A preliminary exploration in the correlation of cybersickness and gaze direction in VR

Master Thesis

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Abstract:

Virtual Reality(VR) has been on the rise for the last six years with promises of intricate and immersive experiences. However, despite the heavy investments in the technology, some of the basic problems of VR remains unsolved such as cybersickness which is a major problem in VR experiences. In this study the connection between cybersickness and eye movements was explored, in order to enlighten the understanding of the eyes movement and the body's reaction to VR, with the perspective of a better understanding of cybersickness and the possible solutions to it. The experiment was conducted using within subject design and used a visual stimuli created Unity in which test participants (n=27) would be exposed to three different conditions, Walking in VR using roomscale; moving with gamepad while sitting; moving a gamepad standing. The experiment used an HTC Vive with an added Pupil Lab eye tracker to capture the eye movement and the simulator sickness questionnaire was used as a self-reported measure of cybersickness. Results showed that participants experienced cybersickness in all of the conditions, as well as it was found that the eyes did not move differently between the conditions. This stands in contrast to what would be expected as physically walking should have caused additional movement of the eyes.

Contents

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Chapter 1

Introduction

In the recent years with the release of Oculus Rift, HTC Vive and PlayStation VR, Virtual reality has gained much attention from the public community and from different industries such as healthcare, education and the entertainment market. With the releases of standalone headsets such as Vive focus, Oculus Go and the upcoming Oculus Santa Cruz it is even more appealing to the consumers, since the need for expensive hardware is reduced. Despite these advances in hardware technology and availability there are some obstacles which are not yet solved despite many years of research.

One of the more important obstacles is visually induced motion sickness also known as cybersickness and VR sickness, it often occurs in scenes that incorporate virtual locomotion, this is thought to be due to a conflict between the physical state in the real world and in the virtual world. This can induce symptoms such as eyestrain, headache, nausea or even vomiting in severer cases [1]. Depending on the severity of these symptoms and the length of exposure it may last from a few minutes to a few days [2]. The specific knowledge and measurements of cybersickness is, despite the many resources put into understanding it, limited. Therefore it would be interesting to see how new technology may help to understand this condition and maybe find the sources to it, which possibly could lead to a solution which could be adjusted or corrected. One of the senses that is connected to the feeling of cybersickness is the vision. Human vision has many aspects of which its movement is one of the more important ones. In spite of moving the eyes all the time, humans are very unaware of their own eye-movements and thus near to all eye-movements are involuntary. The movement of the eyes is connected to the movement of the body[3] and therefore it would be interesting to look into the relation between eye-movements and cybersickness. It would be expected that during a normal roomscale VR scenario where a person moves around the movement of the eyes would correspond to the ones made during real-world walking. However when a person moves around in VR with a gamepad, it is a very unnatural movement with no vestibular input to help, it would therefore be interesting to look into whether there is a difference between the way the eyes move during roomscale walking and during virtual movement with a gamepad.

Chapter 2 presents relevant literature which forms a solid background for the experiment, topics such as cybersickness, locomotion and The eye are presented. Chapter 3 Covers the research question and hypotheses, the methods for data gathering, chapter 4. presents the experimental design, the stimuli implementation process, tasks and procedures of the experiment. Chapter 5. Presents the data analysis' results and the findings of each test. chapter 6 discusses the findings of the study and answers the research question and finally chapter 7. concludes upon the findings and the study as a whole.

Chapter 2

Background

In the following section it was explored what the symptoms and causes behind cybersickness could be and how cybersickness could be measured. Section 2.4 reviews relevant locomotion techniques commonly used in entertainment experience as well as a review of some the latest studies conducted within the field. Section 2.5 covers the eyes physiology, different eye movement types and the general aspects of tracking the eyes movements and how this can be done in an HMD

2.1 Self-motion perception

Motion is represented by two information parameters; the Temporal and spatial information, to determine a given motion. The displacement of an object between two locations in the spatial dimensions determines an object's direction of motion. The second parameter is the amount of time an object must travel to reach the second locations - this determines its' speed of motion also known as velocity i.e. the temporal distance. Thus a motion can be characterized by the parameters of speed and direction or collectively the motion/velocity vector[4].

