timeframe of this thesis. The implementation in the other two studies that reduce the texture complexity are simpler, but adjustments would have to be applied manually for every different experience by the developer.

The remaining methods were less suitable for testing and implementation for a variety of reasons. Using olfactory stimuli, galvanic cutaneous stimulation, airflow or head-worn haptic feedback requires extra hardware that does not provide any other added value for the Virtualizer. Slow deliberate breathing needs training, which could result in an entry barrier for new users. Lastly, white noise and cognitive distractions could interfere with the intended experience of the developer or customer.

In conclusion, I decided to test the virtual body representation, movement speed and movement speed smoothing. From the tested methods I implemented those that were statistically significant in mitigating cybersickness into a cybersickness reduction system. Before every test, I measured the IPD of the participants and matched the IPD of the HMD with that of the participant.

7 User Study

In the following chapter, I discuss the experimental setup and the pilot experiment. The main goal of the user study was to find out if any of the cybersickness reduction methods selected in the previous chapter have a significant effect on the level of cybersickness. Additionally, this experiment sought to find if other sickness-inducing factors exhibit themselves while using the Virtualizer with VR. Lastly, the study tested the suitability of using the headset for measuring cybersickness indicated by postural sway. Following faculty requirements of the partner university, this experiment was reviewed by the Ethics Committee Computer & Information Science of the University of Twente. The review can be found in 1.1.1.1.1.1Appendix A.

7.1 Experiment Design

The three parameters, movement speed, movement smoothing and the avatar, were tested in four sessions. In the control condition, the parameters were all set to the configuration that was hypothesised to induce the least amount of sickness. This meant a movement speed multiplier of 0.5, a movement speed smoothing factor of 20, and the avatar turned on. Each other condition had one parameter changed that would according to the hypothesises, discussed further down this section, lead to more sickness. So, either the movement speed multiplier was increased to 1.0, the smoothing turned off or there was no avatar.

I chose a within-subject setup, to have the possibility to compare different conditions on the same participants. All conditions were performed in the same experiment session with 10-minute breaks in-between. A major issue, however, is that the cybersickness induced by previous conditions also could have affected the results of the following conditions. Even with a break in-between, cybersickness can still sustain for a longer period [22], thus still play a part in the following conditions. Additionally, there was the chance for the adaptation effect. For example, Fernandes and Feiner found that participants who started with the condition of the FOV reduction also reported less cybersickness in the control condition that followed the next day [29]. So, this result suggests that a cybersickness reducing technique can be used to let users get used to VR and eventually be turned off. To minimise the order effect, I shuffled the condition order with a Latin square design (Table 2).

Table 2: Latin Square Experiment Design

Part. group \ Session	1	2	3	4
1	High Speed	Control	No Avatar	No Smoothing
2	No Avatar	No Smoothing	High Speed	Control
3	Control	No Avatar	No Smoothing	High Speed
4	No Smoothing	High Speed	Control	No Avatar

The hypothesises that were tested with this experiment are as follows:

- H1: Removing the avatar increases the cybersickness reported by participants compared to the control condition.
- H2: Heightening the speed multiplier from 0.5 to 1 increases the cybersickness reported by participants compared to the control condition.
- H3: Removing movement speed smoothing increases the cybersickness reported by participants compared to the control condition.

7.2 Procedure

To minimize confounding factors, I asked participants not to drink excessively within the 24 hours before the experiment, to make sure they had a good sleep and not to have a big meal right before the test. At the start, participants had to answer some questions on demographics and their history of motion sickness. Additionally, I measured their interpupillary distance to avoid sickness because of non-fitting VR glasses. After that, participants were introduced to VR and the Virtualizer in a short training session. In the training session, I told them that they cannot run or speed walk during the experience. This was to diminish the chance that people that are new to the Virtualizer fall. Also, requesting everybody to only walk ensured to keep the movement speed more consistent between participants and sessions. They were not told of the specific difference between the conditions. This was to avoid creating demand characteristics. Participants might have started to expect less sickness in the control condition and thus unconsciously alter their answers.

Before starting every condition and after each session, participants had to stand still and focus their gaze on a small red square in front of them. Each maze session lasted eight minutes, whereas the breaks lasted around 10 minutes. While in VR, the participant was asked every minute their level of sickness between zero and 20. Before and after each condition, participants had to fill in the CSQ and the Spatial Presence Experience Scale (SPES) [120]. During the break, I had a non-structured interview with the participant. At the end of the experiment, participants were also asked about their subjective experiences.

In VR, the participants were stuck in a warehouse maze (Figure 5). From the pilot testing with experts, I had found that finding your way within the maze can be a bit too difficult. Therefore, I added a minimap that is blank but is filled in as a user explores more areas (Figure 6). Also, I added a battery system to the minimap to make the experience more interactive and appealing to play for 32 minutes. The minimap had a battery life of a 100 seconds. If the minimap would run out of battery life, the minimap turned black with a text telling the user to pick up a battery. To keep the minimap alive, participants had to pick up batteries with one of their controllers along the way. When participants finished a maze, they continued with a new maze.

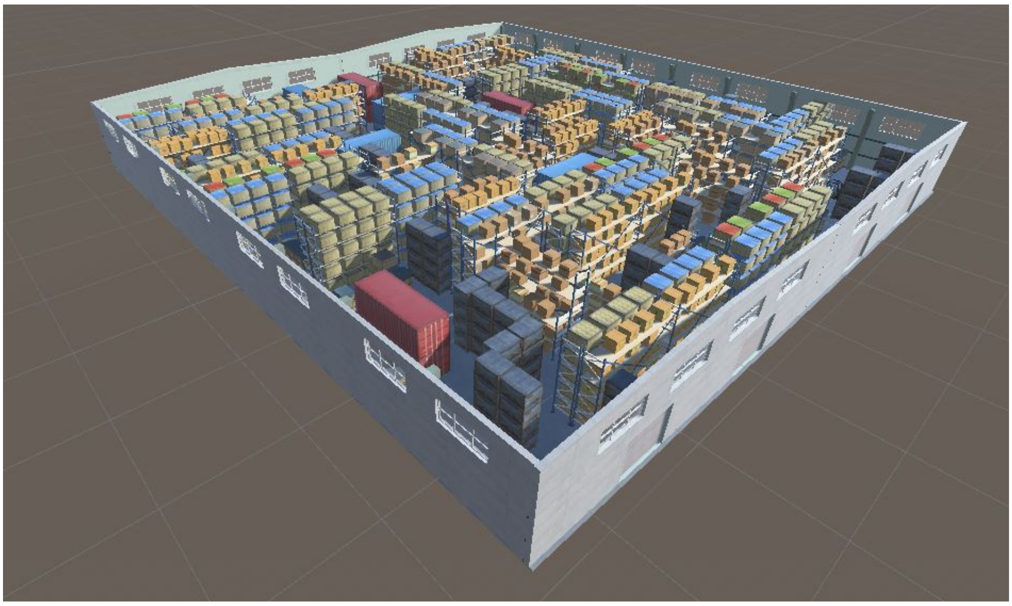

Figure 5: Maze

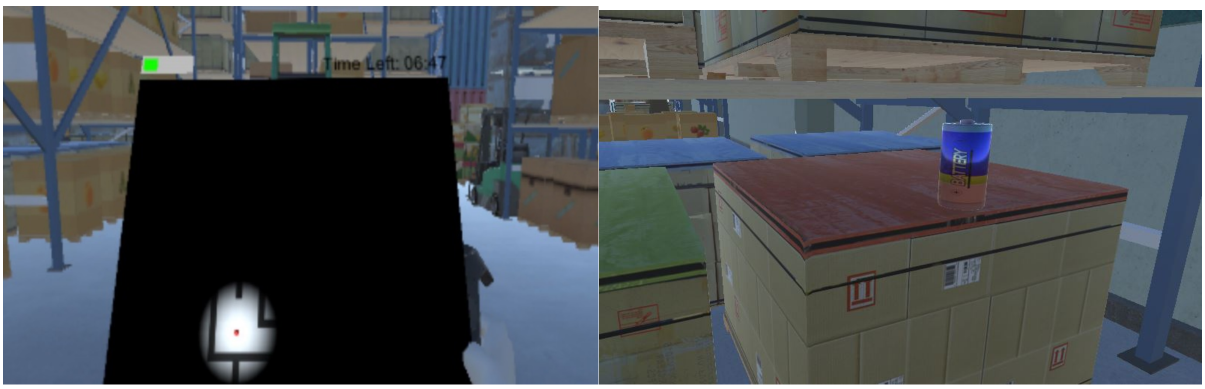

Figure 6: Minimap (left) and Battery (right)

There was a risk that participants would get too sick. Thus, there needed to be a protocol to avoid that people got unwantedly (too) sick. First, participants were informed of the risks when they were recruited and before the experiment commenced. Also, they were told that they can stop the experiment at any moment without repercussion. During the experiment, their level of sickness was monitored with the FMS [17]. If they reached the threshold score of 10, they were asked if they wished to discontinue the experiment. If the score reached 15, the experiment was immediately terminated. These thresholds were based on the suggestions of Hutton et al. who found that a termination threshold of 20 was too high [121]. Experiments that were not discontinued, took generally between two and a half and three hours per participant.

7.3 Materials

All experiments were conducted with the HTC Vive Pro and Vive controllers with participants walking on the Virtualizer ELITE 2. As walking on the Virtualizer is more exhausting than normal walking, a small ventilator was always turned on to provide a bit of cooling for participants. The windows were also opened to have better air circulation.

By adding some code to the Cyberith SDK, I could change the movement speed and smoothing in the Unity project in which the VR experience was built. As the actual movement speed of a Virtualizer user is based on the speed that they are walking, what was changed in the code was the speed multiplier rather than the actual speed. Determining what was a realistic multiplier was done by looking at what multiplier the feet of the avatar were not moving in relation to the virtual floor while they were sliding. In other words, the virtual floor was moving longitudinally at the same speed as the feet making it seem like your feet were stationary. In real walking, your feet would also be stationary when they are placed on the ground, and you push your body forwards.

The smoothing was also implemented as a factor. It took a part of the previous speed value and added that to the current speed value. The movement speed calculation with smoothing was as follows:

Movement Speed Filter Factor: $F = 1 - 1/x$

Movement Speed: $V_{new} = (V_{old} * F) + (V_{virt} * (1 - F)$

In the first equation x is the smoothing factor. This is then used in the second equation in which the previous movement speed is V_{old} and the new movement speed as measured by the Virtualizer is V_{virt}. If the smoothing factor is one, it will result in zero smoothing. The smoothing factor of 20 I defined by finding the smallest value that could still filter incorrect feet movements. I tested this by simulating incorrect movements myself and trying out different smoothing values. After that, I validated the chosen value of 20 by doing the same test of incorrect movements with two employees at Cyberith.

The virtual body I added by implementing the “IK System” that was in development by Cyberith (Figure 7). This system uses inverse kinematics to realistically portray a human body based on the locations of the head (provided by the HMD), the hands (provided by the Vive controllers), the height of the waist (provided by the Virtualizer) and the feet (provided by HTC Vive trackers placed on the feet). The IK System was based on the Final IK asset developed by RootMotion. I built the VE using the “Big Warehouse Pack”, “Survival Game Tools” and “Free Trees” assets from the Unity Asset Store[3].

Figure 7: Avatar Hands

[3] https://assetstore.unity.com

7.4 Information Gathered

Participants answered several questionnaires. First, I recorded their age and sex as that has been correlated before with cybersickness [36], [102], [111]–[113]. I also chose to use the MSSQ instead of the VIMSSQ, to gather more general data about participants' susceptibility to motion sickness instead of sickness induced only by screens. Before and after each condition, participants had to answer the CSQ. By asking before each session, I had a baseline for every session. I decided on the CSQ instead of the SSQ as it had shown better validity according to Sevinc and Berkman [16] and it did not include the symptoms of fatigue and sweating. Walking on the Virtualizer tends to be more tiring than normal walking. Thus, the fatigue and sweating were likely to come from walking and not necessarily from cybersickness.

After each condition, there was also the SPES questionnaire. I chose to also record the feeling of presence, as it has been correlated with cybersickness before [113], [122]. There are several other similar questionnaires, for example, the Presence Questionnaire by Witmer et al. [123] or the Igroup Presence Questionnaire [124]. However, these are considerably longer. Thus, to avoid participants rushing through the questionnaires due to their length, I chose the shorter SPES that only consists of eight items. All the comments made by participants during their time in the maze were noted down if they related to their experience or the experiment. In the breaks, participants were interviewed about their experiences and specific comments they made. At the end of the experiment, participants were asked for general open comments, to choose which session they preferred and to rank the four conditions based on what they perceived as the most or least sickness-inducing. All questionnaires can be found in 1.1.1.1.1.1Appendix B.

During the experience, I asked participants every minute to verbally rate their level of sickness from zero, no sickness, to 20, very sick. At the same time, the positional (x, y, z) and rotational (pitch, yaw, roll) data of the HMD and feet trackers were recorded. The positional and rotational data were relative to the player position and rotation. At the beginning and the end of each condition, participants had to stare at a small red square in front of them for 30 seconds while standing still. These samples could be compared more easily than the data recorded while walking, as the pose was more consistent when standing still. I decided to not measure the physiological state, as most measures (e.g., heart rate, galvanic skin response, respiration) might have gotten distorted by the exercising nature of the experiment. Moreover, the experiment setup would have been complicated more by the hardware, making the experiment lengthier than it already was.

To evaluate the hypothesises, my primary measure was the CSQ. The data from the FMS, thematic analysis of the comments, the headset, SPES, participant characteristics (age, sex and MSSQ), and post-experiment questionnaire were also analysed for other factors and to validate the CSQ results. Other data was recorded for future analyses.

7.5 Participants

34 participants finished the whole experiment, whereas five others started it, but dropped out before finishing the last maze due to cybersickness. For this experiment, I recruited participants that had little or no experience in VR. This was to avoid having participants that are already used to VR and therefore do not become sick at all no matter the condition. Almost half of the participants, 19, experienced VR only once, whereas 12 used it two to five times, seven participants never and one participant did VR six to 10 times.

On the other side, it was also important to not have participants that are too susceptible to sickness, as they are more likely to not finish the experiment and it puts them in unnecessary discomfort. Thus, only participants that did not have a self-diagnosed history of severe motion sickness were recruited.

Of the 39 participants, 13 were female, 25 were male and one participant did not disclose their sex. The age ranged from 17 to 52 with a mean age of 29.67 and standard deviation of 8.04. Participants were sampled based on convenience. Most participants were recruited by advertising a signup form in Facebook groups and on Reddit, whereas the remainder were friends and family who were not closely connected to the project. Participants received the information brochure beforehand and had to sign an informed consent form at the start after receiving the briefing. These documents can be found in 1.1.1.1.1.1Appendix C.

7.6 Pilot test

To find any problems or potential improvements with the experiment protocol and to check if the virtual body representation was accurate, a pilot test was performed with two experts (employees of Cyberith) and four novice Virtualizer users. The experts focused on the technical implementation and evaluating the protocol, whereas the novice users followed the protocol and answered an additional pilot test questionnaire. This questionnaire surveyed the participants about the accuracy of the virtual body, the difficulty of the game and the duration.

There were two main takeaways from the expert pilots. First, during the pilot testing, it became clear that making the experiment task too mundane and constant could have made it less motivating for participants to finish the whole experiment. In an early version, a user could only just walk through a maze. Therefore, I added a minimap with a battery life that decays in 100 seconds. To avoid that the minimap would run out of battery life, users could pick up batteries spread around in the maze with their controllers. This made the experience more interactive and added a small recurring goal, keeping the minimap alive, which was easier to complete than the goal of finding the end of the maze. During testing, it was also found that the maze could be disorienting. So, the minimap helped in making it easier for users to find their way. Besides, it gave participants immediate feedback on their progress.

The other takeaway was that of ensuring that the technical procedure and implementation were as much as possible without sickness-inducing factors. For example, a low framerate could be cybersickness inducing, so the expert pilot also looked at what could be done to improve the performance of the VR scene. Another factor could be that of the (in)correct attachment of the Virtualizer and the HMD to the user. If the Virtualizer harness is not put on correctly, the forward direction of the participant might not be perfectly aligned with the forward direction of the Virtualizer. This causes the movement to be off-centre. If the HMD is put on too low or too high, the user's view will be blurry. So, extra attention was put to these factors when assisting participants.

The participants that tested the full experiment consisted of one female and three male participants. One participant had already experienced VR often (more than 10 times), whereas the others were relatively new to VR, and this showed in the results. The experienced participant did not exhibit any sickness symptoms during or after the experience, except for sweating and fatigue which were related to the exercise of walking in the Virtualizer. The other participants did experience significant sickness in all conditions. Although neither participant felt too sick that they wished to stop, it showed still that there was a risk of participants getting too sick. Thus, I decided to take some measures to reduce the sickness-inducing factor of the experiment. First, I reduced the time of each VR session from 10 minutes to eight. By asking participants every minute how sick they were feeling, I found that for the first three to five minutes the level of sickness was mostly stable. After that sickness started to increase for the two participants that got sick.

The other measure that I took was to flip the parameters that changed per condition. Before, the control condition had all the parameters set to the setting that was hypothesised to be more sickness-inducing: high speed, no smoothing, and no avatar. Every other condition had one parameter changed that would be hypothetically less sickening: realistic speed, smoothing and visible avatar. Assuming that at least one of the parameters affects cybersickness, I decided to make the control the hypothetically least sickness-inducing condition, realistic speed, smoothing and visible avatar, whereas the other conditions only had one parameter set to a more sickening level.

After these pilots, it also became clear that the batteries lasted too short, which lead to frustration. In two of the experiments, there was a bug with the lighting, causing the batteries to be very dark and hard to find. In the other experiment, this was fixed making them much easier to find. As the movement speed was going to be lower on average in the real experiment, I chose to put down more batteries in the environment and make them last longer.

From the evaluations of the virtual body, it can be concluded that participants perceived it to be almost perfectly aligned with the real body. Participants were asked to rate how well each body part aligned from not at all to perfectly. The results showed that the arms performed slightly better than the legs and the torso. The legs might have not felt completely accurate as it could happen that the virtual knees slightly bent while standing up straight. The torso was also commented as being too large in the chest area.

8 Experiment Results

There were several objective and subjective measurement methods employed during the experiment. For the analysis, however, I will only focus on a part of those measurements. This chapter discusses the results of the quantitative data and thematic analysis of the comments.

8.1 Quantitative Data

For the quantitative data, I analysed the CSQ, FMS, headset data, SPES and participant characteristics.

8.1.1 Cybersickness Questionnaire

The main measure of cybersickness in this study was the CSQ. The CSQ does not result in one total score like the SSQ. However, the ratings of the nine symptoms result in two scores: dizziness and difficulty to focus. Thus, for this analysis, two scores were calculated and analysed. As the questionnaire is filled in before and after each session, I subtracted the scores that resulted from the pre-session questionnaire from the scores of the post-session questionnaire. From now on, I will refer to the scores as ΔDizzy (difference in dizziness) and ΔFocus (difference in difficulty to focus).

The VR experience was sickening for a substantial number of people as they could not finish the experiment due to getting too motion sick. In the end, five participants had to stop due to cybersickness. Nevertheless, I observed from the total CSQ ratings that, on average, those participants that did make it to the end, did not report high levels of cybersickness. As can be seen in Figure 8, most ratings of the symptoms in the post-session questionnaire, 871 out of 1224, were “None”, whereas 303 were “Slight”, 47 were “Moderate” and 3 were “Severe”.

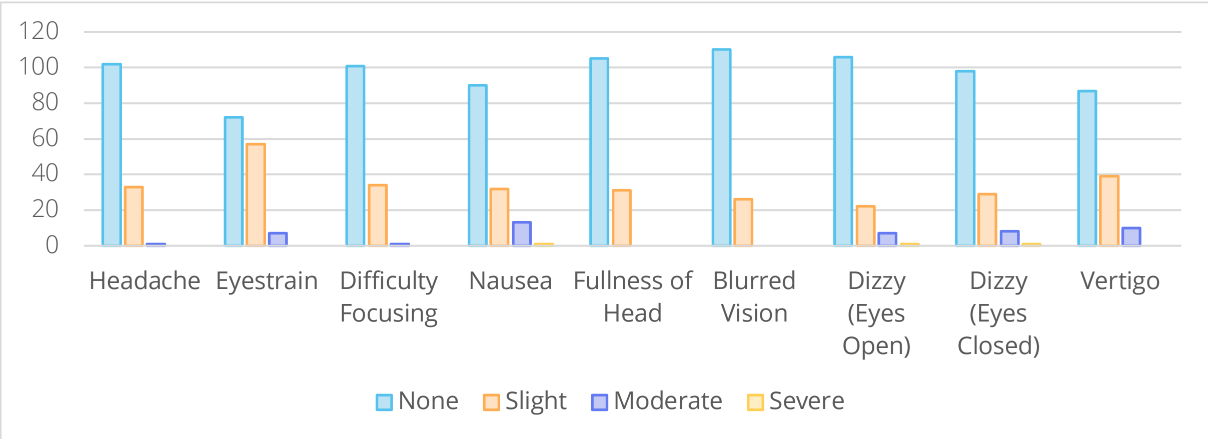

Figure 8: Post-Session Symptom Rating Occurrence

CSQ data of participants that did not finish the experiment were discarded. The data of the participants that finished the experiment showed a clear difference between some conditions for the ΔDizzy score, but less so for the ΔFocus score. The data has been plotted in Figure 9 and Figure 10. The means and the standard deviations can be found in Table 3. The sessions that had double the movement speed compared to the other sessions, had the most participants reporting higher levels of sickness, compared to the control condition. On the other hand, removing the avatar did not seem to have a noticeable effect according to the CSQ results. Due to the large number of people experiencing little or no sickness at all, the medians of all conditions except the high speed one were around zero.

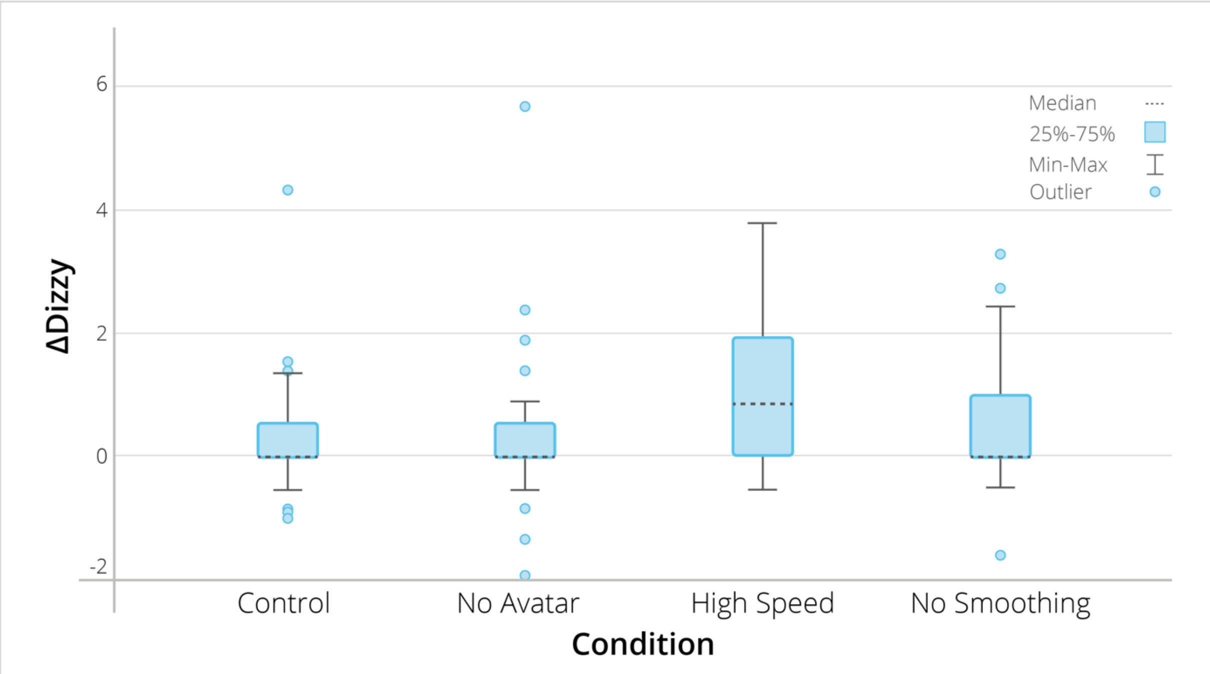

Figure 9: Boxplot ΔDizzy Scores

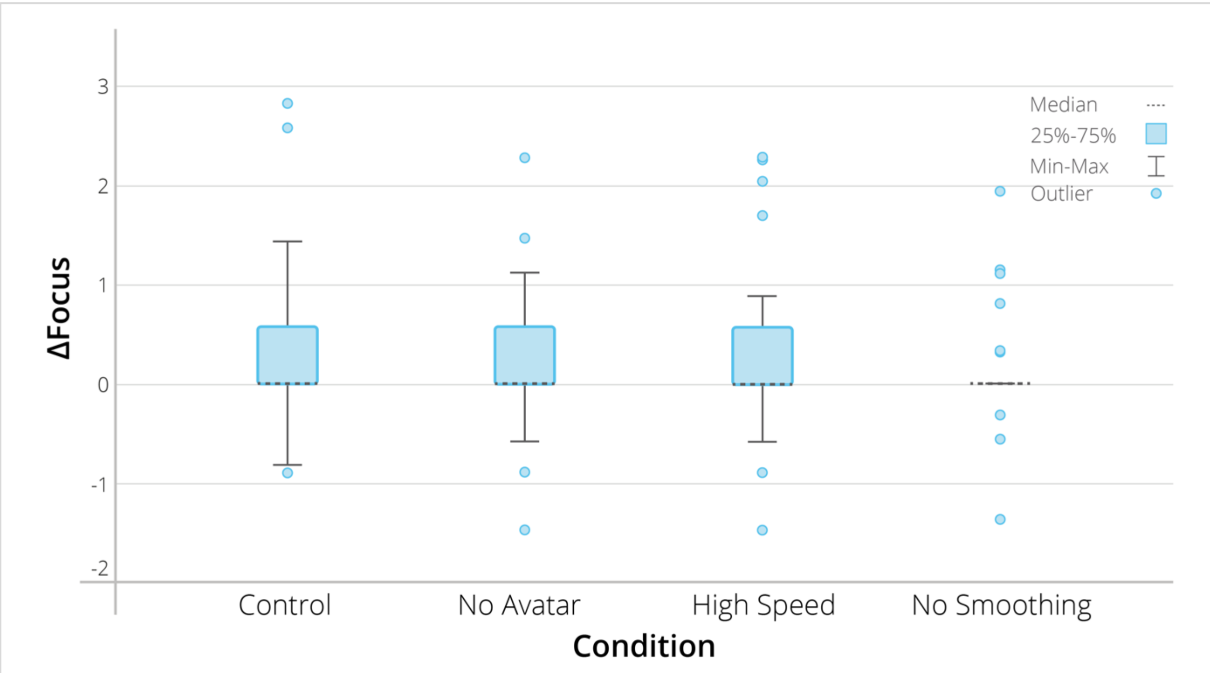

Figure 10: Boxplot ΔFocus Scores

Table 3: CSQ Mean and Standard Deviation per Condition

Condition	**ΔDizzy Mean**	**ΔDizzy Standard Deviation**	**ΔFocus Mean**	**ΔFocus Standard Deviation**
Control	0.2247	0.9723	0.1906	0.8359
No Avatar	0.3279	1.2588	0.1812	0.7327
High Speed	1.0194	1.2598	0.3506	0.8914
No Smoothing	0.6824	1.1780	0.1350	0.5538

Participants were also asked every minute in the maze how sick they were feeling from zero to 20 (FMS). These scores showed a similar trend as the ΔDizzy scores. The sessions were relatively close to each other. So, it was possible for participants to still feel sick from the previous session after their break finished. Thus, for the analysis, I subtracted the first score of the session, the start of the first minute, from the last reported score of that session. This resulted in a ΔFMS score (See Figure 11 and Table 4). For the statistical analysis, which is discussed in 8.1.4, I also included the data of the last FMS score reported. This data is referred to as lastFMS.

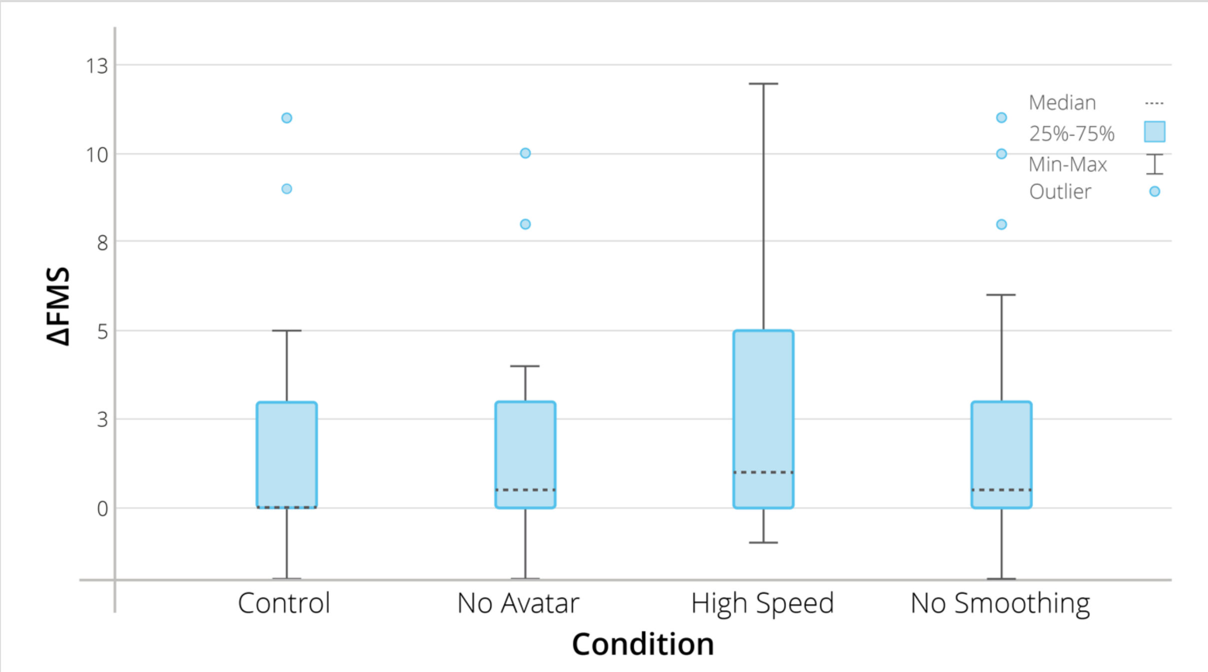

Figure 11: Boxplot ΔFMS Scores

Table 4: ΔFMS Mean and Standard Deviation per Condition

Condition	ΔFMS Mean	ΔFMS Standard Deviation
Control	1.68	2.815
No Avatar	1.44	2.427
High Speed	2.85	3.517
No Smoothing	2.00	3.065

The average CSQ scores per session did not differ as much as the differences between the conditions. The means and standard deviations of the sessions can be found in

Table 5.

Table 5: CSQ Mean and Standard Deviation per Session

Session	ΔDizzy Mean	ΔDizzy Standard Deviation	ΔFocus Mean	ΔFocus Standard Deviation
1	0.6935	1.3800	0.2144	0.7493
2	0.4397	1.0979	0.2756	0.7855
3	0.5156	1.1507	0.1615	0.6993
4	0.6056	1.1990	0.2059	0. 8306

8.1.2 Head Dispersion

Before and after each session, participants had to focus their gaze on a red square in front of them. During this task, the positional and rotational data of the headset was recorded per frame. For the analysis, I wrote a Python script that collected the data, calculated the variance and max of both the measurement before and after the session and subtracted the first variance and max value. A high variance should mean that the participant moved a lot, also known as head dispersion. The max data was also included to the statistical analysis discussed in 8.1.4. as it might be that participants that were more unstable moved further from the centre. By subtracting the pre-session values from the post-session values, I could evaluate if the amount of change in head dispersion is higher or lower depending on the condition. The Python script used for data processing can be found in 0.

The data of the participants who stopped during one of the sessions or the measurements were discarded. Another participant's data was removed from the dataset as he looked completely to the side while doing one of the measurements. This left the analysis with the data of 32 participants. The first 450 frames, approximately five seconds, were removed to take away any movement that was a result of starting the measurement with their controller. In Unity, rotations only go from zero to 360 in value. This means that even though in the measurement the values 359 and one were only 2 degrees apart, the calculated variance is very high. Thus, I subtracted 360 from all data points that had a value above 180, so that the data was more continuous and distributed around zero. The means of the positional and rotational headset variance can be found in Figure 12, Figure 13 and Table 6. The standard deviations are summarised in Table 7. The unit of the positional numbers is in meters, whereas the rotational ones are in degrees.

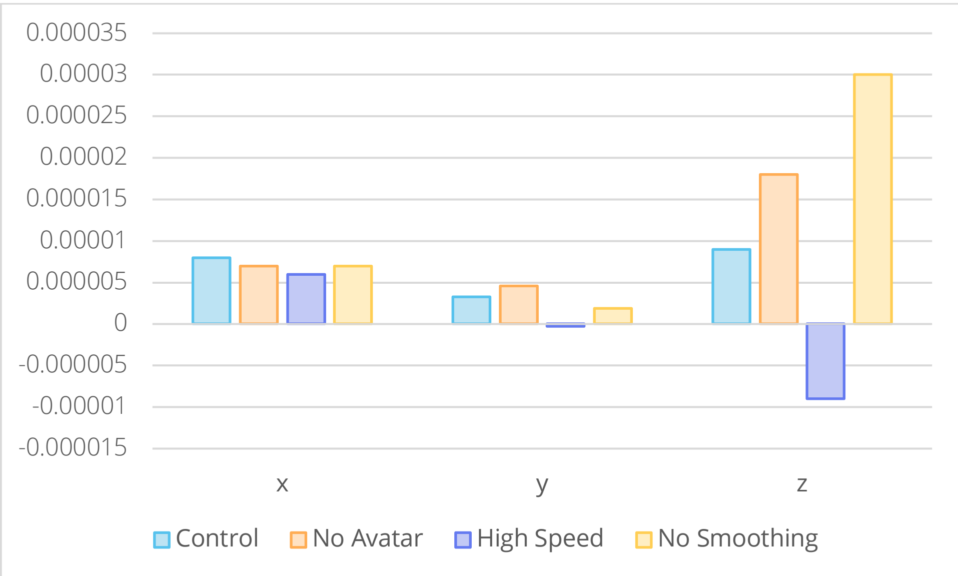

Figure 12: Positional Headset Variance Means per Condition

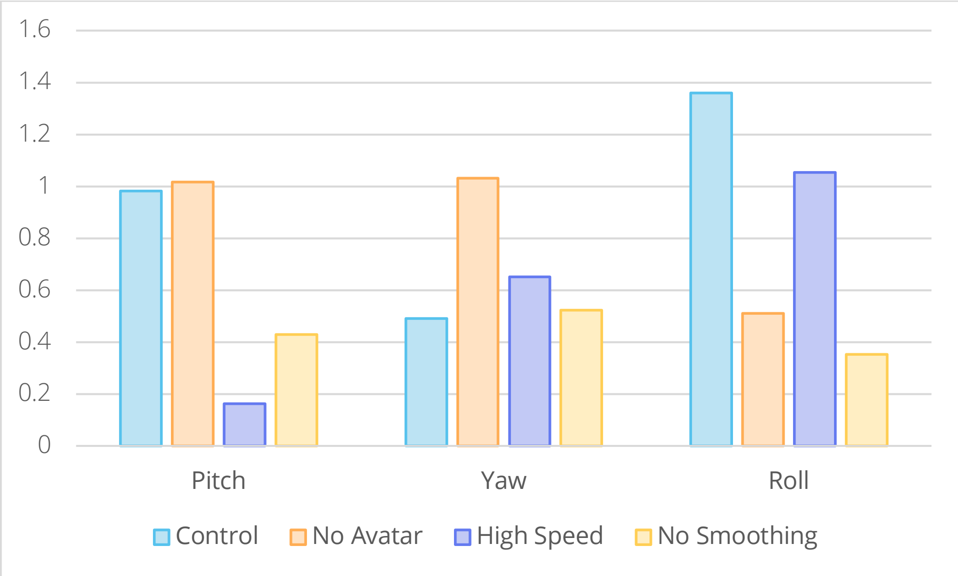

Figure 13: Rotational Headset Variance Means per Condition

Table 6: Positional and Rotational Headset Variance Means per Condition

Condition	x	y	z	Pitch	Yaw	Roll
Control	0.000008	3.279698e-06	0.000009	0.981935	0.491071	1.358531
No Avatar	0.000007	4.574297e-06	0.000018	1.017020	1.032384	0.511357
High Speed	0.000006	-2.829466e-07	-0.000009	0.162481	0.650876	1.052933
No Smoothing	0.000007	1.920265e-06	0.000030	0.428625	0.522248	0.352143

Table 7: Positional and Rotational Headset Variance Standard Deviations per Condition

Condition	x	y	z	Pitch	Yaw	Roll
Control	0.000015	0.000010	0.000033	2.825909	0.999579	5.712235
No Avatar	0.000020	0.000013	0.000048	2.575909	3.713860	1.529223
High Speed	0.000043	0.000007	0.000078	1.764715	4.067367	5.159091
No Smoothing	0.000013	0.000007	0.000078	2.151687	1.280255	1.012030

The study of Rebenitsch and Quinby found that the variance of the headset on the x- and y-axis, and the roll had a statistically significant effect on cybersickness in an experiment that was not on a treadmill [7]. However, in the case of this experiment none of the conditions, when taking the x, y or roll parameter, seemed to show a clear effect on variance. While analysing the boxplots of the x, y and roll variance (see Figure 14, Figure 15, and Figure 16), I found that there were some extreme outliers, especially for the roll. These could have come from participants that also looked away from the red square for a short while. Therefore, I tried to filter the data by removing data points that were above or below a certain threshold and the data points in a range around it. However, after trying several different thresholds and removal ranges, I found that my method of filtering did not improve the data. I did not manage to properly remove extreme outliers without lowering the variance to an insignificant level.

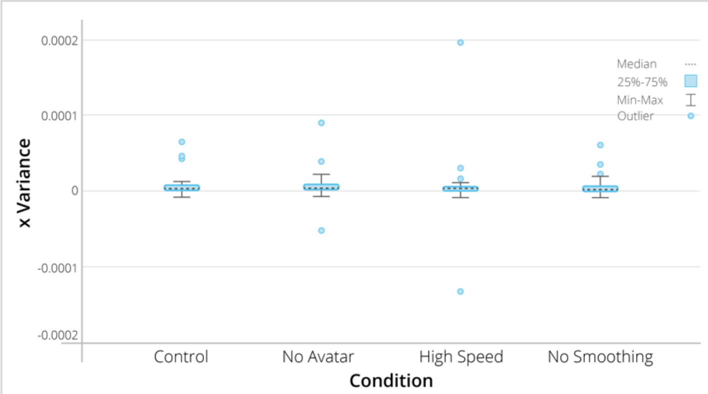

*Figure 14: Boxplot x Variance * Condition*

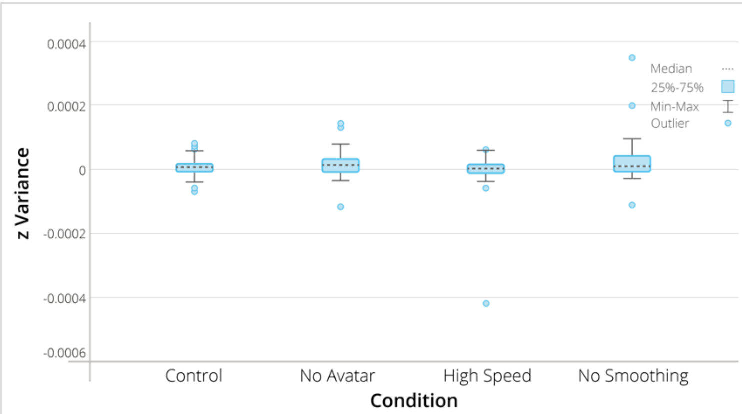

*Figure 15: Boxplot z Variance * Condition*

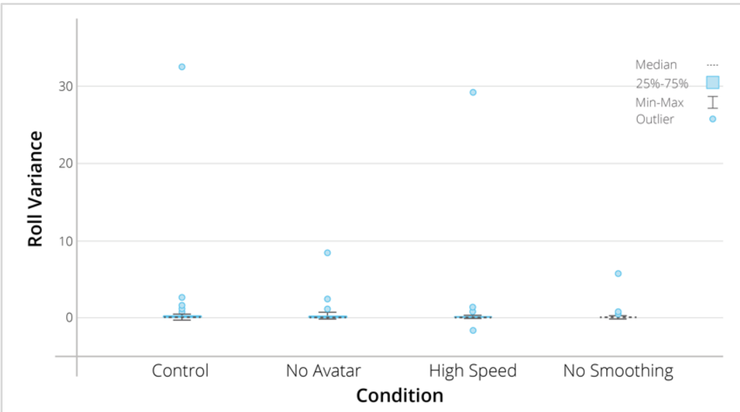

*Figure 16: Boxplot Roll Variance * Condition*

8.1.3 SPES

After every session, participants did not only fill in the CSQ, but also the SPES questionnaire. The results of the SPES questionnaire give indicate how high the feeling of presence was for participants. The results are summarised in

Table 8. The no avatar condition reached the highest SPES score with 30.6, whereas the control condition had the lowest score with 28.9.

Table 8: SPES Statistics Summary

Condition	SPES Mean	SPES Standard Deviation
Control	28.9118	1.03621
No Avatar	30.6176	0.89165
High Speed	29.9412	1.06051
No Smoothing	30.1471	0.89675

8.1.4 Statistical Analysis

The ΔDizzy and ΔFocus data were tested on normality with the Kolmogorov-Smirnov and the Shapiro-Wilk tests. Both tests showed that the data was significantly different from a normal distribution. Thus, a statistical test that required the data to be normally distributed, e.g., a paired-sample t-test, could not be used. Therefore, an ANOVA was performed on a linear mixed effect model having the response variables (ΔDizzy, ΔFocus, SPES, ΔFMS, lastFMS age, sex, VR experience, MSSQ and variance and max data of the headset) and condition as fixed factors, and subject as a random factor. Regarding the analysis on ΔDizzy, a significant main effect was found for factor condition ($F(3,99) = 5.32$, $p < 0.01$). Post hoc tests were performed on the fitted model using pairwise comparisons adjusted with the Tukey correction. The high speed condition was found to have a higher value of ΔDizzy compared to control ($p < 0.01$) and no avatar ($p < 0.05$). Regarding the analysis on ΔFMS, a significant main effect was found for factor condition ($F(3,99) = 3.57$, $p < 0.05$). Post hoc tests were performed on the fitted model using pairwise comparisons adjusted with the Tukey correction. The high speed condition was found to have a higher value of ΔFMS compared to the control ($p < 0.05$) and no avatar conditions ($p < 0.05$). Regarding the analysis on lastFMS, a significant main effect was found for factor condition ($F(3,99) = 3.28$, $p < 0.05$). Post hoc tests were performed on the fitted model using pairwise comparisons adjusted with the Tukey correction. Condition high speed was found to have a higher value of lastFMS compared to the control ($p < 0.05$) and no avatar condition ($p < 0.05$).

8.2 Thematic Analysis Comments

Getting the CSQ scores showed which conditions induced more sickness, but it did not provide the full picture. Motion sickness in VR can depend on many different factors. Therefore, it was important to also analyse what participants were saying during the experiment. It provided extra support to the CSQ results, but also added new insights on other sickness-inducing factors that were not specifically targeted in this research.

All the verbal comments made by participants were collected in a list that also included the session, condition, and minute in which each comment was made. After that, comments were classified with one or more keywords that defined more general themes. The final list consisted of 587 quotes.

8.2.1 General Sickness

The most common topic for comments was sickness. From the 587 quotes, 142 (24,2%) were related to sickness. By counting the number of times participants commented about their sickness increasing or decreasing and in which condition (Figure 17), I could observe similar results to the CSQ results. Participants discussed most often an increase in sickness when the speed was high (35 times), as compared to the other conditions (control 23 times, no avatar 22 times, no smoothing 25 times). On the other hand, the control and no avatar condition saw the most comments regarding the sickness going down (16 and 13 times, respectively). Participants were mainly talking about symptoms they were experiencing at that moment or aspects which were causing sickness. For instance, P36 told me about the high speed session, “It was probably the worst of them all. I felt like all the symptoms doubled, I don't know why. It's weird that it hits you as soon as it starts. My vision started to get blurry and my tummy started feeling strange”. Six participants also mentioned that during the break specifically, their sickness went up. For example, P24 said, “I got nauseous, but after the game, not during the game”.