Vision is the most dominant sensory input in regards spatial awareness and as such is the sense that the brain relies most on for important activities regarding perception of motion[5]. Such an activity could be trying to cross a street and assessing the distance of an approaching car. A lot of calculations goes into the process but the first process is to detect what part of the visual stimuli is moving, separating the car from the stationary background, then assessing its' velocity and direction for the brain to make a judgment on whether to cross the street or not. On a neuron level the motion is detected in the ganglion layer and the lateral geniculate nucleus (LGN) detects features in the retina image. Motion detection neuron exists on a higher level which responds to features moving from one spot to another on the retina thus detecting motion [5]. More on the eye and its' physiology is presented in section 2.5.

Another perception of motion is the illusion of self-motion also called vection which occurs when a user feels as if their body is moving when no motion is taking place. A good example is when the you stand at a train station looking at a train moving and feeling that it is yourself that is moving, this would be the illusion of self motion. This also occurs when in VR as field of view play an important role in causing vection illusions, since the larger the field of view the more the visual stimuli covers the retinal periphery [6]. Further investigation into vection is presented in section 2.3.2.3.1 however vection is not primary scope for the project.

2.1.1 The vestibular system

The vestibular system is located within temporal bone in the inner ear and provides information about the head's movement, orientation and acceleration [7]. The system consists of three semicircular canals which detect angular acceleration [6]. Each of the canals correspond to the three World space dimensions X Y Z, meaning it detects movement in each individual plane and combined can detect motion (rotational acceleration) from any direction. The fluid (endolymph) flows within the canals the direction of the flow is determined by the movement and positioning of the head. The canals ends in the utricle which is a sac containing the fluid which responds to a static head position, beneath that is the saccule another fluid filled sac handling the inputs regarding static head position such as the vertical and horizontal forces [7]. This also means that the utricle and the saccule play and important part in providing vertical orientation in respect to gravity [6] e.g. balance during postural instability, and the body is swaying back and forth, this is the utricle and saccule trying the correct orientation.

The Ampulla which is the enlarged region of the semicircular canal, contains the receptor cells (fiber hairs) of the vestibular system. The small hairs cells are similar those of the auditory system, and are very precise in detecting changes in the orientation of the fluid coming from the canals [7].

2.1.1.0.1 Perceptional cues from the vestibular system The impact of the perception from the vestibular system is rather weak compared to the visual senses in regards of spatial awareness, since vision is the dominant sensory input. This affects the general perception of the world and can cause issues, as when human vision is blocked it can be difficult to determine which way is up even though being provided gravitational perception from the vestibular system the brain may still not be convinced which way is correct. This visual dominance become an issue in VR for example when a mismatch is created between the senses and can cause nausea, vertigo, sweating etc. [5]. More on this in the following Sections on Motion sickness 2.2 and Cybersickness 2.3.

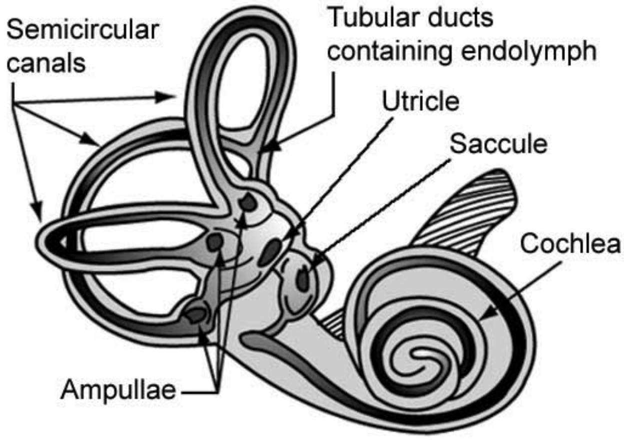


Figure 2.1: Overview of the described vestibular system [8]

2.2 Motion Sickness

Motion Sickness is an umbrella term covering several different types of sickness, all of these are characterized by common symptoms, such as nausea, headache, cold sweating and in severe cases vomiting [9]. There are six general forms of motion sickness, the Coriolis Effect, Sea Sickness , Effects of Micro- and Hypergravity, Air and Car Sickness, Simulator Sickness and Clinical Vertigo. In common for these are that they challenge the vestibular and visual system in different ways. Bles et al. suggests that what all of the forms of motion sickness have in common is that they create a mismatch between the expected and the sensed subjective vertical, and therefore motion sickness is highly related to the personal orientation in relation to the ground[10]. The 1977 Skylab results confirm this theory as astronauts who had been in space for a couple of days were no longer subject to motion sickness during tests that challenged their subjective vertical, this would make sense as their body had gotten used to weightlessness and lack of a constant vertical [11].