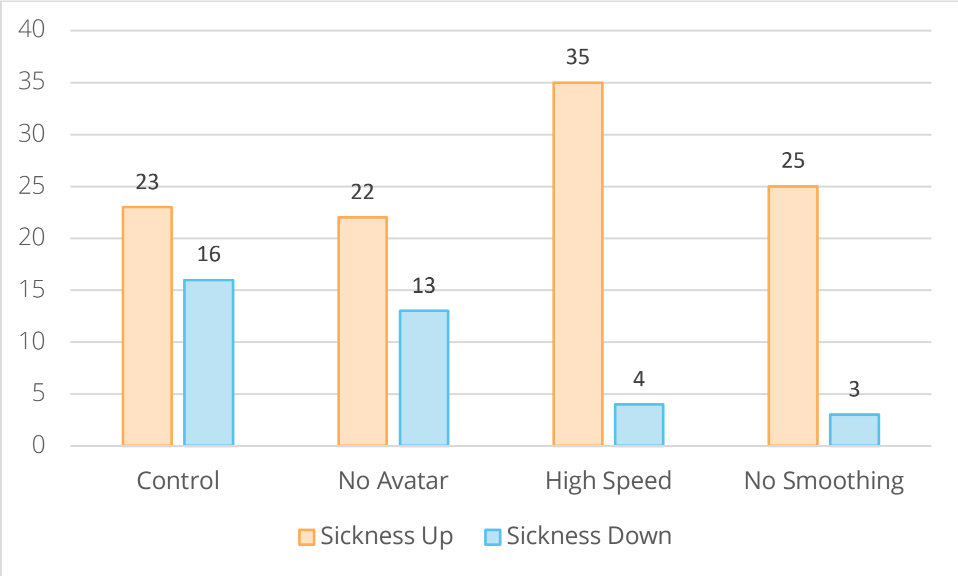

Figure 17: Comments About Sickness

8.2.2 Movement Speed

The movement speed was the most talked-about parameter with a total of 108 comments (18,7%). Eleven participants noticed that a higher speed made them sicker and they voiced this: "The faster movement feels worse" (P11). A few participants even started to regulate their speed and started walking slower. For example, P36 said in one of the breaks "When I tried to calm down and walk slower the symptoms lessen a bit". Although the higher speed was causing more cybersickness to a part of the participants, it was also perceived to be more enjoyable: "I could walk less fast. This was annoying. The other one [high speed session] was better, but it did make me less dizzy now" (P38). Of the participants that talked about the speed, 21 perceived the realistic speed to be too slow and even unrealistic: "I had the impression I was working really hard to move and it was not letting me. I felt like the mafia gave me those concrete shoes they give you right before they throw you in the sea" (P27). Only one participant mentioned that the lower speed was more realistic compared to the high speed, whereas two others did comment on the high speed being unrealistically fast.

8.2.3 Turning

Another aspect that caused difficulties and induced sickness was making turns in VR. 66 comments were regarding this theme. For some, like P5, it was even the worst part of the experience: "I feel the sickest when turning a corner". One participant even decided to walk only on a straight part of the maze for the remainder of that session, to avoid having to turn a lot. There was not one source of discomfort that was standing out. In the comments several causes could be found:

- Several participants mentioned that walking during turning was difficult and made it more unstable.
    - "When I turn and then walk, it is much better than when I try to turn and walk around the corner at the same time. It felt better, but also less natural than what I do in the real world." (P32)
    - Mentioned nine times.
- The platform of the Virtualizer moves when a user turns. This caused instability.
    - "The rotating made it feel like on a ship as the platform was moving as well. Like a wave hit the boat." (P4)
    - Mentioned seven times.
- Participants reported that turning too fast, made it harder or induced more sickness.
    - "I figured out if I slowly turn corners, it is better than when I turn fast." (P5)
    - Mentioned six times.

- Just turning the head was pinpointed by some as a cause of discomfort. Thus, it was the rotational visual flow that people reported as making them sicker.
    - "It's moving the head that makes me dizzy" (P23)
    - Mentioned five times.
- For a few participants, it was also a problem that there was a small delay until the platform tilt had followed their body orientation.
    - "I felt like the floor is not exactly turning at the same time as the rest of my body." (P28)
    - Mentioned three times.
- Sometimes participants slipped with their feet after doing a turn.
    - "If I did not slip, the turns were not a problem." (P30)
    - Mentioned two times.

8.2.4 Shifting and Stuttering

Although many participants easily noticed the movement speed, only some took note of small uncontrolled speed variations during walking or when stopping. Uncontrolled speed variations were unintended changes of the speed that were a result of incorrect movements of the user. 28 comments were about the camera "shifting" when the user had stopped or intended to stop, mostly when they were trying to pick up a battery: "The interaction with the battery felt glitchy, the movement went forwards and backwards multiple times, like shaking. I felt it was then when I started feeling sick, dizzy sickness." (P8). Additionally, there were eight comments on the camera motion stuttering when walking: "I felt like there was a little bit of a stop between my steps. I got used to it, but it is not how walking looks like because then I am at a constant speed." (P32). These comments were mainly coming up in the high speed and no smoothing sessions (Figure 18).

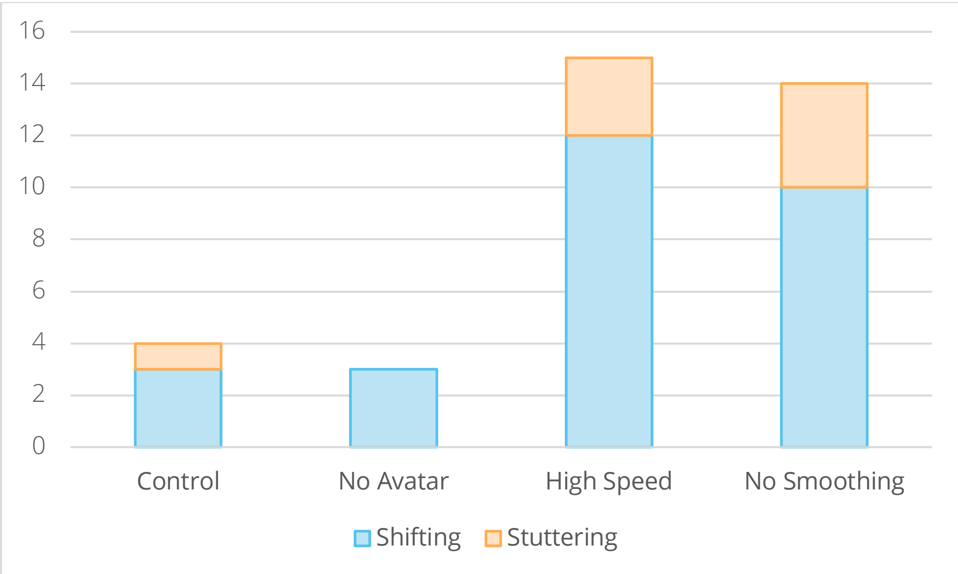

Figure 18: Comments About Uncontrolled Speed Variations

8.2.5 Minimap and Mental Focus

Two other factors for the cybersickness were the minimap and the mental focus. Six participants reported that looking at the minimap while walking made them feel sicker, although one claimed the opposite. Five participants talked about how focus or distractions had an impact on the degree of sickness they were experiencing. By having something to be mentally focused on or be distracted by, some participants felt less sick. For example, P19 said, "I concentrated very hard on finding batteries that I had no time to feel dizzy or something else. If I would have just stood there, looked and walked a bit it would have been worse".

8.2.6 Adaptation and Habituation

Many participants seemed to adapt their walking to the Virtualizer and learnt better how to move as the sessions progressed. 39 quotes discussed how participants either got used to VR and walking on the Virtualizer or adapted their walking style to be more comfortable and effective in walking. For most participants the adaptation was small, like P27 who told me “Big steps weren't working, so I started moving better when I did smaller steps”. Others mentioned it was the getting used to it, that made it better. Adaptation or habituation was talked about the most in the second session, followed by the third session and less in sessions one and four, as can be seen in Figure 19.

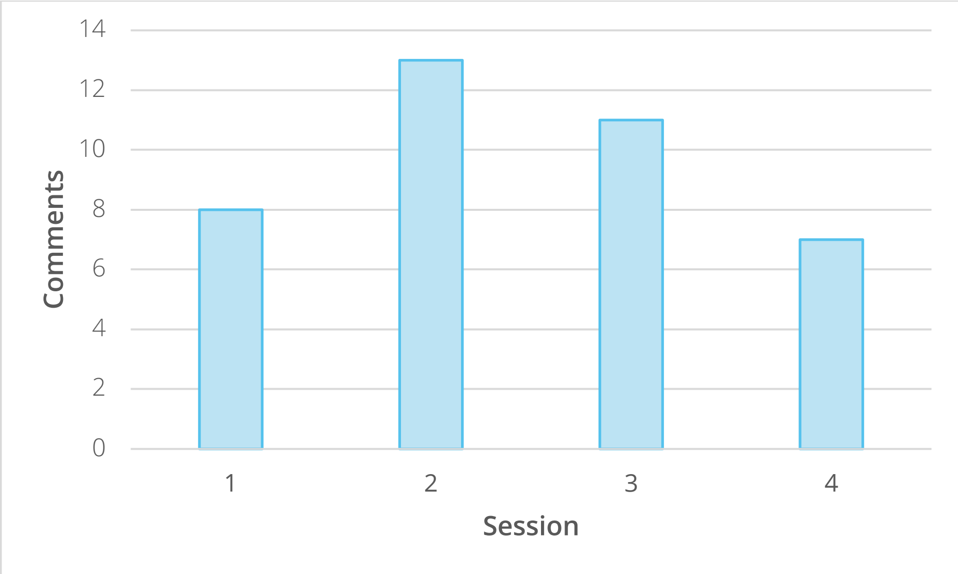

Figure 19: Comments On Adaptation/Habituation Per session

8.2.7 Awareness

Even though speed was an often-discussed topic, not every participant noticed that the speed was artificially changed, and the differences of the other conditions were noted even less so. Some participants did notice they were going faster, but related it to getting better at walking: “I think I was getting around faster. I explored more of an area than last time. I think it is about getting more used to the system” (P25, high speed condition). Six times a participant explicitly told me that they perceived nothing had changed compared to previous sessions, of which some included sessions that had double or half the movement speed compared to the previous session. Although stuttering was noted more often in sessions that did not have any smoothing, participants did not relate it to a change in experiment parameters. In general, people were the least aware of the avatar, even though they were always pointed to the existence of the avatar the first time a participant calibrated the avatar. Only two participants mentioned the non-existence of the avatar, whereas others only rediscovered it after some time: “I only noticed the avatar in the last session. I was not aware of it before” (P5). During my informal conversations after the experiment, when I explained the conditions, I found out that participants rarely realised that the avatar had gone missing in one of the sessions.

During the experience, participants sometimes also noted bugs or (temporary) problems with the hardware. For example, due to a bug with the colliders participants sometimes moved vertically a little bit for a very short time. This was mentioned in four comments. The headset image got blurry sometimes when it was either not strapped properly or when the lenses got foggy due to sweat. Four participants talked about this headset problem explicitly. Four times users commented on the walking direction being off-centre, caused by the harness being slightly shifted.

8.2.8 Presence

29 times participants discussed how immersed they felt or what made them feel less or more immersed. Most factors that resulted in a reduced or increased feeling of presence were only mentioned once. Three participants said that involving the walking motion made it more immersing and one participant also noted that the higher speed added to that as well. However, for some others, there were aspects about the walking that made it less immersive. For example, two participants pointed to turning, another two to shifting and one to slipping as a cause of feeling less present. The most talked-about immersion-breaking aspects with three times were the ventilator, verbal contact with the experimenter and the lack of tactile interaction with objects in the game. For

example, P31 said about the first two aspects: “When I was not thinking about where I was, I felt inside. But when I heard your voice or felt the fan, I realised that my body was somewhere else [the office] than where I thought it was”.

8.2.9 Other Issues

Participants did not enjoy every facet of the experience, so they raised some issues during the experiment. Even though the targeted pace for participants was always a walking speed, it was still tiring for many participants. Several participants complained during the experiment about getting tired. 20 comments were related to physical tiredness, three were on mental tiredness and another three were about sweating. Although participants were told beforehand that it would be more tiring than normal walking, it was still surprising to some: “It's a lot more tiring than I thought” (P39). Of all the physical tiredness comments, only one was concerning the high speed condition, whereas the other conditions had a similar number of comments.

Two in-game factors that lead to frustrations were the colliders, also known as hitboxes, of the walls and reaching a dead end. When a participant hit a wall collider, the platform underneath them would start vibrating to give them feedback on the spatial limits. However, it was mentioned 10 times by several participants that they perceived the colliders to be too big. For example, P6 said: “Sometimes I felt like I wasn't hitting the wall, but it still buzzed”. When participants hit a dead end, frustrations were sometimes aggravated by the fact that they had to walk a long way back before they can explore a new path: “You know what I am sick of? These dead ends” (P26). Most mentions of dead ends, seven out of nine, were made in the second session.

8.3 Post-Experiment Questionnaire

When all sessions were finished, participants also answered a few questions about the complete experience. They had to pick their most preferred session, explain their choice, and order the sessions from least sickness-inducing to most sickness-inducing. For the analysis, the session numbers were then transformed to the corresponding condition. Participants also had the option to still write any remaining comments they had on the VR experience or the experiment in general. Those that wrote an answer did only repeat what was already discussed verbally before, so I decided to not include it in the analysis.

The most preferred session was the third one and the most preferred condition was the high speed condition (see Figure 20). On the other hand, the least amount of people preferred the second session and the control condition. There were a variety of reasons behind the decision for the preferred session. Eight of the participants that chose the high speed condition, wrote that the reason for their choice was the speed. Two other participants chose the same reason but for different conditions. Sickness was mentioned seven times as a factor for choosing the best session. Seven participants also wrote that getting used to VR and walking had played a part in their decision. Six participants liked their favourite session because of finding a tree. Lastly, four participants described that their preference for the first session mainly had to do with initial excitement.

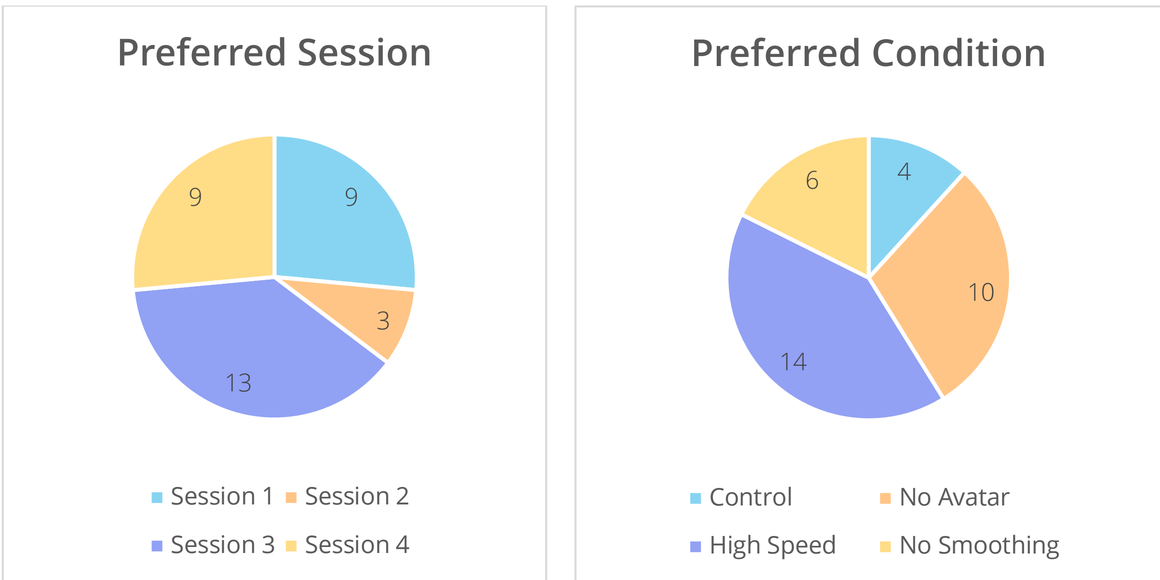

Figure 20: Preferred Session and Condition

During the experiment, I referred to the conditions as numbers, one to four. There are some signs that this led to confusion for some participants when they had to pick their preferred session. For example, several times participants asked while filling out the questionnaire if the numbers in the question were referring to the condition number or the session number. Also, one participant chose session three as their favourite but then wrote: “It was the first go and it was new to me”. As his first session was condition number three, this suggests he was thinking he had to pick a condition.

Looking at the distribution of answers for ordering the sessions, participants rated the high speed as most sickness-inducing the most often, whereas the difference between the conditions for the least sickness-inducing is less clear. The answer for the least sickness-inducing session seemed to coincide often with a participant’s favourite session. 18 out of 34 participants chose the same session as least sickness-inducing and as their preferred session.

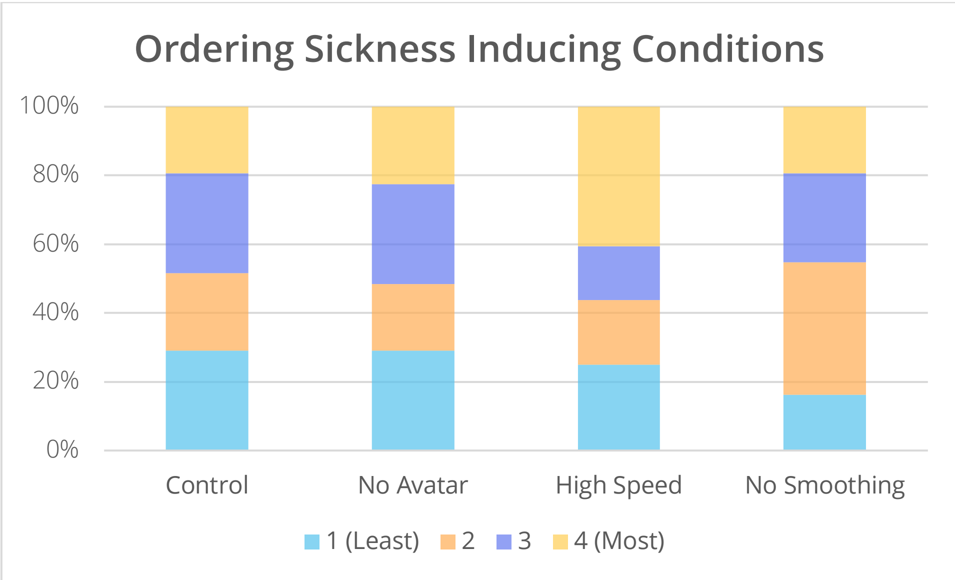

Figure 21: Ordering Sickness Inducing Conditions

9 Discussion

This thesis sought to find out what can be done to reduce cybersickness for users that walk in VR with the Virtualizer. The experiment has exhibited a variety of factors, related and non-related to the conditions, that are influencing the level of reported cybersickness.

9.1 Comparing Experiment Condition Scores

The main purpose of the user study was to see if there was a significant effect of the three chosen methods, avatar, speed, and smoothing, on cybersickness. This was determined by comparing the scores that came out of the CSQ. Although the total difficulty to focus scores did not reach statistical significance in the linear mixed effect model, the dizziness scores did in some of the pairwise comparisons of the conditions.

The high speed condition had the highest average ΔDizzy and ΔFocus scores. Applying no smoothing and omitting the avatar only had a non-significant increase in the mean ΔDizzy. This confirms that reducing the movement speed to a level I defined as realistic can lower the reported cybersickness. The ΔFMS scores support the ΔDizzy results, as only the high speed condition was statistically significant when compared to the control and no avatar condition. Taking away smoothing did result in a mean increase of the ΔFMS scores, but the result was not significant when compared to other conditions. In conclusion, H2 was proven on a subjective level based on the CSQ scores, whereas the scores failed to show significance to prove H1 and H3.

Looking at the ΔDizzy boxplot (Figure 9), it can also be observed that more participants felt sicker after the high speed condition than the other conditions. The median for the other conditions is on zero, whereas for the high speed it is slightly below one. I think that this might partly be a result of smoothing only influencing the sickness of participants with a particular walking style. Participants that have a walking style that does not result in speed fluctuations or only very little, will not experience much change due to the smoothing. Thus, taking away the smoothing should not result in much difference compared to the control condition for these participants.

Although there was a significant difference that could be observed from the dizziness and FMS scores, that was less so for the focus scores. A reason for this could be that the reduction methods mainly influence motion or the perception of motion. Consequently, the conditions should affect the symptoms related to motion and balance, for example, vertigo and feeling dizzy, rather than the other symptoms, for example, headache or blurred vision. As the motion-related symptoms are included in the dizziness score and not in the difficulty to focus score, the former could be expected to have a more observable difference between the conditions than the latter.

That the higher speed caused more sickness is something that participants often also explicitly mentioned. Comparing between conditions the number of comments that discussed sickness going up or down (Figure 17) supports the conclusion as well that a higher speed can result in more cybersickness. The condition without smoothing shows only a small difference compared to the control in the number of comments talking about sickness increasing. On the other hand, the control does have a lot more comments on the sickness decreasing compared to the no smoothing condition. This difference might be higher than it should be because the control generally came after the high speed condition, whereas the no smoothing condition most of the time followed after the no avatar condition. Therefore, participants were often experiencing a bigger difference in sickness inducement compared to the previous session in the control, than in the no smoothing condition.

When participants had to order the sessions from least to most sickness-inducing, the high speed condition also came out on top (Figure 21). However, the differences between the other conditions are minor. Many participants experienced little or no cybersickness at all, which meant that for them it was hard to order the sessions, as the sessions would probably all seem the same regarding cybersickness inducement. It might be that some participants replaced this question with an easier to answer question: how would I order my sessions from most to least liked? This would explain why 18 out of 34 participants chose their preferred session as the least sickness-inducing, even though only eight participants mentioned sickness as a reason for preferring a certain session. Possibly, participants were anchored by the multiple-choice question about their favourite session, which came right before ordering the sessions on sickness inducement.

9.2 No Effect from the Avatar

There might be a variety of reasons as to why adding or removing the avatar constituted in minor and non-significant differences in the cybersickness means. First, it could be that my hypothesis is plain incorrect and that virtualisation of your own body does not provide a sufficient frame of reference that can reduce cybersickness. Another explanation could be that it did not work as most participants reported afterwards that they did not notice that the avatar was gone in one of the sessions. However, I doubt this could be a factor as the process of choosing a reference frame is an unconscious process. This is confirmed by the research of Wienrich et al., who reported that participants generally did not notice the virtual nose they added, even though the virtual nose did have a significant effect on sickness [28].

What might have created more variation in the possible effectiveness of the avatar was the fact that the body parts were not always within the visual field of the participants. I did not measure this, but I could observe that a significant part of the participants had their arms lowered. After trying it out myself with the same arm positions, I found that the avatar is not visible when you look straight forwards. Only when the arms are raised, or if a user looks down or to their shoulders, it is possible to see the avatar. The vertical FOV of the used HTC Vive Pro, 91[4]/108°[5], is significantly smaller than the human vertical FOV, 150° [125]. Thus, when participants lower their hands, they move sooner out of their visual field than they would in the real world. If none of the body parts is visible, it will not have the hypothesised effect on cybersickness as it cannot provide a visual frame of reference then.

For the participants that did have their hands and arms within their visual field, there might have been an issue that could have influenced the effect of the avatar on cybersickness as well. One participant noted that the framerate dropped when he looked at the minimap. When I investigated the issue, I found that some kind of rapid visual vibration of the avatar, the minimap and controller models occurs when you rotate your body very quickly. This had nothing to do with rotating on the Virtualizer, as that only affects the movement direction. The visual vibration also occurred when stepping out of the Virtualizer and rotating quickly. It might be that this vibration reduced the suitability of the avatar as a stable reference frame.

The last aspect that might have minimised the effect is the fact that participants could still see the controllers and the minimap attached to their right controller when they were in the no avatar condition. The minimap did become invisible if participants did not tilt their hands up, but some participants still permanently held it up. If participants perceived the controllers and the minimap as attached to their hands, it might have also acted as a frame of reference that reduced cybersickness. Thus, it is not clear yet if the hypothesis is wrong or if the experimental conditions led to the effect of the virtual body representation being non-significant.

9.3 Cybersickness Factors Influenced by Speed

Although my assumption beforehand was that having a high speed would induce more sickness because of the increase in visual flow and the addition of a proprioceptive-visual mismatch, the comments tell a bit of a different story. Participants often noted that their movement was unintentionally shifting or stuttering, mainly in the high speed and no smoothing conditions (Figure 18). Thus, these results suggest that increasing the movement speed or taking away the smoothing exacerbated the issues of shifting and stuttering. Accelerations were higher in the high speed and no smoothing conditions, which made the uncontrolled speed variations more intense and apparent to the participants.

After closer examination of the shifting problem, I found what caused the sudden movement backwards. For many participants shifting happened when they tried to stop, mainly when picking up a battery. So, I tried to recreate the shifting phenomenon for myself. I found that the movement direction very shortly turned backwards when making a sudden stop after walking. Although I intended to fully stop my feet, it was possible to sometimes slide a little bit still with the feet. It looks like the sensors in the platform are too sensitive to slight feet sliding when stopping. The sensors were too precise and reacted too quickly. Consequently, the Virtualizer sensed participants trying to shortly walk backwards, until coming to a full stop, causing the shifting sensation. As the stopping problem is known now, Cyberith is working on a quick firmware update that can fix the issue by lowering the sensitivity when stopping.

Even more surprising to me was that participants repeatedly told me that the speed that I defined as realistic, was unrealistic and too slow. Although the speed was matching the distance their feet were setting with each step, participants felt the speed did not match with how fast they were moving physically. The participants were not so aware of the horizontal distance of their steps as I was expecting. One possible explanation for this is that participants might rather use the amount of effort they put in per step to predict how far each step should go, instead of taking the actual distance of each physical step. Walking on the Virtualizer tends to be a bit more

[4] https://www.infinite.cz/blog/VR-Field-of-View-measured-explained
[5] https://risa2000.github.io/hmdgdb/

tiring than normal walking, thus there is more energy spent per step. Therefore, many participants felt like P16 during the sessions with the realistic movement speed: “There is a lot of energy going in, but little is coming out”. That the realistic speed feels more tiring than it should be, is also confirmed by the fact that 19 out of 20 comments on tiredness were in the sessions with the realistic speed. This might have resulted also in the high speed condition being the most preferred condition (Figure 20).

In conclusion, a higher speed might not only result in higher cybersickness levels due to more visual flow but also because the earlier described issue of stopping is intensified. Furthermore, the realistic speed might have still exhibited a proprioceptive-visual mismatch as the effort of the muscles did not match the visual distance participants were making. Therefore, the definition of realistic speed might not have been chosen optimally. A third speed level that is in between the tested speed factors might better reflect the muscle effort and lead to a better perceived visual-proprioceptive match. Further research is required to clarify the cybersickness inducing factors behind movement speed.

9.4 Additional Cybersickness Factors

The comments of the participants during the experiment do not only confirm the CSQ scores but also provide insights on other potential factors of cybersickness when wearing a VR headset and walking in the Virtualizer. For example, turning was often noted as not only difficult to do but also sickness-inducing.

9.4.1 Turning

Participants discussed several aspects that made turning troublesome, but none of these were standing out as the main source. From most to least mentioned, participants talked about difficulties from walking while turning, the platform moving, turning too fast, just rotating the head, a delay in the platform movement and slipping after turning. Turning too fast might have had an aggravated effect due to the visual vibration of the avatar, minimap and controllers when rotating.

Several participants mentioned that just rotating the head caused sickness, suggesting that the problems related to turning were, at least partly, not related to the Virtualizer. The Virtualizer does not affect the visual rotations, it only affects the direction of movement. When turning the head, the view in VR precisely follows the movement of the head. Thus, there should not be a visual-vestibular mismatch, unless in the case of a bug in the software. However, I did not find anything wrong with the tracking when trying out head rotations. Therefore, the cybersickness might have had another cause. An explanation I might have, has to do with finding a stationary object to fixate the eyes on when rotating. It might be that when rotating quickly, participants found it hard to focus their gaze on an object that could act as a rest-frame. The maze pathways were narrow. So, most objects that were within the visual field of the participants were close to them. Possibly these objects moved too quickly out of view, making them not usable as reference frame anymore. As participants moved quicker, it might have gotten even harder to find a rest-frame. The narrow pathways also might have forced participants to make sharper and more abrupt turns.

What might be another reason why participants felt uncomfortable turning, is that it made them feel unstable. This instability could also be what was making participants sicker. P30 put it like this: “I think this session [control condition] would be better if you are more motion sick because you are much more stable. The other one [high speed condition] I was much more unstable or more slippery. It was flowing more, a bit on ice”. The higher speed did not physically affect the Virtualizer, but it might be that participants got more unstable as their body tried to compensate for the fast visual accelerations in VR.

Instability causing cybersickness is in accordance with several studies that looked at postural instability and cybersickness, also discussed in the literature review [43], [46], [61]–[63]. In this study, the direction of the relation between cybersickness and instability did not always seem one-way. The comment of P38 suggests that sickness also causes instability: “The walking went well until I got dizzy”. This comment fits the studies of Weech et al. and Akiduki et al. that saw a negative effect of cybersickness on postural stability [5], [6].

9.4.2 Minimap

Although not a major factor, some participants noticed that looking at the minimap made them feel sicker. After trying it out myself, I realised the sensation is similar to quickly rotating your whole body around your vertical axis for a while and fixating your eyes at something you are holding in front of you. Nobody elaborated on what about looking at the minimap made them feel sick, so it is hard to pinpoint the exact reason. The only participant that noted the visual vibration of the minimap, did not specify if it made him sick. Nevertheless, the minimap might have made this participant still unconsciously cybersick. A partial explanation might be found in the research of Pöhlmann et al. that found that the periphery is the part that is the most visually sensitive to longitudinal motion [60]. It might be that when looking at the minimap, the peripheral motion stimuli become more dominant, as the centre is focused on the minimap, which barely exhibits any motion. Another explanation could be that when focusing on the minimap, it blocks a large part of their view. As a consequence, they might be losing a significant part of the visual-spatial information required to find a rest-frame. Therefore, they lose their frame of reference and get sicker because of the visual motion visible around the minimap. Furthermore, by focusing the view on the minimap, it is not possible anymore to focus your view on stationary objects around you. Similar to when you are rotating rapidly around your own vertical axis, it could help to look at something stationary in the environment when rotating quickly.

9.4.3 Mental focus

In the literature review section on potential cybersickness reduction methods, I discussed using cognitive distraction to reduce sickness. Bos already had success proving distracting worked for regular motion sickness [119]. Some of the comments suggested that being cognitively focused on something unrelated to the sickness or being distracted also reduced sickness in my VR experiment. Several participants said they felt sickness going down when they had something to focus on or when talking to me. Although it might be true that cognitive focus or distractions influence how much sickness participants are reporting, it is not clear if it is just reducing the awareness of the symptoms, or if it is affecting the mechanisms that cause cybersickness to arise. Considering the effect of mental focus, it might also be that by asking participants every minute about their level sickness, participants were more focused on their sickness. Thus, they perceived to experience a higher level of cybersickness, than they might have felt if they would not have been reminded of it on an interval.

9.4.4 Adaptation and Habituation

Several studies already found that susceptibility to motion sickness in VR or simulators can lessen as time spend in virtual environments increases [22]–[27]. This research adds to that body of knowledge that in the case of the Virtualizer, improvements could already happen within the time frame of several sessions of just eight minutes. Participants often mentioned that they got better at walking or felt more comfortable in VR as they got more used to it. This adaptation and habituation effect could also explain why the first session had a higher average ΔDizzy score than the other sessions (

Table 5).

9.5 Head Dispersion as an Indicator

The CSQ and the comments provided a significant indication as to which tested conditions have an effect on cybersickness, but they are subjective measures. The research of Rebenitsch and Quinby demonstrated that measuring head dispersion using the headset data showed great promise as an objective measurement of cybersickness [7]. However, my study did not manage to find a statistically significant difference between the conditions in regards to the positional and rotational variance and max of the headset. In general, there was very little difference between the variance values before and after the sessions. For example, the average difference in the variance for the z parameter was 0.01 mm. Considering these results, the hypotheses cannot be proven on an objective level.

Even though it might have influenced the results that not all participants kept their gaze constantly fixated for 30 seconds. I think the main reason for the lack of significant difference in the results is that participants were kept stable the Virtualizer ring. The Virtualizer ring limited the movement of their body on the transverse plane. Thus, stabilised the user. Therefore, there was less space for postural sway. No or limited postural sway also meant that the effect on head dispersion was smaller. Furthermore, the movement might have been limited too much as well by having participants try to keep their heads still. Rebenitsch and Quinby, on the contrary, took their headset data from participants that were active in VR [7]. Thus, any head dispersion as a result of cybersickness might have been too small to measure. Especially, considering the headset data is noisy, as mentioned by Rebenitsch and Quinby [7].

9.6 Presence

The reason behind asking participants about their feeling of presence was to see if the cybersickness scores would correspond with the presence scores, like what Grassini et al. and Weech et al. found in their studies [113], [122] However, the results show that participants did not feel particularly more present in the conditions that exhibited more cybersickness. Surprisingly, participants reported feeling the most present when the avatar was gone, although no statistical significance was found. There does not seem to be a clear explanation as to why the SPES scores were the highest for the sessions without an avatar. Participants were generally unaware of the avatar disappearing, so it is remarkable then that it might have still led to a change in their perceived immersion.

9.7 Practical Implications

The results of this experiment have several practical implications for the Virtualizer, but also the field of VR in general. Cybersickness is a problem that exists for a significant part of the VR users, as exhibited by my experiment. Thus, it is important for the development of VR hardware and software to consider the factors that can cause sickness.

9.7.1 Cybersickness vs. Satisfaction

First off, there is a clear trade-off for movement speed in VR. Participants were, in general, favouring the higher speed, as it felt less tiring, made the game faster and helped them in achieving their goal of finding the tree in time. However, to some, it also caused significantly more cybersickness. Therefore, it is important that the speed can be adjusted to a level that the user finds comfortable. A balance can then be found in a speed that does not feel too slow but also does not induce significant sickness. It might not make sense to have a low speed for users that are completely not susceptible to cybersickness and want to go fast. On the other hand, the system needs to be able to slow down for users that tend to get very sick at high speeds. Finding this balance is not easy, as the ideal speed factor seems to be an individual preference. So, it would help if this can be adjusted while users are in VR. That way, the effect of the speed change can be immediately judged by the user.

Making the speed changeable during the VR experience, also allows for adjusting the settings as users adapt or habituate to the experience. When starting the experience, the speed could be set at a low level to first find out how the user reacts to VR. As they get more comfortable in moving, the speed could be raised then in small steps. It is better to start slow, because as soon as you get sick it can take a while until it is gone. Thus, going back to a slower speed after starting at a higher speed might be too late if the participant gets very sick.

9.7.2 Adjusting Movement Speed Smoothing

Albeit a smaller trade-off, there is still a drawback to increasing movement speed smoothing. It does not only compensate for stuttering steps; it also introduces filter lag. When the smoothing is high, the system comes to a lower acceleration when starting and a slower stop, whereas without smoothing the starting and stopping should be near instantly. For some, the immediate reaction might be more important than the benefit smoothing is bringing. So, it would be good for those users to have the possibility to adjust the smoothing as well.

The data was not statistically significant in proving that cybersickness was affected by smoothing. Nevertheless, I do think it might still have a considerable effect, but only on specific participants and with higher speeds. In the experiment, the speed was in three out of four conditions low (the realistic speed), making speed fluctuations less intense. It might be that with a higher speed, the effect of removing smoothing would have been more significant.

It is important to note, though, that many users might not actively realise the impact of changing the smoothing. Participants of the experiments generally noticed the speed changing, but they were less aware of the smoothing or its effects. Increasing the speed might have obvious implications but smoothing might be a less clearly defined concept. If a future system enables the adjustment of the smoothing, the interface needs to be intuitively displayed. It should not be just a knob or a slider. Direct visual feedback explaining the outcome could help the user understand the effect of applying movement speed smoothing.

9.7.3 Improving Stability and Turning

The experiment was focused on studying the effects of speed, smoothing and an avatar, but the results also showed that turning was difficult and potentially cybersickness inducing for many. Looking at the sources of discomfort that participants discussed, it seems that increasing stability could be an important factor in improving the experience.

Part of the discomfort and cybersickness might have come from the visuals created by the VR app I developed and the VR hardware. Possibly, turning can be improved by increasing the walking space in the VE. This allows for wider turns and puts stationary objects farther away in the visual field. These objects might then be easier to fixate the eyes and use as a stable frame of reference. Also, removing the visual vibrations of the controllers, minimap and avatar, might improve the comfort of visually turning.

The movements of the platform and its slipperiness might be adding to the perceived instability. So, more research is required into finding if there is a relation between the Virtualizer platform, stability and cybersickness. Potential directions could be studying the effects of the platform motion speed or the characteristics of users that are walking while turning.

Solving the earlier described issue of stopping could also help in improving stability. When the shifting occurs, the body tries to counteract the sudden uncontrolled movement the user is seeing. However, as there is no actual physical movement it only results in more instability. An update of the Virtualizer firmware is in development to take away this problem. The planned software change will make the Virtualizer platform sensors ignore small forward feet movements when a quick stop is initiated.

9.8 Future Research

The results of the experiment give insight into some factors of cybersickness with the Virtualizer. There are, however, still things that remain unclear or new questions that have popped up. Future studies could pick up these topics and extend the knowledge regarding cybersickness, VR and omnidirectional treadmills like the Virtualizer.

9.8.1 Take a Closer Look at the Avatar

In the first place, new studies could test again the effect of a virtual body representation on cybersickness with an improved experimental setup. As I discussed earlier, several factors might have minimised the effectiveness of the avatar to a degree it did not reach significance anymore. A new experiment could take those factors into account and then have a better chance of finding a statistically significant result.

A first step could be to find a VR device that has a higher vertical FOV than the one used for my experiment, the HTC Vive Pro. Potential candidates could be the Star VR One or the Pimax 8K Series[6]. A higher vertical FOV increases the chance that the hands and arms will be within the visual field of the participants. Another way to increase the visibility of the arms would be to set up a user task that forces or stimulates participants to lift their hands.

[6] https://www.infinite.cz/blog/VR-Field-of-View-measured-explained
https://risa2000.github.io/hmdgdb/

In my experiment, participants could still see the controllers and a minimap when the avatar was gone. This might have curtailed the effect of no visible avatar on cybersickness. Therefore, future experiments should remove any in-game models that are attached to the body or the controllers that could act as a reference point for users.

If the avatar has a statistically significant effect, I expect it to still be less noticeable than the smoothing or the movement speed. Thus, it is quintessential to remove or reduce any external factors. One way to do that would be to only test a session with the avatar and without the avatar, instead of testing multiple parameters as I did. This takes away the chance of a parameter of the preceding session affecting the session testing the avatar.

9.8.2 Motion Characteristics While Walking

This research did not manage to find a significant result when comparing the head dispersion of different conditions. It might be that taking the variance or max is too simple, and a more complex model is required to measure cybersickness from headset data. Nevertheless, the same headset data was also gathered while the participants were walking. From what I could observe when watching the participants walk, there was more variation in the manner and amount of head movement of each participant. So, it might be that statistical significance can be found for the headset variance or other motion characteristics when comparing conditions. If certain motion characteristics can be successfully related to cybersickness, an early warning system or a closed-loop system, like the one made by Islam et al. [79], could be developed for the Virtualizer. A system like that could help operators to keep track of the level of cybersickness of the user, without having to ask them constantly and pulling the user's attention to the sickness.

Data were also recorded from the feet trackers, but that was not analysed. In the future, this data could be specifically analysed for gait parameters. If the gait parameters can be derived from the data, it might be possible to develop a system that can detect Cybersickness, like the classifier built by Feigl et al. [81]. The gait data could be combined as well with the headset data to see if accuracy in measuring cybersickness can be improved.

9.8.3 Visual-Proprioceptive Mismatch

Beforehand, I hypothesised that a speed that matches up the horizontal feet movement should be the most realistic. However, the user study has shown that participants did not perceive it that way. The comments suggested that there was still a visual-proprioceptive mismatch during the speed I defined as realistic. Future research could investigate how people exactly relate their proprioceptive senses to their visual system. In other words, what properties of walking gives them a certain expectation of speed they are supposed to be going at in VR.

I discussed that it could be that users related their muscle effort to how fast they expect to go. A new study could test this hypothesis by performing an experiment in which the physical effort required for walking and the VR speed can be adjusted. Finding the mechanisms of the visual-proprioceptive mismatch could support further development in making walking in VR more realistic and improve immersion.

10 Implementation

The experiment has shown that adjusting the movement speed had a significant effect on reported cybersickness and satisfaction. Also, there are signs that smoothing might reduce cybersickness as well. Therefore, it might be important for users or operators to have the option to change this to their preferences. At the moment of writing this thesis, it was already possible to adjust speed and smoothing. However, this could only be done by editing some text in an ini file which was loaded at the start of the VR program (Figure 22). Any edits while the VR program is running, did not result in any changes. So, the user needed to first quit the software before they could adjust the speed again. Therefore, a new implementation was required that allowed operators or Virtualizer users to easily adjust the speed and smoothing at runtime.

Considering the limited time I had in the thesis next to the user study, the goal was to make a rough implementation that functions but would not be tested by users within the scope of the thesis. First, I will explain the current state of the Cyberith software ecosystem, as of writing this, and the implications the structure had on the implementation I developed.

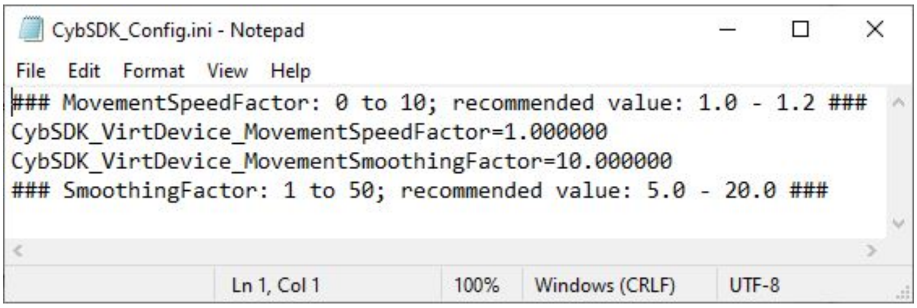

Figure 22: Configuration File for Adjusting Speed and Smoothing

10.1 Current State

There are several parts of the software ecosystem of Cyberith, and they communicate with each other in specific ways. This has an impact on how an external user interface for speed and smoothing can interact with Virtualizer software. Three main parts are involved for reading the data, interpreting it, and sending the output to the VR app: The Virtualizer firmware, the Cyberith library and the Cyberith Unity/Unreal Engine plugin.

10.1.1 Virtualizer Firmware

The firmware of the embedded system on the Virtualizer collects all the sensor data and inteprets the corresponding values that can be used by the PC. Examples of data that gets sent to the PC are the player orientation, ring height, movement direction and speed. It also controls the haptic actuators and the motors that are attached to the platform. Developers do not directly interact with the firmware, except for updating it using the firmware update tool provided by Cyberith.

10.1.2 Cyberith Library

The library, which is a DLL (dynamic linked library) file, takes care of reading the USB data from the Virtualizer firmware and provides an interface for other applications to access this data and control the haptic vibrations. The DLL file can be found in the VR application folder. This means that it can also be swapped with a new DLL file in case of an update. So, the version is not dependent on the developer rebuilding their app. Users can decide to use newer versions of the Cyberith library.

The DLL is also the part that is responsible for creating and reading the configuration file (Figure 22) that enables changing the speed and smoothing factor. It is only read once by the DLL when the VR app is initialising. If it is edited while the app is still running, nothing changes for the app. Only when it is restarted, the change is processed.

10.1.3 Cyberith Unity/Unreal Engine Plugin

The plugin, which is available for both Unity and Unreal Engine, provides the tools for developers to implement the Virtualizer into their VR projects. It includes the code required to interact with the Cyberith library. Developers can adjust this code to make it fit their needs. As the plugin is implemented by the developer, it is their choice to update to a newer version or not. Elements that are part of the plugin cannot be updated or exchanged without the developer updating their app.