2.3 Cybersickness

A VR experience can cause intense discomfort with symptoms of nausea and disorientation, which is one of the medium's largest problems. This problem is often referred to as VR sickness, cybersickness or visually induced motion sickness. Cybersickness has a close relationship with motion sickness and simulator sickness as there are a number of symptoms which occur in both conditions; Eye strain, headache, sweating, disorientation, nausea, vomiting etc [6, 12].

However, it is important to note their difference though they produce the similar symptoms. Cybersickness is a condition where visual stimuli to the vestibular system alone is enough to produce similar symptoms to motion sickness [13], which is contrary to motion sickness and simulator sickness which are conditions that can occur without stimuli to the visual system, although vision can be a contributing factor [6, 12, 14].

2.3.1 Theories on Causes and symptoms

There is not a definite theory on the exact cause of Cybersickness, as both cybersickness and motion sickness are often described as polygenic (symptoms differ from individual to individual) [2, 14]. In contrast to motion sickness it is apparent that in cybersickness, it occurs in most cases while no physical motion is taking place and the illness is originating for a visually induced motion [6, 14]. In, all cases of motion sickness the symptoms are the same. However, the severity in which they occur differs, as a study by Stanney et al. concluded [15]. The study specifically investigated the difference between simulator sickness and cybersickness and found a significant difference in which categories scored the highest in the two conditions determining the severity of symptoms[15] See table 2.1. The study also found that the severity of cybersickness is three times more intense than simulator sickness. Thus increasing the need for finding the cause to provide guidance to a solution. The most common theories on Cybersickness is; Sensory Mismatch, postural instability, Rest frame and Poison. The following paragraphs will look into the details of these.

Table 2.1: Symptom Profiles [15]

	Cybersickness	Simulator Sickness
Highest Rating	Disorientation	Oculomotor
Middle Rating	Nauseagenic	Nauseagenic
Lowest Rating	Oculomotor	Disorientation

2.3.1.0.1 Sensory Conflict Theory This is the most widely accepted theory on the cause of cybersickness [2, 6, 13]. The theory describes a mismatch between sensory systems causing a perceptual conflict which the body does not know how to process[6]. The primary senses involved is the vestibular system (proprioceptive senses may also be involved) and the visual senses. These senses provide information about the individuals orientation and perceived motion, a mismatch of between the information gained from different sources will cause a conflict. For example, one sensory system may inform the central nervous system(CNS) that the body is stationary while the visual system sends information about motion occurring. Thus creating a sensory mismatch which causes cybersickness [5, 13].

Another mismatch could be caused by the engineered stimuli, where the perceived stimuli does not match up to the one expected by the CNS. These artificial factors include but are not limited to; display resolution, low framerates, latency, flicker, optical distortion and aliasing [5, 6]. Cybersickness have often been linked to vection, and believe to be the underlying condition introduced in the sensory conflict theory [1]. However it is known that an increase of visual-vestibular conflicts will increase the level of cybersickness however it does not necessarily increase the the level of vection [16].

2.3.1.0.2 Postural Instability Riccio and Stoffregen dismisses the idea that the concept of sensory conflict exist and have proposed another theory; postural instability [17]. The theory is based around main goal for an individual is to maintain constant postural stability within the physical environment, when exposed to prolonged instability the symptoms of cybersickness will occur [2, 13, 17]. Rebernitsch & owen describes the phenomenon as the body orientation trying to correct for the visual stimuli provided by i.e. an HMD, but as the gravitational pull is straight down the posture of the individual may become unstable when being exposed for a longer period of time, and the more unstable the posture is the more is the person likely to become ill [2].

Another factor that sensory conflict theory does not account for the physical environment relationship between the given interaction and the individual performing the action, which this theory heavily relies on. For example The environment have an influence on the body's stability, when an individual is seated and resting against the back of a chair the body is in a state of stability and instability is less likely to occur. This can be taken further, by restraining the individuals ability to move and locking them to a stationary object, which would immobilize them and make it difficult for cybersickness to occur, though not impossible [17]. Being completely immobilized is not the ideal in cases such as flight simulations or other interactive experiences, Ricco and Stoffregen therefore suggest the most optimal postural setting to eliminate cybersickness would be to lay down on the back in a stationary setting [17].

2.3.1.0.3 Poison The theory states that a person may be affected by cybersickness if the individual perceive an environment incorrectly and the perception could be an effect from past exposure. The nauseagenic symptoms are occurring due to an incorrect application of the fight and flight survival mechanism imprinted into the human psychology. However the theory is not testable nor used in practice[2].