10.1.4 Other Cyberith Apps

There are other apps that Cyberith has developed that support customers in their use of the Virtualizer. First, there is the Virtualizer Control Panel. This app can be used to check if the Virtualizer is working correctly. It provides several troubleshooting tools. For example, users can see the current data of the Virtualizer or test the haptic vibrations of the platform. The Control Panel cannot be used simultaneously with another app that is connected to the Virtualizer. Users will first need to disconnect the Control Panel before they can start another app that uses the Virtualizer data.

The last important app is the Cyberith Arcade. The Arcade is a launcher for VR apps that have support for the Virtualizer and tools for VR and the Virtualizer, for example, the Control Panel. There is a trainer experience included that prepares new users to for VR and the Virtualizer. It also comes with a configuration app that can be launched from the Arcade. Additionally, it is possible to launch the trainer app before launching a VR game or experience.

10.1.5 Implications for Implementation

The benefit of the current system is that users are not dependent on the VR app developers for the configuration file to work. If they have a VR app with an older version of the DLL that does not support changing the speed or smoothing, they can just swap out the DLL to a newer version. So, preferably my implementation communicates with the library directly. This avoids the system being dependent on the developer.

One major hurdle, however, is that the library has been programmed to only allow one app to directly communicate to it at the same time, the VR app in this case. This is the reason why the Control Panel needs to be disconnected before any VR app is started. So, a new system needs to be able to communicate with the DLL, without interfering with the VR app using the library.

10.2 List of Requirements

From the discussions with my supervisor at Cyberith, the results of the experiment and analysing the current system, I came to a list of requirements for the implementation.

- The system must contain parameters that have a proven effect on cybersickness.
  The user study made clear that adjusting the movement speed can affect cybersickness. So, that parameter must be implemented in the system. Smoothing did not have a statistically significant effect, but the thematic analysis indicated that it could have an effect on the occurrence of shifting and stuttering and cybersickness. Thus, I decided to include smoothing as well. None of the experiment measurements indicated that the avatar might have influenced cybersickness, so it was not included for the implementation. Furthermore, the DLL would not be able to instantiate an avatar. The software of the avatar would need to be included by the developer in Unity or Unreal Engine.
- The method variables must be adjustable by the VR user and/or operator before and during the VR experience.
  Users will have different preferences when it comes to the speed or smoothing factor that they feel comfortable at. Users that are not susceptible to cybersickness might prefer faster speeds than very susceptible users. So, for them, it could be useful to be able to change these parameters themselves or let an operator do it. As I mentioned in the section on practical implications, having the option to change speed or smoothing during the experience allows the user to immediately try out the change. Furthermore, the speed could be adjusted as the user gets more used to VR and walking on the Virtualizer.
- The graphical user interface (GUI) must visualise and/or explain the effect of changing a parameter.
  What the effect is of changing the movement speed might be easy to understand for most, but for smoothing the effect might not be so obvious for everyone. During the experiment, participants did not explicitly notice either when the smoothing was changed. Therefore, the GUI must provide some visual information on what changes when the parameter is adjusted. More information on the (cybersickness) effects of the parameters should also be easily accessible from the user interface.
- If the VR user wants to adjust themselves, they must be able to do it while within VR.
  Generally, an operator should be nearby that could adjust the parameters. However, in the case of no operator, the user should not have to get out of the Virtualizer to be able to adjust the configuration. Thus, there must be a method implemented to make changes while in VR.

- It must be possible to hide the VR controls of the system.
  The controls must not interfere with the experience of the user or the workflow of the operator. Thus, the VR controls of the parameters should not always be visible.
- The system must be able to work independently from the VR app.
  Customers of the Virtualizer should be able to easily update the Cyberith Library including this system, without being dependent on the developer of the VR app. The system must be able to function as a separate app that communicates to the Cyberith library that is run by the VR app.
- The system must be backwards compatible with the old configuration system.
  If a VR app uses an older version of the Cyberith library, the system must be able to still utilise the old configuration method. Although it will not be possible to change parameters in real-time with the old configuration system, users can still make use of the new interface to adjust the settings before running the VR app.
- The system must work on all PCs running Windows 7 or later.
  Cyberith requires all of its software to be compatible with older Windows versions, down to Windows 7.

10.3 Ideation

When I first started ideating based on the requirements I defined, I focused first on the possible interactions in VR. I sketched out those ideas, to have an overview of options (Figure 23). However, I quickly realised that the software-based interactions would require the involvement of the VR app developer. Thus, these interactions could not work independently from the VR app, which was one of the requirements. The hardware-based interaction ideas I discarded as well, as previous customers could then not easily update without receiving new hardware. Therefore, I decided to focus on developing a configuration PC app that could communicate with the Cyberith library and be updated independently from the VR app.

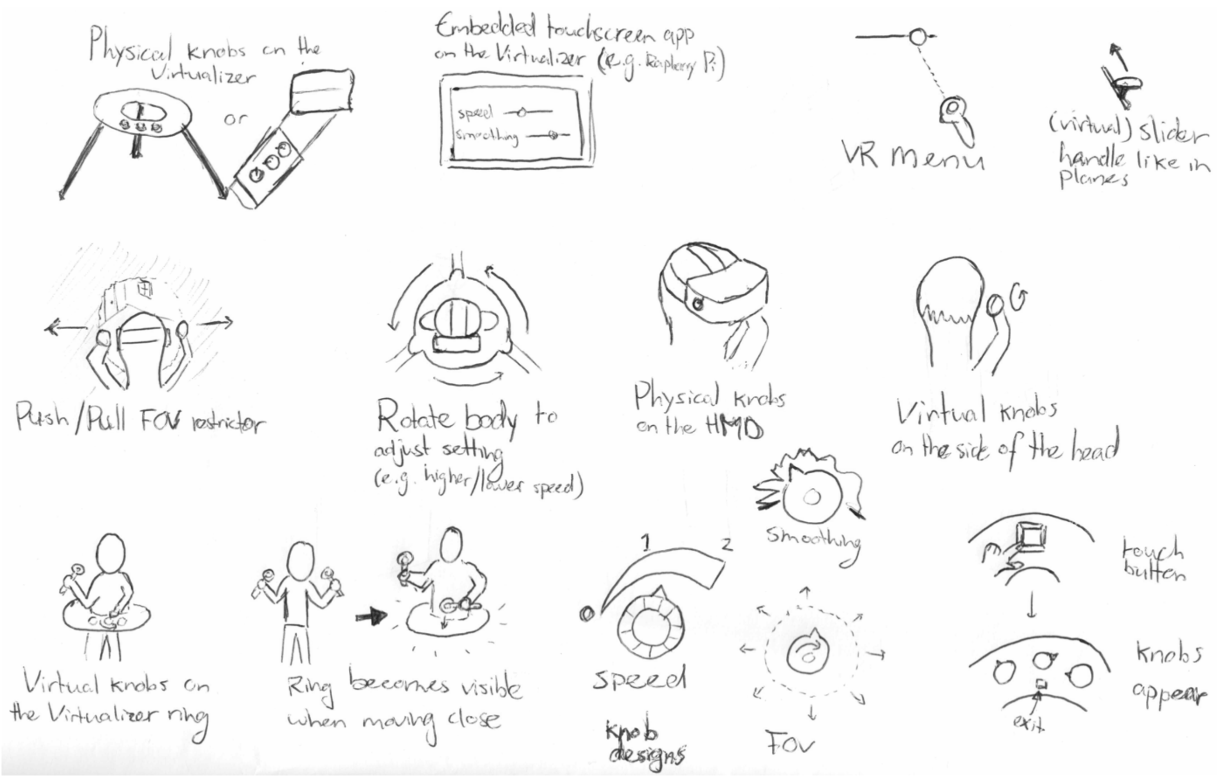

Figure 23: VR Interaction Ideation

10.3.1 App GUI Ideation

For the ideation of the GUI, I looked for ways to visually explain the effect of changing the smoothing or the speed. I came up with several ways to design a slider or knob that is visually related to what it is affecting. The sketches can be found below in Figure 24.

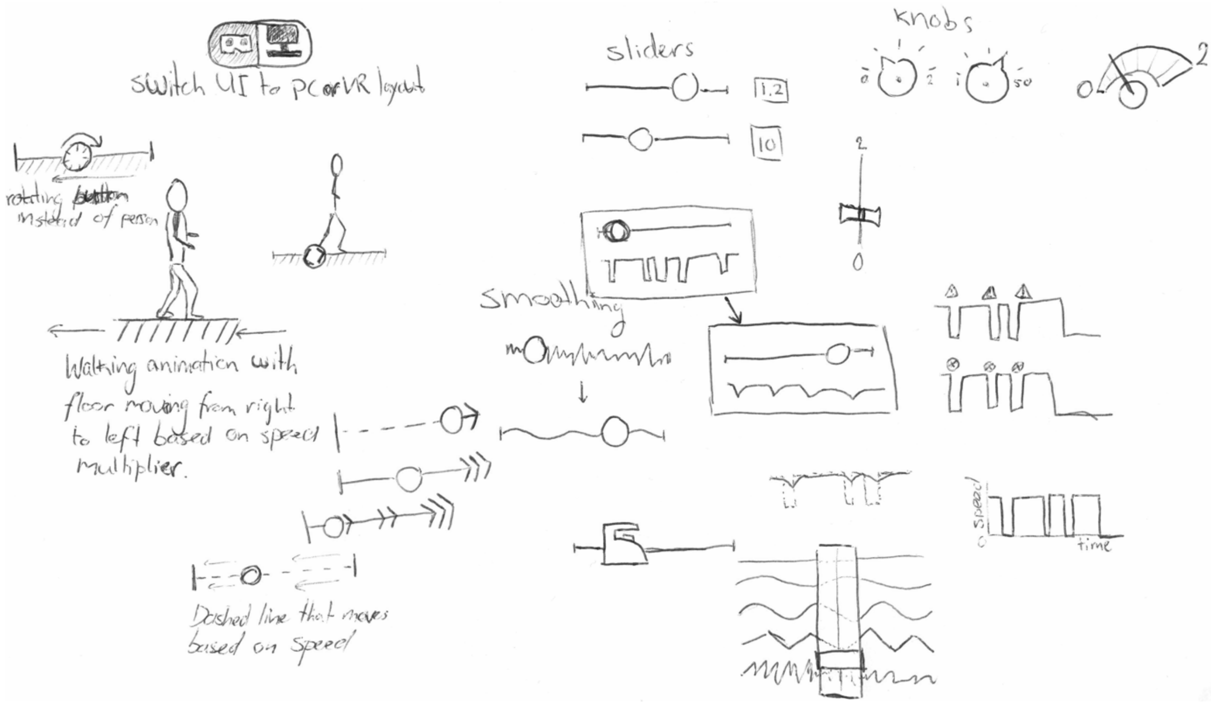

Figure 24: App GUI Elements Ideation

For the parameter interaction, I thought about two options: a slider or a dial button. A movement speed dial could work well as a metaphor for a speedometer, but it might be less suitable for the VR interface. When I tried out the difference between a slider or a dial in VR, I found that a dial might be less suitable as it requires more precise hand movement. Thus, I decided to continue with only sliders.

I sketched variations of the sliders for both the movement speed and smoothing. The main theme with most sketches was to show the effect of the parameter on the slider line. For example, smoothing could be visualized metaphorically with a jagged line that becomes smoother as the factor is raised. In the literature review, I used a graph to explain the effect of smoothing on the speed (Figure 4). Here, I decided that integrating this graph in the slider could visually explain to people the direct effect of the smoothing factor. The movement speed could be visualised with the slider line moving from right to left when it is dragged. However, all these animations might become too overwhelming. I assumed that movement speed needs less explanation than smoothing, so it was better to keep it visually simple. Thus, no animations for the movement speed slider.

10.3.2 Mid-Fidelity Prototypes

The next step was to create variations of some of the concepts in Figure 24 that are interactive. I used Axure RP to make several sliders that built upon the idea of the smoothing graph. I tried several ways of visually clarifying the smoothing effect and positioning the graph as can be seen below in Figure 25. Although adding more visual information, like the stick figure, might have made the meaning clearer, it also clutters the interface. In the end, I decided for the first version of the app to keep it simple and only incorporate the graph itself into the slider. However, in the future, I would like to test with novice users if the graph is sufficient.

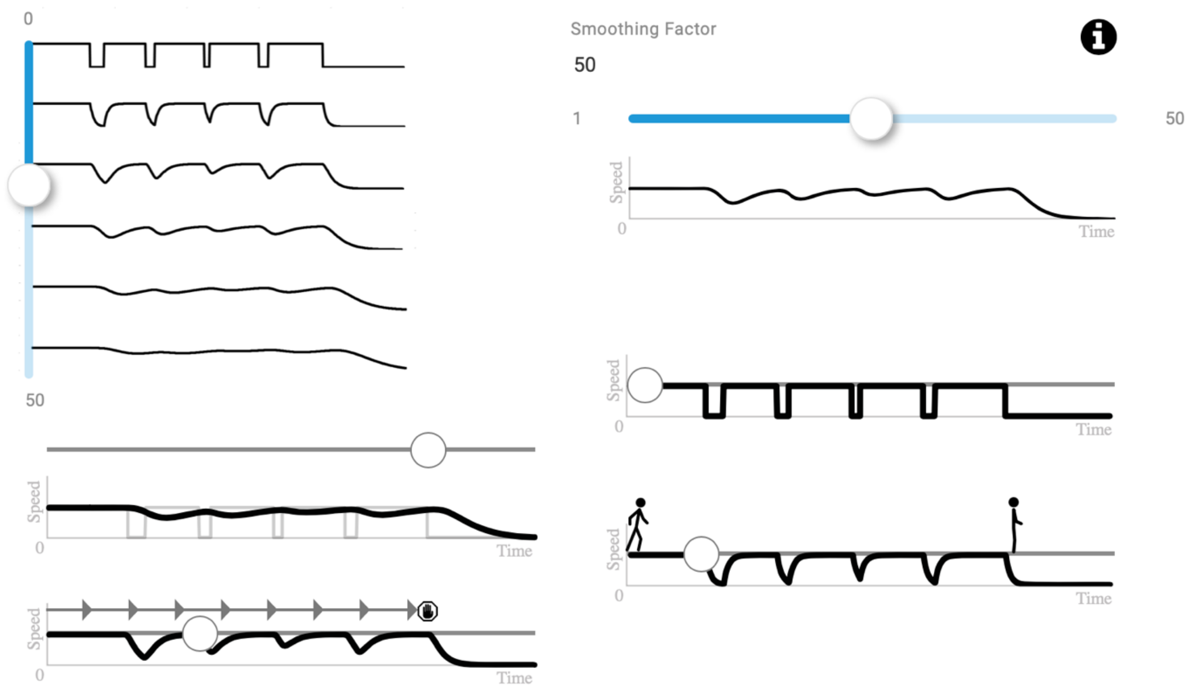

Figure 25: Axure Smoothing Slider Prototypes

10.4 Technical Implementation

Part of the implementation was also the software that needed to be written. I chose to use WinForm as a basis for the configuration app, as other Cyberith programs used the same setup and I experienced WinForm to be easy to learn.

10.4.1 Independent Communications

The first issue I tackled was that of communications. The app needed to be separate from other software, but still be able to communicate new speed and smoothing values to the Cyberith library that is run by the VR app. The solution I found was utilising named pipes. Named pipes are a form of interprocess communications, which allows communication and data sharing between applications on the same computer or network[7]. The server, in my case the Cyberith library, could create a named pipe, whereas the client, the app I developed, could connect to it. In contrast to using a Windows messaging protocol like WM_COPYDATA, named pipes did not require both processes to have a window. Thus, it worked with the Cyberith library process, which did not have a window of its own.

Named pipes could operate while the VR experience is running. Therefore, it made it possible to adjust speed and smoothing while users were in VR. Furthermore, named pipes minimum supported client was Windows 2000 Professional[8]. So, it was going to be compatible with all PCs running Windows 7 or newer.

10.4.2 Interacting in VR

Although the named pipes enabled changing parameters while the VR app is running, users still could not change it from within VR. One option was to develop a user interface that could be implemented into the VR app. However, this would have created the problem of dependency as discussed before. The developer would have needed then to decide to update their app to add support for the new interaction.

An option that I considered to be more suitable was the desktop view that can be accessed through the SteamVR menu within VR. Users could interact with their PC by opening the desktop view. With this interface, users could also use the app I developed while they are in VR. The only disadvantage was that the buttons and controls were made for use on a regular computer screen. Thus, I added a VR mode that could increase the

[7] https://docs.microsoft.com/en-us/windows/win32/ipc/named-pipe-operations
[8] https://docs.microsoft.com/en-us/windows/desktop/api/Winbase/nf-winbase-createnamedpipea

size of the buttons and made the interface more suitable for VR. This could be switched on and off whenever, hiding the VR controls when they are not required.

10.4.3 Backwards Compatibility

The system also needed to be able to deal with older Cyberith library versions. It was not possible to communicate to older versions of the DLL while it was running, but communication with the ini file was possible. So, I added the function that if no active named pipe could be found, the app would write the new parameter settings to the ini file. That way the configuration app had the option to still change the parameters for older versions, albeit only before the VR app had started.

10.5 Final Design

The final product is an app that can configure the speed and smoothing of the Virtualizer before starting and while running a VR app. It has two layouts: PC (Figure 26) and VR (Figure 27). The VR layout is simpler but larger, as it focuses on adjustments being quick and easy to do with VR controllers. Reading text is less comfortable in VR, so I tried to minimise that for the VR layout. Users can switch the layout by clicking the switch button in the bottom-right corner. Thus, it is possible to use the same app both on the PC and from within VR when using the desktop view of SteamVR.

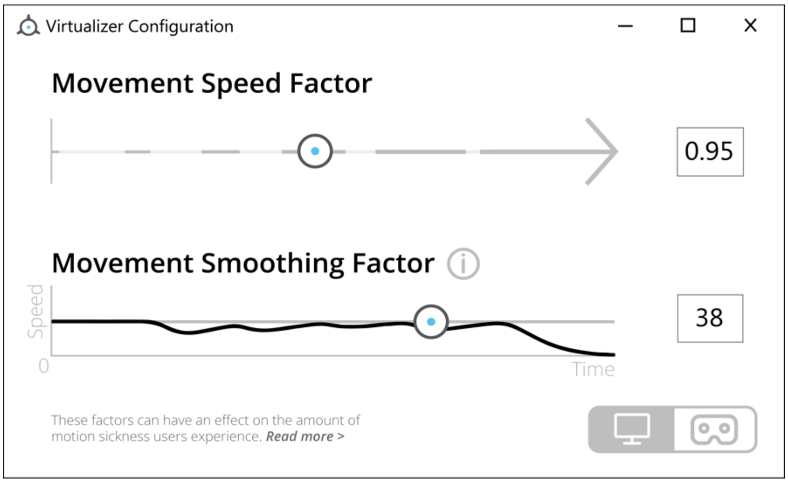

Figure 26: Virtualizer Configuration App (PC Layout)

The PC layout (Figure 26) has a few more elements that also include more text to read. For example, there is a small notice on the bottom that can make users or operators aware of the potential effects of changing the parameters. If users want to know more, they can click the link and read Cyberith's documentation on cybersickness. Furthermore, there is an info button next to the "Movement Smoothing Factor" that pop-ups a little text box when clicked on. The graph gives some visual information on the effect of smoothing, but if more info is required the button provides a short extra explanation on the why and how of smoothing. The last PC element that cannot be found in the VR layout is the text input box. If users wish to have a precise factor, they can type in a number.

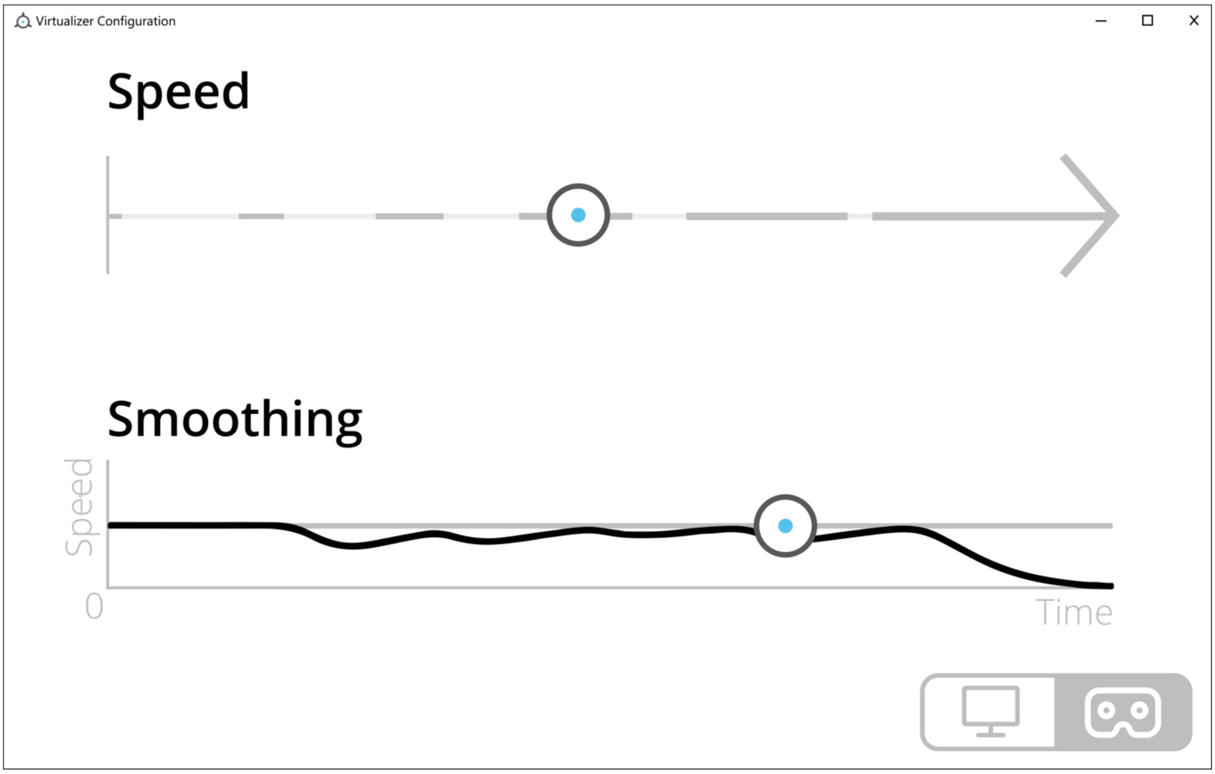

Figure 27: Virtualizer Configuration App (VR Layout)

The configuration app can deal with both the old system, by reading and writing the ini file, and the new system, by communicating with the DLL through a named pipe. It does not depend on the VR app used, so customers of Cyberith can easily update their software and add the configuration app.

10.5.1 Future Steps

The final design is a first version that is ready for testing. It works theoretically, but it has not been tested with real users yet. Several assumptions have been made on how easy it is to understand the GUI. Testing it with a variety of users should show if those assumptions hold. For example, an important question is if operators and users will understand what the smoothing graph is supposed to portray. If the graph is not clear enough, new solutions must be developed. The user study has shown that reducing the speed can lower cybersickness inducement. Now, a new study could be done with operators to see if they can use the tool effectively.

Not only the GUI might need to be improved, but also the discoverability could be increased. With the old system a user needed to be aware of the existence of the configuration file before they could start to edit it. Not everybody reads or remembers all manuals provided, so that is why I think it is important to make it easy to discover functionalities that can have a large impact on the VR experience. In a future update, a function could be added to the Cyberith library that automatically starts the configuration app when a VR app is initiated. That way the app pops up every time the user starts a Virtualizer VR app, making them aware of its existence. Also, the app could be added to the Cyberith Arcade.

11 Limitations

Several factors in this research resulted in limitations. In this section, I will discuss those limitations, how they influenced some of my choices and what could have been done differently.

A significant portion of the participants got sick of the experience, but another sizeable portion did not get sick at all or only very little. This meant that for them the conditions did not have a significant effect on their level of cybersickness. Thus, a part of the sample size consists of participants that did not show any distinguishable result. Assuming there is an order effect, it can matter for the results if one of the condition orders is overrepresented by participants that are not cybersickness susceptible. For analysing the CSQ data, it might be an option to define a threshold beforehand on which you decide when data should be included in the analysis. Data from participants below this threshold should be discarded then. This way every condition order will be ensured to have an equal number of participants that are susceptible to cybersickness.

To try to minimise the order effect, I asked the CSQ before and after each session and used a Latin square design for the condition orders. Nevertheless, it could be possible that the results were distorted by conditions being affected by the preceding session. The order of the conditions was not properly shuffled. Resulting in the same conditions coming after the other for most orders. For example, the control followed the high speed condition, except when the order started with the control.

The breaks were there to give the participants some time to rest, but also to try to normalise the participant's mental and physical state a bit. For some, this break might have been too short, and sickness could have still been increasing from the previous session as they start a new one. This could have been avoided by doing only one session per day and experiment for four consecutive days. However, I decided to not do this because of practical reasons. Considering many of my participants were working jobs or were only in Vienna for a short time, I would expect it to be near impossible to recruit enough participants that are available for four days in a row. Also, there is a higher risk that participants do not show up on one of the days. About a quarter of the people that signed up for the experiment did not reply anymore or cancelled.

Another option could be to do the experiment with a between-subject setup. That way you only need participants for one session on one day. The problem, however, is that you need four times as many participants to get to the same number of sessions. Furthermore, there is no option anymore to compare different conditions within the same participant. I would need to make sure that the susceptibility to cybersickness would be around equal between the different participant groups. A better option, in my opinion, is to limit the number of conditions to be tested. If you only need to test one condition and a control condition, there is less risk that the other sessions distort the results. Also, finding participants for two consecutive days is easier than finding participants for four days.

As the participants had to do all four sessions with only 10-minute breaks in between, it was also quite tiring for several participants. It might be that the tiredness influenced the participant's ratings for the CSQ and FMS. A person that feels very tired, might also then feel more negative about their current cybersickness state. If tiredness significantly affected the sickness rating, I would expect higher CSQ scores in later sessions. However, this was not the case. For example, the highest ΔDizzy mean was for the first session (

Table 5), albeit that the differences are small.

A last limitation of the experiment was that the VR experience had a few bugs and hardware problems that might have affected the level of cybersickness. For example, when the player character hit a Unity object collider the player sometimes went up a little bit, instead of being virtually stopped by the collider. These problems were relatively uncommon and did not exhibit in any condition specifically. Thus, I do not think they biased the scores for any of the conditions in particular, but they might have raised the sickness on average. Doing more pilot testing might have helped me in spotting some of the bugs before starting the main experiment.

Finally, the design of the configuration app has not been proven to work yet with users. Many of the design choices and the parameters were based on the user study, but they might not hold in the context of this app. Thus, with user tests, it should be figured out if the configuration app can be a useful tool to lower cybersickness even during the VR experience.

12 Conclusion

The primary goal of this thesis was to research how a system could reduce cybersickness for users of Cyberith's Virtualizer while they were in a VR experience. First, I looked in the academic literature for the theories behind the causes of cybersickness, ways of measuring cybersickness and methods to reduce it. After selecting the methods, I wanted to test, I set up a user study with the Virtualizer. In this study, I compared three parameters: movement speed, movement smoothing and a virtual body representation. The results of the experiment I used to implement a small app that could adjust the speed and smoothing to the user's (cybersickness) preferences before and during a VR experience. The resulting answers to the sub-questions of the thesis I will discuss below.

12.1 What Are the Causes of Cybersickness?

The most discussed theory of cybersickness that I found, was the Sensory Conflict Theory [2]. The theory posits that sickness comes from the mismatch between two sensory systems, for example, the vestibular and visual systems. For the Virtualizer, it would mainly be the mismatch between seeing forwards motion, but not perceiving acceleration forwards. Other theories put postural instability [4] or the lack of a stationary reference frame, a rest-frame [3], forward as causational factors in cybersickness. Although, postural instability might also be a result of becoming motion sick in VR [5], [6].

The experiment results showed that in the case of the Virtualizer the sensory mismatch played a significant part. Increasing the movement speed, in turn intensifying the visual-vestibular mismatch, had a statistically significant effect on the reported cybersickness levels. Not only did it speed up the visual flow, but the comments suggested that the higher speed worsened the issues of stopping and stuttering steps. Similarly, the smoothing might have helped in reducing reported cybersickness by in part lessen the impact of the stopping problem and stuttering steps. However, the CSQ results for the no smoothing condition were not statistically significant.

Another major cause of discomfort for participants was making turns. Although turning was not specifically tested, the comments suggested that instability because of turning was a cause of sickness. A closer investigation is required, however, to determine the specific cybersickness inducing factors involved in turning. A last minor cybersickness inducing factor that I identified from the comments was looking at the minimap.

12.2 What Are Solutions That Can Effectively Reduce Cybersickness When Using the Virtualizer?

In the literature review, I discussed 15 methods that could potentially reduce cybersickness. The most often researched solutions, with success, were reducing the FOV [29]–[35] and adding a rest-frame [28], [70], [71], [87], [88]. For my user study, I selected three methods that did not have as much proof as FOV reduction and the rest-frame. I tested if cybersickness could be reduced by decreasing the movement speed to a level that I defined as realistic, applying movement smoothing and adding a virtual body representation.

The CSQ and FMS results showed that decreasing the movement speed helped to reduce cybersickness inducement. I did not manage to prove that the avatar and movement smoothing had a statistically significant effect on cybersickness. From the comments, there were signs, however, that the smoothing compensated for stuttering steps and shifting. Which might have had an impact on cybersickness. A Virtualizer firmware update will resolve the issue of stopping, taking away the cybersickness that might have been specifically caused by this issue. The thematic analysis also indicated that participants already started to adapt and habituate after a few sessions of eight minutes each. Furthermore, some participants reported that being cognitively distracted helped in reducing sickness.

12.3 How Can the Level of Experienced Cybersickness, As Well As the Susceptibility to It, Be Measured Before, During or After a Session?

Cybersickness or susceptibility to it can be measured in several objective and subjective ways. The most common method of measurement is the SSQ, even though the CSQ and VRSQ showed better validity for VR according to the study of Sevinc and Berkman [16]. For the experiment, the CSQ was chosen because of its better validity and not including sweating and fatigue as symptoms. The FMS [17] and MISC [18] are examples of one-dimensional scales that allow researchers to measure cybersickness while participants are in VR. Susceptibility to cybersickness could be measured with the VIMSSQ [19], whereas the MSSQ looks at past motion sickness experiences in general [20].

Apart from questionnaires, the physiological state also provides information on the degree of cybersickness participants are experiencing. The benefit of collecting physiological data is that it can be done during the VR experience, and it is a source of objective data. In contrast with the questionnaires, there is not a type that is the most popular. Measurement options that I found in the literature review were ECG, blood pressure, galvanic skin response, eye-tracking, heart rate, respiration, and cutaneous thermoregulatory vascular tone [8]–[12]. I decided to include neither of those as some data might have gotten distorted by the physiological reaction to exercise. Also, the hardware would have further complicated the experiment setup and extended the duration of an already long experiment.

Another option for objective data is measuring postural sway or gait parameters. Rebenitsch and Quinby had demonstrated that certain positional and rotational parameters of the VR headset were correlated with cybersickness [7]. Therefore, I decided to analyse the VR headset motion variance and max data from the measurement I did before and after the participants walked in the maze. However, I did not find any significant difference between the conditions. I did not analyse the data that was recorded during walking, so it might be that a significant difference could be found for this specific dataset.

12.4 How Could a System Be Adjusted to a User's Specific Cybersickness Needs?

The experiment proved that reducing the speed can lower cybersickness, but also affect satisfaction. Therefore, I decided to develop an app in which users could quickly adjust that parameter. Smoothing was also included as it might reduce stuttering and shifting. The final result is an app that can communicate with the Cyberith software, without being dependent on the VR app that is using the Virtualizer. Operators or users can adjust the parameters to their needs inside and outside of the VR experience. The GUI provides a visual explanation of the effects of both parameters.

12.5 Closing Statement

Looking at the results, it becomes clear that cybersickness is a multifaceted issue. There is no one solution (yet) that solves everything for everyone. Fortunately, many solutions have been thought of already. Some being more effective than others. By testing and further investigating cybersickness and its underlying mechanisms, we can get closer to a VR experience that is free of cybersickness for everybody. One-by-one cybersickness inducing factors could be eliminated. This thesis supports this goal by providing proof for one solution, movement speed, showing signs that smoothing might have an impact as well, and extending the knowledge on several other factors of cybersickness. By reducing the speed and applying smoothing, the first step can be set by new users to get more comfortably used to VR and the Virtualizer.

13 References

[1] M. E. McCauley and T. J. Sharkey, “Cybersickness: Perception of Self-Motion in Virtual Environments,” *Presence: Teleoperators and Virtual Environments*, vol. 1, no. 3, Jan. 1992, doi: 10.1162/pres.1992.1.3.311.

[2] J. T. Reason and J. J. Brand, *Motion Sickness*. London, New York: Academic Press, 1975.

[3] J. D. Prothero and D. E. Parker, “A Unified Approach to Presence and Motion Sickness,” in *Virtual and Adaptive Environments: Applications, Implications, and Human Performance Issues*, Boca Raton, FL, USA: CRC Press, 2003, pp. 47–66.

[4] G. E. Riccio and T. A. Stoffregen, “An ecological Theory of Motion Sickness and Postural Instability,” *Ecological Psychology*, vol. 3, no. 3, Sep. 1991, doi: 10.1207/s15326969eco0303_2.

[5] S. Weech, J. P. Varghese, and M. Barnett-Cowan, “Estimating the sensorimotor components of cybersickness,” *Journal of Neurophysiology*, vol. 120, no. 5, Nov. 2018, doi: 10.1152/jn.00477.2018.

[6] H. Akiduki, S. Nishiike, H. Watanabe, K. Matsuoka, T. Kubo, and N. Takeda, “Visual-vestibular conflict induced by virtual reality in humans,” *Neuroscience Letters*, vol. 340, no. 3, Apr. 2003, doi: 10.1016/S0304-3940(03)00098-3.

[7] L. Rebenitsch and B. Quinby, “Cybersickness and Postural Sway Using HMD Orientation,” in *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, 2019, vol. 11574 LNCS, pp. 500–509. doi: 10.1007/978-3-030-21607-8_39.

[8] G. Y. Menshikova, A. I. Kovalev, O. A. Klimova, and V. v. Barabanschikova, “The application of virtual reality technology to testing resistance to motion sickness,” *Psychology in Russia: State of the Art*, vol. 10, no. 3, pp. 151–164, 2017, doi: 10.11621/pir.2017.0310.

[9] R. Islam *et al.*, “Automatic Detection and Prediction of Cybersickness Severity using Deep Neural Networks from user’s Physiological Signals,” Nov. 2020. doi: 10.1109/ISMAR50242.2020.00066.

[10] C. Nakagawa, “Toward the detection of the onset of virtual reality sickness by autonomic indices,” Oct. 2015. doi: 10.1109/GCCE.2015.7398740.

[11] E. Nalivaiko, S. L. Davis, K. L. Blackmore, A. Vakulin, and K. v. Nesbitt, “Cybersickness provoked by head-mounted display affects cutaneous vascular tone, heart rate and reaction time,” *Physiology & Behavior*, vol. 151, Nov. 2015, doi: 10.1016/j.physbeh.2015.08.043.

[12] L. Rebenitsch and C. Owen, “Review on cybersickness in applications and visual displays,” *Virtual Reality*, vol. 20, no. 2, pp. 101–125, Jun. 2016, doi: 10.1007/s10055-016-0285-9.

[13] R. S. Kennedy, N. E. Lane, K. S. Berbaum, and M. G. Lilienthal, “Simulator Sickness Questionnaire: An Enhanced Method for Quantifying Simulator Sickness,” *The International Journal of Aviation Psychology*, vol. 3, no. 3, Jul. 1993, doi: 10.1207/s15327108ijap0303_3.

[14] W. B. Stone III, “Psychometric Evaluation of the Simulator Sickness Questionnaire as a Measure of Cybersickness,” 2017.

[15] H. K. Kim, J. Park, Y. Choi, and M. Choe, “Virtual reality sickness questionnaire (VRSQ): Motion sickness measurement index in a virtual reality environment,” *Applied Ergonomics*, vol. 69, May 2018, doi: 10.1016/j.apergo.2017.12.016.

[16] V. Sevinc and M. I. Berkman, “Psychometric evaluation of Simulator Sickness Questionnaire and its variants as a measure of cybersickness in consumer virtual environments,” *Applied Ergonomics*, vol. 82, Jan. 2020, doi: 10.1016/j.apergo.2019.102958.

[17] B. Keshavarz and H. Hecht, “Validating an Efficient Method to Quantify Motion Sickness,” *Human Factors: The Journal of the Human Factors and Ergonomics Society*, vol. 53, no. 4, Aug. 2011, doi: 10.1177/0018720811403736.

[18] A. H. Wertheim, J. E. Bos, and A. J. Krul, “Predicting Motion Induced Vomiting from Subjective Misery (MISC) Ratings Obtained in 12 Experimental Studies,” Soesterberg, NL, 2001.

[19] B. Keshavarz, B. Murovec, N. Mohanathas, and J. F. Golding, "The Visually Induced Motion Sickness Susceptibility Questionnaire (VIMSSQ): Estimating Individual Susceptibility to Motion Sickness-Like Symptoms When Using Visual Devices," *Human Factors: The Journal of the Human Factors and Ergonomics Society*, Apr. 2021, doi: 10.1177/00187208211008687.

[20] J. F. Golding, "Motion sickness susceptibility questionnaire revised and its relationship to other forms of sickness," *Brain Research Bulletin*, vol. 47, no. 5, Nov. 1998, doi: 10.1016/S0361-9230(98)00091-4.

[21] T. Hartmann *et al.*, "The Spatial Presence Experience Scale (SPES)," *Journal of Media Psychology*, vol. 28, no. 1, Jan. 2016, doi: 10.1027/1864-1105/a000137.

[22] N. Duzmanska, P. Strojny, and A. Strojny, "Can simulator sickness be avoided? A review on temporal aspects of simulator sickness," *Frontiers in Psychology*, vol. 9, no. NOV. Frontiers Media S.A., Nov. 06, 2018. doi: 10.3389/fpsyg.2018.02132.

[23] B. Cheung and K. Hofer, "Desensitization to strong vestibular stimuli improves tolerance to simulated aircraft motion," *Aviation, Space, and Environmental Medicine*, vol. 76, no. 12, pp. 1099–1104, Dec. 2005.

[24] J. E. Domeyer, N. D. Cassavaugh, and R. W. Backs, "The use of adaptation to reduce simulator sickness in driving assessment and research," *Accident Analysis & Prevention*, vol. 53, Apr. 2013, doi: 10.1016/j.aap.2012.12.039.

[25] A. M. Gavgani, K. v. Nesbitt, K. L. Blackmore, and E. Nalivaiko, "Profiling subjective symptoms and autonomic changes associated with cybersickness," *Autonomic Neuroscience*, vol. 203, Mar. 2017, doi: 10.1016/j.autneu.2016.12.004.

[26] K. J. Hill and P. A. Howarth, "Habituation to the side effects of immersion in a virtual environment," *Displays*, vol. 21, no. 1, Mar. 2000, doi: 10.1016/S0141-9382(00)00029-9.

[27] H. Ujike, K. Ukai, and K. Nihei, "Survey on motion sickness-like symptoms provoked by viewing a video movie during junior high school class," *Displays*, vol. 29, no. 2, Mar. 2008, doi: 10.1016/j.displa.2007.09.003.

[28] C. Wienrich, C. K. Weidner, C. Schatto, D. Obremski, and J. H. Israel, "A Virtual Nose as a Rest-Frame - The Impact on Simulator Sickness and Game Experience," Sep. 2018. doi: 10.1109/VS-Games.2018.8493408.

[29] A. S. Fernandes and S. K. Feiner, "Combating VR sickness through subtle dynamic field-of-view modification," Mar. 2016. doi: 10.1109/3DUI.2016.7460053.

[30] K. Carnegie and T. Rhee, "Reducing Visual Discomfort with HMDs Using Dynamic Depth of Field," *IEEE Computer Graphics and Applications*, vol. 35, no. 5, Sep. 2015, doi: 10.1109/MCG.2015.98.

[31] K. Lim, J. Lee, K. Won, N. Kala, and T. Lee, "A novel method for VR sickness reduction based on dynamic field of view processing," *Virtual Reality*, vol. 25, no. 2, pp. 331–340, Jun. 2021, doi: 10.1007/s10055-020-00457-3.

[32] J. E. Bos, S. C. de Vries, M. L. van Emmerik, and E. L. Groen, "The effect of internal and external fields of view on visually induced motion sickness," *Applied Ergonomics*, vol. 41, no. 4, pp. 516–521, 2010, doi: 10.1016/j.apergo.2009.11.007.

[33] B. Keshavarz, H. Hecht, and L. Zschutschke, "Intra-visual conflict in visually induced motion sickness," *Displays*, vol. 32, no. 4, pp. 181–188, Oct. 2011, doi: 10.1016/j.displa.2011.05.009.

[34] J. Jeng, W. Lin, H. B. L. Duh, D. E. Parker, H. Abi-Rached, and T. A. Furness, "Effects of Field of View on Presence, Enjoyment, Memory, and Simulator Sickness in a Virtual Environment," 2002.

[35] A. F. Seay, D. M. Krum, L. Hodges, and W. Ribarsky, "Simulator sickness and presence in a high field-of-view virtual environment," 2002. doi: 10.1145/506443.506596.

[36] M. C. Howard and E. C. van Zandt, “A meta-analysis of the virtual reality problem: Unequal effects of virtual reality sickness across individual differences,” *Virtual Reality*, 2021, doi: 10.1007/s10055-021-00524-3.

[37] A. Mazloumi Gavgani, F. R. Walker, D. M. Hodgson, and E. Nalivaiko, “A comparative study of cybersickness during exposure to virtual reality and ‘classic’ motion sickness: are they different?,” *Journal of Applied Physiology*, vol. 125, no. 6, Dec. 2018, doi: 10.1152/japplphysiol.00338.2018.

[38] R. H. Y. So, W. T. Lo, and A. T. K. Ho, “Effects of Navigation Speed on Motion Sickness Caused by an Immersive Virtual Environment,” *Human Factors: The Journal of the Human Factors and Ergonomics Society*, vol. 43, no. 3, Sep. 2001, doi: 10.1518/001872001775898223.

[39] R. H. Y. So and W. T. Lo, “Cybersickness: an experimental study to isolate the effects of rotational scene oscillations,” 1999. doi: 10.1109/VR.1999.756957.

[40] A. J. A. Lubeck, J. E. Bos, and J. F. Stins, “Motion in images is essential to cause motion sickness symptoms, but not to increase postural sway,” *Displays*, vol. 38, Jul. 2015, doi: 10.1016/j.displa.2015.03.001.

[41] C.-L. Liu and S.-T. Uang, “A study of sickness induced within a 3D virtual store and combated with fuzzy control in the elderly,” May 2012. doi: 10.1109/FSKD.2012.6234149.

[42] F. Bonato, A. Bubka, and S. Palmisano, “Combined Pitch and Roll and Cybersickness in a Virtual Environment,” *Aviation, Space, and Environmental Medicine*, vol. 80, no. 11, Nov. 2009, doi: 10.3357/ASEM.2394.2009.

[43] D. Risi and S. Palmisano, “Effects of postural stability, active control, exposure duration and repeated exposures on HMD induced cybersickness,” *Displays*, vol. 60, pp. 9–17, Dec. 2019, doi: 10.1016/j.displa.2019.08.003.

[44] C. Diels and P. A. Howarth, “Visually induced motion sickness: Single- versus dual-axis motion,” *Displays*, vol. 32, no. 4, Oct. 2011, doi: 10.1016/j.displa.2011.02.005.

[45] S. Palmisano, F. Bonato, A. Bubka, and J. Folder, “Vertical Display Oscillation Effects on Forward Vection and Simulator Sickness,” *Aviation, Space, and Environmental Medicine*, vol. 78, no. 10, Oct. 2007, doi: 10.3357/ASEM.2079.2007.

[46] L. J. Smart, T. A. Stoffregen, and B. G. Bardy, “Visually Induced Motion Sickness Predicted by Postural Instability,” *Human Factors: The Journal of the Human Factors and Ergonomics Society*, vol. 44, no. 3, Sep. 2002, doi: 10.1518/0018720024497745.

[47] L. J. Hettinger, R. S. Kennedy, and M. E. McCauley, “Motion and human performance,” in *Motion and space sickness*, Boca Raton, FL: CRC Press, 1990, pp. 411–441.

[48] N. A. Webb and M. J. Griffin, “Eye movement, vection, and motion sickness with foveal and peripheral vision,” *Aviation Space and Environmental Medicine*, vol. 74, no. 6, pp. 622–625, Jun. 2003.

[49] N. A. Webb and M. J. Griffin, “Optokinetic stimuli: motion sickness, visual acuity and eye movements,” *Aviation, Space and Environmental Medicine*, vol. 73, no. 4, pp. 351–358, 2002.

[50] J. D. Prothero, M. H. Draper, T. A. Furness III, D. E. Parker, and M. J. Wells, “The use of an independent visual background to reduce simulator side- effects,” *Aviation Space and Environmental Medicine*, vol. 70, no. 3 Pt 1, pp. 277–283, Mar. 1999.

[51] F. Bonato, A. Bubka, S. Palmisano, D. Phillip, and G. Moreno, “Vection Change Exacerbates Simulator Sickness in Virtual Environments,” *Presence: Teleoperators and Virtual Environments*, vol. 17, no. 3, Jun. 2008, doi: 10.1162/pres.17.3.283.

[52] O. X. Kuiper, J. E. Bos, and C. Diels, “Vection does not necessitate visually induced motion sickness,” *Displays*, vol. 58, pp. 82–87, Jul. 2019, doi: 10.1016/j.displa.2018.10.001.

[53] M. W. Greenlee *et al.*, “Multisensory Integration in Self Motion Perception,” *Multisensory Research*, vol. 29, no. 6–7, 2016, doi: 10.1163/22134808-00002527.

[54] A. M. Green and D. E. Angelaki, "Multisensory integration: resolving sensory ambiguities to build novel representations," *Current Opinion in Neurobiology*, vol. 20, no. 3, Jun. 2010, doi: 10.1016/j.conb.2010.04.009.

[55] M. Gallagher and E. R. Ferrè, "Cybersickness: A Multisensory Integration Perspective," *Multisensory Research*, vol. 31, no. 7. Brill Academic Publishers, pp. 645–674, 2018. doi: 10.1163/22134808-20181293.

[56] L. Ungerleider, "'What' and 'where' in the human brain," *Current Opinion in Neurobiology*, vol. 4, no. 2, 1994, doi: 10.1016/0959-4388(94)90066-3.

[57] J. Dichgans and T. Brandt, "Visual-Vestibular Interaction: Effects on Self-Motion Perception and Postural Control," in *Perception*, Berlin, Heidelberg: Springer Berlin Heidelberg, 1978. doi: 10.1007/978-3-642-46354-9_25.

[58] A. Delorme and C. Martin, "Roles of retinal periphery and depth periphery in linear vection and visual control of standing in humans.," *Canadian Journal of Psychology/Revue canadienne de psychologie*, vol. 40, no. 2, 1986, doi: 10.1037/h0080091.

[59] I. P. Howard and T. Heckmann, "Circular Vection as a Function of the Relative Sizes, Distances, and Positions of Two Competing Visual Displays," *Perception*, vol. 18, no. 5, Oct. 1989, doi: 10.1068/p180657.

[60] Pöhlmann K.M.T., Föcker J., Dickinson P., Parke A., and O'Hare L., "The effect of motion direction and eccentricity on vection, VR sickness and head movements in virtual reality," *Multisensory Research*, vol. 34, no. 6, 2021, doi: 10.1163/22134808-bja10049.

[61] B. Arcioni, S. Palmisano, D. Apthorp, and J. Kim, "Postural stability predicts the likelihood of cybersickness in active HMD-based virtual reality," *Displays*, vol. 58, Jul. 2019, doi: 10.1016/j.displa.2018.07.001.

[62] D. Risi and S. Palmisano, "Can We Predict Susceptibility to Cybersickness?," Nov. 2019. doi: 10.1145/3359996.3364705.

[63] S. Litleskare, "The relationship between postural stability and cybersickness: It's complicated – An experimental trial assessing practical implications of cybersickness etiology," *Physiology & Behavior*, vol. 236, Jul. 2021, doi: 10.1016/j.physbeh.2021.113422.

[64] M. S. Dennison and M. D'Zmura, "Cybersickness without the wobble: Experimental results speak against postural instability theory," *Applied Ergonomics*, vol. 58, Jan. 2017, doi: 10.1016/j.apergo.2016.06.014.

[65] M. Dennison and M. D'Zmura, "Effects of unexpected visual motion on postural sway and motion sickness," *Applied Ergonomics*, vol. 71, Sep. 2018, doi: 10.1016/j.apergo.2018.03.015.

[66] K. A. Pettijohn, D. Geyer, J. Gomez, W. J. Becker, and A. T. Biggs, "Postural Instability and Simulator Seasickness," *Aerospace Medicine and Human Performance*, vol. 89, no. 7, Jul. 2018, doi: 10.3357/AMHP.4998.2018.

[67] K. A. Pettijohn, D. v. Pistone, A. L. Warner, G. J. Roush, and A. T. Biggs, "Postural Instability and Seasickness in a Motion-Based Shooting Simulation," *Aerospace Medicine and Human Performance*, vol. 91, no. 9, Sep. 2020, doi: 10.3357/AMHP.5539.2020.

[68] A. K. T. Ng, L. K. Y. Chan, and H. Y. K. Lau, "Effect of Sensory Conflict and Postural Instability on Cybersickness," Mar. 2019. doi: 10.1109/VR.2019.8797781.

[69] L. Warwick-Evans and S. Beaumont, "An Experimental Evaluation of Sensory Conflict Versus Postural Control Theories of Motion Sickness," *Ecological Psychology*, vol. 7, no. 3, Sep. 1995, doi: 10.1207/s15326969eco0703_1.

[70] E. Chang, I. Hwang, H. Jeon, Y. Chun, H. T. Kim, and C. Park, "Effects of rest frames on cybersickness and oscillatory brain activity," Feb. 2013. doi: 10.1109/IWW-BCI.2013.6506631.

[71] A. Somrak, M. Pogačnik, and J. Guna, “Impact of different types of head-centric rest-frames on vrise and user experience in virtual environments,” *Applied Sciences (Switzerland)*, vol. 11, no. 4, pp. 1–33, Feb. 2021, doi: 10.3390/app11041593.

[72] R. Reinhard *et al.*, “The best way to assess visually induced motion sickness in a fixed-base driving simulator,” *Transportation Research Part F: Traffic Psychology and Behaviour*, vol. 48, Jul. 2017, doi: 10.1016/j.trf.2017.05.005.

[73] B. Keshavarz and H. Hecht, “Pleasant music as a countermeasure against visually induced motion sickness,” *Applied Ergonomics*, vol. 45, no. 3, May 2014, doi: 10.1016/j.apergo.2013.07.009.

[74] N. McHugh, S. Jung, S. Hoermann, and R. W. Lindeman, “Investigating a physical dial as a measurement tool for cybersickness in virtual reality,” Nov. 2019. doi: 10.1145/3359996.3364259.

[75] J. F. Golding, A. Rafiq, and B. Keshavarz, “Predicting Individual Susceptibility to Visually Induced Motion Sickness by Questionnaire,” *Frontiers in Virtual Reality*, vol. 2, Feb. 2021, doi: 10.3389/frvir.2021.576871.

[76] P. Caserman, A. Garcia-Agundez, A. Gámez Zerban, and S. Göbel, “Cybersickness in current-generation virtual reality head-mounted displays: systematic review and outlook,” *Virtual Reality*, 2021, doi: 10.1007/s10055-021-00513-6.

[77] A. M. Gavgani, K. v. Nesbitt, K. L. Blackmore, and E. Nalivaiko, “Profiling subjective symptoms and autonomic changes associated with cybersickness,” *Autonomic Neuroscience*, vol. 203, Mar. 2017, doi: 10.1016/j.autneu.2016.12.004.

[78] M. S. Dennison, M. D’Zmura, A. v. Harrison, M. Lee, and A. J. Raglin, “Improving motion sickness severity classification through multi-modal data fusion,” in *Artificial Intelligence and Machine Learning for Multi-Domain Operations Applications*, May 2019. doi: 10.1117/12.2519085.

[79] R. Islam, S. Ang, and J. Quarles, “CyberSense: A closed-loop framework to detect cybersickness severity and adaptively apply reduction techniques,” in *Proceedings - 2021 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops, VRW 2021*, Mar. 2021, pp. 148–155. doi: 10.1109/VRW52623.2021.00035.

[80] E. Chang, H. T. Kim, and B. Yoo, “Virtual Reality Sickness: A Review of Causes and Measurements,” *International Journal of Human-Computer Interaction*, pp. 1658–1682, 2020, doi: 10.1080/10447318.2020.1778351.

[81] T. Feigl *et al.*, “Sick Moves! Motion Parameters as Indicators of Simulator Sickness,” *IEEE Transactions on Visualization and Computer Graphics*, vol. 25, no. 11, pp. 3146–3157, Nov. 2019, doi: 10.1109/TVCG.2019.2932224.

[82] J. R. Chardonnet, M. A. Mirzaei, and F. Mérienne, “Features of the Postural Sway Signal as Indicators to Estimate and Predict Visually Induced Motion Sickness in Virtual Reality,” *International Journal of Human-Computer Interaction*, vol. 33, no. 10, pp. 771–785, Oct. 2017, doi: 10.1080/10447318.2017.1286767.

[83] Y. Wang, J. R. Chardonnet, and F. Merienne, “VR sickness prediction for navigation in immersive virtual environments using a deep long short term memory model,” in *26th IEEE Conference on Virtual Reality and 3D User Interfaces, VR 2019 - Proceedings*, Mar. 2019, pp. 1874–1881. doi: 10.1109/VR.2019.8798213.

[84] N. Norouzi, G. Bruder, and G. Welch, “Assessing vignetting as a means to reduce VR sickness during amplified head rotations,” Aug. 2018. doi: 10.1145/3225153.3225162.

[85] K. Stanney, C. Fidopiastis, and L. Foster, “Virtual Reality Is Sexist: But It Does Not Have to Be,” *Frontiers in Robotics and AI*, vol. 7, Jan. 2020, doi: 10.3389/frobt.2020.00004.

[86] J. M. Fulvio, M. Ji, and B. Rokers, “Variations in visual sensitivity predict motion sickness in virtual reality,” *Entertainment Computing*, vol. 38, May 2021, doi: 10.1016/j.entcom.2021.100423.

[87] Z. Cao, J. Jerald, and R. Kopper, “Visually-Induced Motion Sickness Reduction via Static and Dynamic Rest Frames,” in *25th IEEE Conference on Virtual Reality and 3D User Interfaces, VR 2018 - Proceedings*, Aug. 2018, pp. 105–112. doi: 10.1109/VR.2018.8446210.

[88] R. Luks and F. Liarokapis, “Investigating motion sickness techniques for immersive virtual environments,” in *ACM International Conference Proceeding Series*, Jun. 2019, pp. 280–288. doi: 10.1145/3316782.3321535.

[89] K. K. K. Kwok, A. K. T. Ng, and H. Y. K. Lau, “Effect of Navigation Speed and VR Devices on Cybersickness,” in *Adjunct Proceedings - 2018 IEEE International Symposium on Mixed and Augmented Reality, ISMAR-Adjunct 2018*, Jul. 2018, pp. 91–92. doi: 10.1109/ISMAR-Adjunct.2018.00041.

[90] A. Agić, E. Murseli, L. Mandić, and L. Skorin-Kapov, “The impact of different navigation speeds on cybersickness and stress level in VR,” *Journal of Graphic Engineering and Design*, vol. 11, no. 1, pp. 5–11, 2020, doi: 10.24867/JGED-2020-1-005.

[91] B. Keshavarz, A. E. Philipp-Muller, W. Hemmerich, B. E. Riecke, and J. L. Campos, “The effect of visual motion stimulus characteristics on vection and visually induced motion sickness,” *Displays*, vol. 58, pp. 71–81, Jul. 2019, doi: 10.1016/j.displa.2018.07.005.

[92] N. Ranasinghe, P. Jain, D. Tolley, S. Karwita Tailan, C. C. Yen, and E. Y. L. Do, “Exploring the Use of Olfactory Stimuli towards Reducing Visually Induced Motion Sickness in Virtual Reality,” Oct. 2020. doi: 10.1145/3385959.3418451.

[93] B. Keshavarz, D. Stelzmann, A. Paillard, and H. Hecht, “Visually induced motion sickness can be alleviated by pleasant odors,” *Experimental Brain Research*, vol. 233, no. 5, May 2015, doi: 10.1007/s00221-015-4209-9.

[94] G. Gálvez-García, “A comparison of techniques to mitigate Simulator Adaptation Syndrome,” *Ergonomics*, vol. 58, no. 8, Aug. 2015, doi: 10.1080/00140139.2015.1005168.

[95] G. Gálvez-García, N. Aldunate, C. Bascour-Sandoval, M. Barramuño, F. Fonseca, and E. Gómez-Milán, “Decreasing motion sickness by mixing different techniques,” *Applied Ergonomics*, vol. 82, Jan. 2020, doi: 10.1016/j.apergo.2019.102931.

[96] G. Gálvez-García, M. Hay, and C. Gabaude, “Alleviating Simulator Sickness with Galvanic Cutaneous Stimulation,” *Human Factors: The Journal of the Human Factors and Ergonomics Society*, vol. 57, no. 4, Jun. 2015, doi: 10.1177/0018720814554948.

[97] H. Chu, M.-H. Li, Y.-C. Huang, and S.-Y. Lee, “Simultaneous transcutaneous electrical nerve stimulation mitigates simulator sickness symptoms in healthy adults: a crossover study,” *BMC Complementary and Alternative Medicine*, vol. 13, no. 1, Dec. 2013, doi: 10.1186/1472-6882-13-84.

[98] T.-L. Tsai, C.-H. Chuang, C.-Y. Chen, P.-J. Wu, and H.-W. Chen, “Research on Reducing Motion Sickness of Playing First Person Shooting VR Game with Texture Blur,” 2020.

[99] G. Y. Nie, H. B. L. Duh, Y. Liu, and Y. Wang, “Analysis on Mitigation of Visually Induced Motion Sickness by Applying Dynamical Blurring on a User’s Retina,” *IEEE Transactions on Visualization and Computer Graphics*, vol. 26, no. 8, pp. 2535–2545, Aug. 2020, doi: 10.1109/TVCG.2019.2893668.

[100] M. Pouke, A. Tiiro, S. M. LaValle, and T. Ojala, “Effects of Visual Realism and Moving Detail on Cybersickness,” Mar. 2018. doi: 10.1109/VR.2018.8446078.

[101] S. E. Stromberg, M. E. Russell, and C. R. Carlson, “Diaphragmatic breathing and its effectiveness for the management of motion sickness,” *Aerospace Medicine and Human Performance*, vol. 86, no. 5, pp. 452–457, May 2015, doi: 10.3357/AMHP.4152.2015.

[102] S. D’Amour, J. E. Bos, and B. Keshavarz, “The efficacy of airflow and seat vibration on reducing visually induced motion sickness,” *Experimental Brain Research*, vol. 235, no. 9, pp. 2811–2820, Sep. 2017, doi: 10.1007/s00221-017-5009-1.

[103] A. Paroz and L. E. Potter, "Impact of air flow and a hybrid locomotion system on cybersickness," in *ACM International Conference Proceeding Series*, Dec. 2018, pp. 582–586. doi: 10.1145/3292147.3292229.

[104] S.-H. Liu, N.-H. Yu, L. Chan, Y.-H. Peng, W.-Z. Sun, and M. Y. Chen, "PhantomLegs: Reducing Virtual Reality Sickness Using Head-Worn Haptic Devices," Mar. 2019. doi: 10.1109/VR.2019.8798158.

[105] Y. Wang, J. R. Chardonnet, and F. Merienne, "Development of a speed protector to optimize user experience in 3D virtual environments," *International Journal of Human Computer Studies*, vol. 147, Mar. 2021, doi: 10.1016/j.ijhcs.2020.102578.

[106] C. Widdowson, I. Becerra, C. Merrill, R. F. Wang, and S. LaValle, "Assessing Postural Instability and Cybersickness Through Linear and Angular Displacement," *Human Factors*, vol. 63, no. 2, pp. 296–311, Mar. 2021, doi: 10.1177/0018720819881254.

[107] S. F. M. Zaidi and T. Male, "Experimenting novel virtual-reality immersion strategy to alleviate cybersickness," Nov. 2018. doi: 10.1145/3281505.3281613.

[108] C. Zhou, C. Luisa Bryan, E. Wang, N. Sertac Artan, and Z. Dong, "Cognitive Distraction to Improve Cybersickness in Virtual Reality Environment."

[109] Ubisoft Entertainment, "Eagle Flight." Oct. 18, 2016.

[110] I. B. Adhanom, N. Navarro Griffin, P. MacNeilage, and E. Folmer, "The Effect of a Foveated Field-of-view Restrictor on VR Sickness," Jun. 2020, pp. 645–652. doi: 10.1109/vr46266.2020.00087.

[111] J. Munafo, M. Diedrick, and T. A. Stoffregen, "The virtual reality head-mounted display Oculus Rift induces motion sickness and is sexist in its effects," *Experimental Brain Research*, vol. 235, no. 3, Mar. 2017, doi: 10.1007/s00221-016-4846-7.

[112] K. M. Stanney, K. S. Hale, I. Nahmens, and R. S. Kennedy, "What to Expect from Immersive Virtual Environment Exposure: Influences of Gender, Body Mass Index, and Past Experience," *Human Factors: The Journal of the Human Factors and Ergonomics Society*, vol. 45, no. 3, Sep. 2003, doi: 10.1518/hfes.45.3.504.27254.

[113] S. Grassini, K. Laumann, and A. K. Luzi, "Association of Individual Factors with Simulator Sickness and Sense of Presence in Virtual Reality Mediated by Head-Mounted Displays (HMDs)," *Multimodal Technologies and Interaction*, vol. 5, no. 3, Feb. 2021, doi: 10.3390/mti5030007.

[114] M. Turner and M. J. Griffing, "Motion sickness in public road transport: passenger behaviour and susceptibility," *Ergonomics*, vol. 42, no. 3, Mar. 1999, doi: 10.1080/001401399185586.

[115] A. Lawther and M. J. Griffin, "Prediction of the incidence of motion sickness from the magnitude, frequency, and duration of vertical oscillation," *The Journal of the Acoustical Society of America*, vol. 79, no. S1, May 1986, doi: 10.1121/1.2023435.

[116] C. Cooper, N. Dunbar, and M. Mira, "Sex and seasickness on the Coral Sea," *The Lancet*, vol. 350, no. 9081, Sep. 1997, doi: 10.1016/S0140-6736(05)62083-1.

[117] M. McGill, A. Ng, and S. Brewster, "I am the passenger: How visual motion cues can influence sickness for in-car VR," in *Conference on Human Factors in Computing Systems - Proceedings*, May 2017, vol. 2017-May, pp. 5655–5668. doi: 10.1145/3025453.3026046.

[118] Seymour. Papert, "Mindstorms: Computers, children, and powerful ideas," *NY: Basic Books*, 1980.

[119] J. E. Bos, "Less sickness with more motion and/or mental distraction," *Journal of Vestibular Research*, vol. 25, no. 1, 2015, doi: 10.3233/VES-150541.

[120] B. Keshavarz and H. Hecht, "Pleasant music as a countermeasure against visually induced motion sickness," *Applied Ergonomics*, vol. 45, no. 3, May 2014, doi: 10.1016/j.apergo.2013.07.009.

[121] C. Hutton, S. Ziccardi, J. Medina, and E. S. Rosenberg, "Please Don't Puke: Early Detection of Severe Motion Sickness in VR," in *IEEE Virtual Reality*, 2018, pp. 579–580.

[122] S. Weech, S. Kenny, and M. Barnett-Cowan, "Presence and Cybersickness in Virtual Reality Are Negatively Related: A Review," *Frontiers in Psychology*, vol. 10, Feb. 2019, doi: 10.3389/fpsyg.2019.00158.

[123] B. G. Witmer and M. J. Singer, "Measuring Presence in Virtual Environments: A Presence Questionnaire," *Presence: Teleoperators and Virtual Environments*, vol. 7, no. 3, Jun. 1998, doi: 10.1162/105474698565686.

[124] T. W. Schubert, "The sense of presence in virtual environments: A three-component scale measuring spatial presence, involvement, and realness," *Zeitschrift für Medienpsychologie*, vol. 15, no. 2, pp. 69–71, Apr. 2003.

[125] T. Mazuryk and M. Gervautz, "Virtual Reality - History, Applications, Technology and Future," Dec. 1999.

Appendix A Ethics Review

RP 2021-196	Comparing different methods to reduce cybersickness in an omnidirectional treadmill for VR
Name of reviewer	Dennis Reidsma
Date	20 september 2021

Conflict of interest of the reviewer

For the reviewer: please indicate whether you have an interest in the research and if relevant, describe the closeness, severity and consequences

none

Review

- *Excellently prepared materials, I see no concerns that have not been addressed adequately*

X No adjustments needed. Secretary can send advice.

☐ Needs minor adjustments, please, send to ethicscommittee-cis@utwente.nl. Secretary can send advice after receiving adjustments.

☐ Needs major adjustments, please send to me for review, with cc to ethicscommittee@utwente.nl.

Appendix B Questionnaires

The questionnaires were created and filled-in on the Google Forms platform. For the appendix, I took the print version.

Pre-Experiment Questionnaire

* Required

1. Participant ID (this needs to be filled in by the researcher) *

____

General Questions

First, there are some background questions

2. What is your current age? *

____

3. What is your sex? *

Mark only one oval.

- ( ) Female
- ( ) Male
- ( ) Prefer not to say
- ( ) Other: ______________________

4. How many times have you approximately experienced VR? *

Mark only one oval.

- Never
- Once
- 2 to 5 times
- 6 to 10 times
- More than 10 times

Motion Sickness Susceptibility Questionnaire

The following section is to assess your history in motion sickness.

5. Do you regard yourself as susceptible to motion sickness? *

Mark only one oval.

- Not at all
- Slightly
- Moderately
- Very much so

CHILDHOOD experience only (before 12 years of age)

For each of the following types of transport or entertainment please indicate:

6. As a child (before age 12), how often have you traveled or experienced: *

Mark only one oval per row.

	Never	1 to 4 trips	5 to 10 trips	11 or more trips
Cars				
Buses or Coaches				
Trains				
Aircraft				
Small Boats				
Ships, e.g. Channel Ferries				
Swings				
Roundabouts: playground				
Big Dippers, Funfair rides				

7. As a child (before age 12), how often you felt sick or nauseated in:

Mark only one oval per row.

	Not Applicable	Never	Rarely	Sometimes	Frequently	Always
Cars						
Buses or Coaches						
Trains						
Aircraft						
Small Boats						
Ships, e.g. Channel Ferries						
Swings						
Roundabouts: playground						
Funfair rides, Big Dippers						

8. As a child (before age 12), how often you vomited in:

Mark only one oval per row.

	Not Applicable	Never	Rarely	Sometimes	Frequently	Always
Cars						
Buses or Coaches						
Trains						
Aircraft						
Small Boats						
Ships, e.g. Channel Ferries						
Swings						
Roundabouts: playground						
Funfair rides, Big Dippers						

Your experience over the last 10 years (approximately)
For each of the following types of transport or entertainment please indicate:

9. Over the last 10 years, how often have you traveled or experienced: *

Mark only one oval per row.

	Never	1 to 4 trips	5 to 10 trips	11 or more trips
Cars				
Buses or Coaches				
Trains				
Aircraft				
Small Boats				
Ships, e.g. Channel Ferries				
Swings				
Roundabouts: playground				
Big Dippers, Funfair rides				

10. Over the last 10 years, how often you felt sick or nauseated in:

Mark only one oval per row.

	Not Applicable	Never	Rarely	Sometimes	Frequently	Alway:
Cars						
Buses or Coaches						
Trains						
Aircraft						
Small Boats						
Ships, e.g. Channel Ferries						
Swings						
Roundabouts: playground						
Funfair rides, Big Dippers						

11. Over the last 10 years, how often you vomited in:

Mark only one oval per row.

	Not Applicable	Never	Rarely	Sometimes	Frequently	Alway
Cars						
Buses or Coaches						
Trains						
Aircraft						
Small Boats						
Ships, e.g. Channel Ferries						
Swings						
Roundabouts: playground						
Funfair rides, Big Dippers						

Pre-session Questionnaire

* Required

1. Participant ID (this needs to be filled in by the researcher)

2. Experiment Condition (this needs to be filled in by the researcher)

   Mark only one oval.

   - 1
   - 2
   - 3
   - 4

Cybersickness Questionnaire

In this questionnaire you are asked to rate symptoms that could potentially point to motion sickness.

3. Rate to what extend you are currently experiencing each symptom, from none to severe: *

Mark only one oval per row.

	None	Slight	Moderate	Severe
Headache				
Eyestrain [e.g. eye fatigue]				
Difficulty focusing vision				
Nausea				
Fullness of head				
Blurred vision				
Dizzy (when eyes open) [e.g. loss of balance, faint, lightheaded]				
Dizzy (when eyes closed) [e.g. loss of balance, faint, lightheaded]				
Vertigo [e.g. spinning sensation]				

Post-Session Questionnaire

* Required

1. Participant ID (this needs to be filled in by the researcher) *

2. Experiment Condition (this needs to be filled in by the researcher) *

   Mark only one oval.

   - 1
   - 2
   - 3
   - 4

Cybersickness Questionnaire

In this questionnaire you are asked to rate symptoms that could potentially point to motion sickness.

3. Rate to what extend you are currently experiencing each symptom, from none to severe: *

Mark only one oval per row.

	None	Slight	Moderate	Severe
Headache	◯	◯	◯	◯
Eyestrain [e.g. eye fatigue]	◯	◯	◯	◯
Difficulty focusing vision	◯	◯	◯	◯
Nausea	◯	◯	◯	◯
Fullness of head	◯	◯	◯	◯
Blurred vision	◯	◯	◯	◯
Dizzy (when eyes open) [e.g. loss of balance, faint, lightheaded]	◯	◯	◯	◯
Dizzy (when eyes closed) [e.g. loss of balance, faint, lightheaded]	◯	◯	◯	◯
Vertigo [e.g. spinning sensation]	◯	◯	◯	◯

Spatial Presence Experience Scale

The following statements are focused on your feeling of being present in the virtual experience. Rate to what extend you agree with each statement.

4. I felt like I was actually there in the VR environment. *

Mark only one oval.

	1	2	3	4	5	
I do not agree at all	◯	◯	◯	◯	◯	I totally agree

5. It seemed as though I actually took part in the action of the VR experience. *

Mark only one oval.

	1	2	3	4	5	
I do not agree at all	◯	◯	◯	◯	◯	I totally agree

6. It was as though my true location had shifted into the VR environment. *

Mark only one oval.

	1	2	3	4	5	
I do not agree at all	◯	◯	◯	◯	◯	I totally agree

7. I felt as though I was physically present in the VR environment. *

Mark only one oval.

	1	2	3	4	5	
I do not agree at all	◯	◯	◯	◯	◯	I totally agree

8. The objects in the VR environment gave me the feeling that I could do things with them. *

Mark only one oval.

	1	2	3	4	5	
I do not agree at all	◯	◯	◯	◯	◯	I totally agree

9. I had the impression that I could be active in the VR environment. *

Mark only one oval.

	1	2	3	4	5	
I do not agree at all	◯	◯	◯	◯	◯	I totally agree

10. I felt like I could move around among the objects in the VR environment. *

Mark only one oval.

	1	2	3	4	5	
I do not agree at all	◯	◯	◯	◯	◯	I totally agree

11. It seemed to me that I could do whatever I wanted in the VR environment. *

Mark only one oval.

	1	2	3	4	5	
I do not agree at all	◯	◯	◯	◯	◯	I totally agree

Post-Experiment Questionnaire

* Required

1. Participant ID (this needs to be filled in by the researcher) *

2. Order of conditions (this needs to be filled in by the researcher) *

   Mark only one oval.

   - 3-1-2-4
   - 2-4-3-1
   - 1-2-4-3
   - 4-3-1-2

General Questions

3. Which VR session did you prefer (not the condition)? *

   Mark only one oval.

   - Session 1
   - Session 2
   - Session 3
   - Session 4

4. Please, explain why: *

5. Please order the VR sessions from least sickness-inducing to most sickness-inducing by writing down the session numbers with a dash in between: *

6. Do you have any other comments regarding the VR experience?

7. Do you have any other comments regarding the experiment in general?

Thank you!

This is the end, thank you for participating in this experiment and answering all questions. Please, click on submit to finish this questionnaire.

Appendix C Information Brochure and Informed Consent Form

Research into several conditions and their effect on presence and motion sickness in VR and the Virtualizer

Information brochure

In Virtual Reality (VR) there are several ways to navigate yourself in the virtual space. For example, teleporting, using a joystick, walking in your room, or walking on an omnidirectional treadmill. Cyberith has developed such a treadmill, called the Virtualizer (Figure 1). The experiment will involve walking in a virtual environment on the Virtualizer.

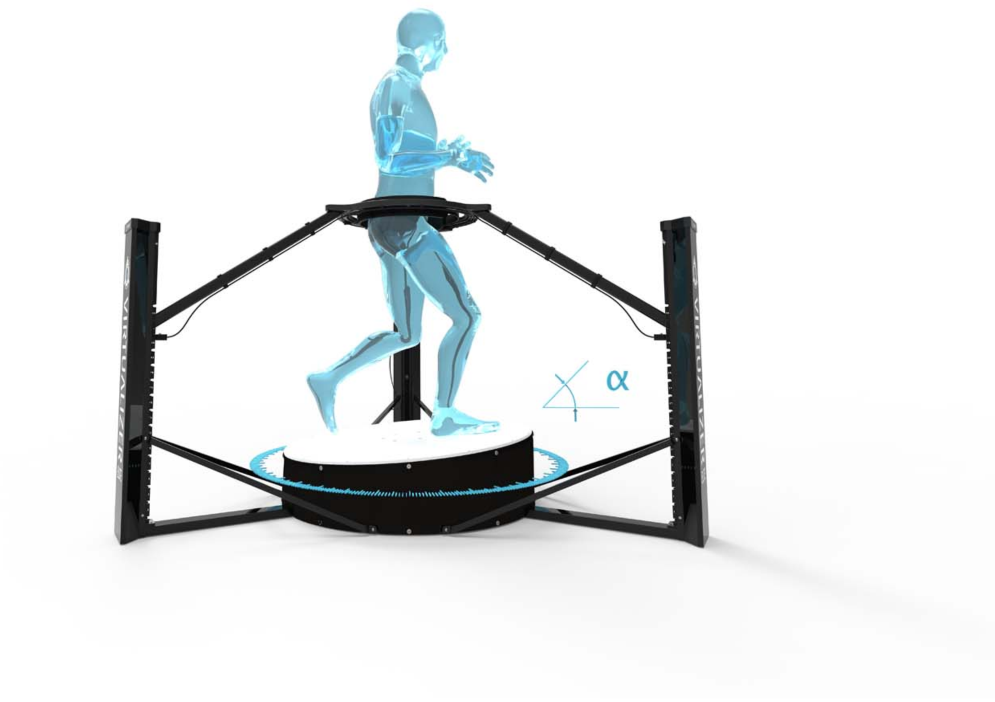

Figure 28: Virtualizer ELITE 2

What will you do?

The goal for you will be to try to find the end of a maze. A minimap will show the area you have already explored. To keep the minimap alive, you can pick up batteries along the way.

Before you start the experiment, you will be introduced first to VR and the Virtualizer. The distance between your eyes (interpupillary distance) will also be measured, so the VR headset can be optimally adjusted to your eyes. The experiment will consist of four VR sessions of eight minutes which have different conditions, each with a 10-minute break in-between. If you find the end of the maze before your time is over, you will continue with a new maze until the session time has expired. Before and after each session, you will have to fill in a questionnaire that we use to assess the degree of sickness and the feeling of presence of each session. During the session, you will be asked each minute how sick you are feeling on a scale from zero (no sickness at all) to 20 (very sick). The positional and rotational data that comes from the VR headset and the feet trackers will also be recorded. At the end of the experiment, you will be asked a few general questions about your experience in VR and the experiment. The only personally identifiable data that will be collected is your age, sex and experience in VR. Your name will only be used for the consent form.

What are the risks?

A risk of using VR is that you experience visually induced motion sickness (also known as cybersickness or VR sickness). This might result in nausea, dizziness, headache, eyestrain, etc. According to current research, these symptoms, if they occur, will disappear after a while and there are no permanent effects. To reduce the chance of becoming sick, it helps to be in a fit state. In other words, it is best to not excessively consume alcohol 24 hours before the experiment, to sleep well and to not overeat right before the experiment or have an empty stomach. If not possible, it is possible to book another time slot for the experiment. It is also important to note that you will be walking during the experiment. As the walking style in the Virtualizer might be new to you, it could cost you more energy than normal walking.

What will happen with the data?

This research is part of an internship/thesis project at Cyberith GmbH in Vienna. The experiment will be held at their office. The experimenter, Jesse Lohman, is a Human Computer Interaction & Design student at the University of Twente in the Netherlands and the University of Trento in Italy. The (anonymized) data from this experiment will be available to Cyberith GmbH, the University of Twente and the University of Trento. The goal of this experiment is to compare four different conditions by looking at your perceived presence in VR and how the different conditions might make you less sick. The results will be used to inform the design of future VR experiences. Cyberith might use this for further development of their software and/or hardware. This involves their Virtualizer hardware and the software package that accompanies the Virtualizer. Your answers to the questionnaire and the data from the headset and the feet trackers will be analysed to find correlations between the conditions and the level of cybersickness. The data might also be reanalyzed in the future to find new correlations. Your anonymized data will be stored indefinitely.

If you participate, you declare to fit the following criteria:

- Participants should be 18 years or older.
- Participants should have no or little VR experience.
- Participants should not be severely susceptible to motion sickness.
- Participants should be able to speak and understand English.

IMPORTANT

- You will always have the right to discontinue the experiment without providing a reason. If your sickness score that is asked for every minute is 15 or higher, the experiment will be stopped immediately as well. Stopping the experiment can be done by taking off the VR headset, releasing the Virtualizer harness and stepping out of the Virtualizer. This can be done independently, but the experimenter will always be available to aid in removing you from the Virtualizer and headset. After stopping your data will be removed from the study. This can be requested until 24 hours after the experiment
- You will always have the right to request for your data to be excluded from the dataset. A request can be made using the contact information at the bottom of this document.
- If you need independent advice or want to send a complaint, you can contact the Computer & Information Science Ethics Committee of the University of Twente through the following email address: ethicscommittee-cis@utwente.nl

If you have any questions regarding VR, the Virtualizer, the data gathered, the risks, or the experiment in general, feel free to contact the experimenter, Jesse Lohman, with the contact details below or ask your questions during the experiment session.

Experimenter

Jesse Lohman

j.lohman@cyberith.com

University of Trento supervisor

Luca Turchet

luca.turchet@unitn.it

University of Twente supervisor

Robby van Delden

r.w.vandelden@utwente.nl

Informed Consent Form

Research into four different conditions and their effect on presence and motion sickness in VR and the Virtualizer, with participants walking through a virtual maze.

Responsible researcher: Jesse Lohman

To be filled in by the participant

I declare that I have been informed through the information brochure and verbally in a manner that is clear to me of the nature, method, purpose and risks and burden of the study. I know that the data, including my age, sex, interpupillary distance, and results of the study will only be disclosed to third parties anonymously and confidentially. I am also aware that my data might be used to inform further development of the hardware and/or software systems of Cyberith GmbH. My questions have been answered to my satisfaction. I know that I have the right to ask more questions if they arise.

I voluntarily agree to participate in this study. I hereby reserve the right to terminate my participation in this study at any time without cause and to request my data to be excluded and removed.

Name participant: ....

Date: .... Signature participant: ....

To be filled in by the researcher

I have provided an oral and written explanation of the research. I will answer remaining questions about the research to the best of my ability. The participant will not be adversely affected by any premature termination of participation in this study or request of data exclusion and removal.

Name researcher: Jesse Lohman

Date: .... Signature researcher: ....

Appendix D Python Scripts for Data Analysis

```
######################################

### Questionnaire Data Processing ###

######################################

import pandas as pd
import os

# Function to convert string values to their respective integer values
def StringToIntScore(score):
    if score == "None":
        return 0
    elif score == "Slight":
        return 1
    elif score == "Moderate":
        return 2
    elif score == "Severe":
        return 2
    return None

# Calculates the two CSQ scores using the weights provided
def calcCSQScores(i, data):
    headache = StringToIntScore(data.at[i, "Rate to what extend you are currently experiencing each symptom, from none to severe: [Headache]"])
    eyestrain = StringToIntScore(data.at[i, "Rate to what extend you are currently experiencing each symptom, from none to severe: [Eyestrain [e.g. eye fatigue]]"])
    difFoc = StringToIntScore(data.at[i, "Rate to what extend you are currently experiencing each symptom, from none to severe: [Difficulty focusing vision]"])
    nausea = StringToIntScore(data.at[i, "Rate to what extend you are currently experiencing each symptom, from none to severe: [Nausea]"])
    fullHead = StringToIntScore(data.at[i, "Rate to what extend you are currently experiencing each symptom, from none to severe: [Fullness of head]"])
    blurVis = StringToIntScore(data.at[i, "Rate to what extend you are currently experiencing each symptom, from none to severe: [Blurred vision]"])
    dizzOpen = StringToIntScore(data.at[i, "Rate to what extend you are currently experiencing each symptom, from none to severe: [Dizzy (when eyes open) [e.g. loss of balance, faint, lightheaded]]"])
    dizzClosed = StringToIntScore(data.at[i, "Rate to what extend you are currently experiencing each symptom, from none to severe: [Dizzy (when eyes closed) [e.g. loss of balance, faint, lightheaded]]"])
    vertigo = StringToIntScore(data.at[i, "Rate to what extend you are currently experiencing each symptom, from none to severe: [Vertigo [e.g. spinning sensation]]"])

    dizzScore = headache * 0.50 + nausea * 0.84 + dizzOpen * 0.89 + dizzClosed * 0.99 + vertigo * 0.54
    difInFocScore = eyestrain * 0.58 + difFoc * 0.89 + fullHead * 0.55 + blurVis * 0.81

    return [dizzScore, difInFocScore]

# Sums all the answers given to the presence questions
def calcPresenceScore(i, data):
    SPES1 = data.at[i, "I felt like I was actually there in the VR environment."]
    SPES2 = data.at[i, "It seemed as though I actually took part in the action of the VR experience."]
    SPES3 = data.at[i, "It was as though my true location had shifted into the VR environment."]
    SPES4 = data.at[i, "I felt as though I was physically present in the VR environment."]
    SPES5 = data.at[i, "The objects in the VR environment gave me the feeling that I could do things with them."]
    SPES6 = data.at[i, "I had the impression that I could be active in the VR environment."]
    SPES7 = data.at[i, "I felt like I could move around among the objects in the VR environment."]
```

```python
    SPES8 = data.at[i, "It seemed to me that I could do whatever I wanted in the VR environment."]

    return SPES1 + SPES2 + SPES3 + SPES4 + SPES5 + SPES6 + SPES7 + SPES8

# Load pre- and post-session files
questionnaireDataFolder = os.getcwd() + "\\Questionnaire data\\"
preData = pd.read_csv(questionnaireDataFolder + "preSessionFormResults.csv")
postData = pd.read_csv(questionnaireDataFolder + "postSessionFormResults.csv")

# Holder for the data rows
dfPieces = []
sessionCounter = 0;

for i in range(len(preData)):
    # Get CSQ scores and then subtract the pre- and post-session scores
    preScores = calcCSQScores(i, preData)
    postScores = calcCSQScores(i, postData)
    deltaDizzScore = postScores[0] - preScores[0]
    deltaDifInFocScore = postScores[1] - preScores[1]

    presenceScore = calcPresenceScore(i, postData)

    # Get session attributes
    participantID = preData.at[i, "Participant ID (this needs to be filled in by the researcher)"]
    conditionNum = preData.at[i, "Experiment Condition (this needs to be filled in by the researcher)"]
    sessionCounter += 1

    # Put it all in a dataframe
    dfRow = pd.DataFrame(
            {
                "id": participantID,
                "sessionNum": sessionCounter,
                "conditionNum": conditionNum,
                "dizzCSQ": deltaDizzScore,
                "focusCSQ": deltaDifInFocScore,
                "SPES": presenceScore,
            },
            index=[0]
    )

    dfPieces.append(dfRow)

    if sessionCounter == 4:
        sessionCounter = 0

# Combine all results into one dataframe
dfCalcResults = pd.concat(dfPieces)

# Save results into file
dfCalcResults.to_csv(questionnaireDataFolder + "CalculatedQuestionnaireResults.csv")


################################

### Tracker Data Processing ###

################################

import pandas as pd
import os
from os import walk
import numpy as np
```

```
dfPieces = []
trackerDataFolder = "\\Tracker data\\"

filenames = next(walk(os.getcwd() + trackerDataFolder), (None, None, []))[2]  # [] if no file
filenames.sort()

sessionCounter = 0;
sceneCounter = 0;

for filename in filenames:
    sceneCounter += 1

    if sceneCounter == 2: #Data from the maze scene won't be processed in this analysis, so skip
        continue

    # Read data from file
    filePath = os.getcwd() + trackerDataFolder + filename
    data = pd.read_csv(filePath)

    # Only need the HMD data and remove the first 5 seconds (approx.)
    data = data.iloc[450:len(data), 1:7]

    # When the direction goes below 0, the value flips to 360, so I subtract it to get continuous values
    for i, row in data.iterrows():
        pitchHMD = data.at[i, "pitchHMD"]
        if pitchHMD > 180:
            data.at[i, "pitchHMD"] = pitchHMD - 360
        yawHMD = data.at[i, "yawHMD"]
        if yawHMD > 180:
            data.at[i, "yawHMD"] = yawHMD - 360
        rollHMD = data.at[i, "rollHMD"]
        if rollHMD > 180:
            data.at[i, "rollHMD"] = rollHMD - 360

    dataMean = data.mean()
    pitchMean = dataMean.at["pitchHMD"]
    yawMean = dataMean.at["yawHMD"]
    rollMean = dataMean.at["rollHMD"]

    ### Data filtering ###
    #indexToBeFiltered = []
    #outlierValue = 10;
    #minOutlier = -10;
    #maxOutlier = 5;
    ## Iterate through data and check if the rotational value is higher or lower than the outlier threshold
    #for i, row in data.iterrows():
    #    pitchHMD = data.at[i, "pitchHMD"]
    #    yawHMD = data.at[i, "yawHMD"]
    #    rollHMD = data.at[i, "rollHMD"]
    #     if pitchHMD > pitchMean + outlierValue or pitchHMD < pitchMean - outlierValue or yawHMD > yawMean + outlierValue or yawHMD < yawMean - outlierValue or rollHMD > rollMean + outlierValue or  rollHMD < rollMean - outlierValue:
    #         indexToBeFiltered.append(i)

    ## Remove the data point and its surrounding data to filter it
    #removeRange = 150
    #for i in indexToBeFiltered:
    #    lowerLimit = i - removeRange
    #    upperLimit = i + removeRange

    #    if i < removeRange:
```

```
    #        lowerLimit = 0
    #    elif i > len(data) - removeRange:
    #        upperLimit = len(data)

    #    data.loc[lowerLimit:upperLimit] = np.nan

    # Parse the filename to get participant ID and condition number
    fileAttr = filename.split("_")
    participantID = fileAttr[0]
    conditionNum = fileAttr[2][-1]
    dfAttr = pd.DataFrame(
        {
            "id": participantID,
            "sessionNum": sessionCounter,
            "conditionNum": conditionNum,
        },
        index=[0]
    )

    # Get the variance and max
    dataVar = data.var()
    dataMax = data.max()

    if sceneCounter == 1:
        print("Participant ID: " + participantID)
        # Save variance series for later
        introVar = dataVar
        introMax = dataMax
    elif sceneCounter == 3:
        sessionCounter += 1

        if sessionCounter == 4:
            sessionCounter = 0

        #Subtract pre-session values from the post-session values
        seriesVarDiff = dataVar - introVar
        seriesMaxDiff = dataMax - introMax
        # convert series output to dataframe and transpose it
        dfVarDiff = seriesStdDiff.to_frame().T
        dfMaxDiff = seriesMaxDiff.to_frame().T
        # Create data row and add to dataframe list
        sessionRow = pd.concat([dfAttr, dfVarDiff, dfMaxDiff], axis=1)
        dfPieces.append(sessionRow)
        sceneCounter = 0;

# Concatenate rows and save dataframe as csv file
dfTotal = pd.concat(dfPieces)
dfTotal.to_csv(os.getcwd() + "\\TrackerVarianceDiffCalculated_NoFilter.csv")
```