2.3.1.0.4 Rest Frame The theory is based on the concept that the sensory mismatch arises when user's visual perception of what is up is different from the one sensed in gravity [2]. This is drawn from observations stating humans have a tendency to look for stationary objects within the view frustum [18]. In VR and Cybersickness it can be difficult for the perceptive system to select something static i.e. a rest frame, since the given scenario of VR causes conflicting information on what is believed to be static and not [6]. The theory also heavily relies vestibulo-ocular reflex (VOR) or the eye's ability to track object while moving the head. If a change occurs in between vestibular and visual system within certain frequencies of movement, the VOR' normal level of movement is inaccurate and the eyes must re-adapt to stabilize for the new VOR change, which is the same thing that occurs when changing the strength of prescription glasses[2]. Some studies have explored the possibility of creating rest frames within the VE creating static objects for the visual perception to use as a reference point. Chang et al. Did a comparative study of two virtual roller-coasters. One had two horizontal lines and two vertical lines creating a static resting frame, the other did not contain a resting frame, The results showed a decrease in measured cybersickness [19], congruent results was found by Duh et Al. in a similar study superimposing a grid on a VE [20].

2.3.1.0.5 Eye Movement Ebenholtz connected eye movement to the potential root mechanism for Cybersickness. As The optokinetic nystagmus (OKN) is invoked by moving visual patterns and can innervate the vagal nerve, which could lead to cybersickness [21, 22]. This theory might not be a complete source of cybersickness but rather a component in the system contributing to cybersickness.

2.3.2 Individual Factors

Individual factors of cybersickness is another unanswered question. Why would some people show symptoms and others seem unaffected. It might have something to do with the polygenic nature of the condition and the human complexity. The main answer to the question remain unanswered, however several trends and observations of the individual factors have been made over the years of cybersickness research. The general findings on this subject will be presented below.

2.3.2.1 Age

Age seem to be a factor which affects an individuals susceptibility of cybersickness/Motion sickness [9], Reason and Brand reported in a study on motion sickness found that children between two and 12 were most susceptible to motion sickness and it then decreased rapidly from 12 to 21, and is non existent after the age of 50 [1], this seem to be a widely accepted fact in Cybersickness [6, 23, 24]. However, a study by Arns & Cerney [23] on cybersickness have showed the relationship between age and cybersickness may not have as strong a connection as it has with motion sickness. In fact the study showed that participants above the age of 50 showed and increased severity in reported cybersickness than the young participants [23]. It is therefore difficult to conclusive say age's effect on the susceptibility of cybersickness.

2.3.2.2 Gender

Gender is an area within cybersickness which have had several studies report that females are more susceptible to cybersickness or their symptoms' severity is greater than men. However there is also evidence that male participants often under-report the severity of their symptoms during self-reported measures [25]. There are many variations of studies trying to pin point the causes of the increased severity in for female participants compared to male participants. It is noted that women have a wider field of view than men, and as there is a correlation between field of view and cybersickness due to flicker perception which could increase their susceptibility [1]. Munafo diedrick and stoffregen also reported that due to women's posture they are more susceptible to cybersickness [26].

2.3.2.3 Exposure Time

This has proved to have an effect on the experience of cybersickness in several studies, or an indication of the amount of exposure time have an effect on the level of severity of measured cybersickness. For example a study by Cobb et al.[27] with 148 participants reported findings that 80% of participants had symptoms of cybersickness within the first ten minutes of exposure to the VE [27]. Another study by Stanney et al. had a 60 minute exposure session where 50% withdrew after 11-20 minutes 20% withdrew after 21-30 minutes and 20% withdrew after 31-40minutes. These findings show clear indication of cybersickness at around 11-20 minutes of exposure [15], however the technological advances must be taken into account, as today's HMD's and software haven evolved rapidly addressing comfort and fidelity.

2.3.2.3.1 Vection This is an individual factor of self perception of motion, the most common way to detect it is through self-report measures which proves to be a complication for determine the correlation between cybersickness and vection[16].In recent years research has gone into the physiological measures for vection such as electrodermal activity or cardiovascular responses. Studies have also investigated the neural correlation of vection with EEG, and it has been shown that optokinetic stimulation inhabits the vestibular areas [28], which makes sense since there have been numerous studies suggesting a correlation between vection and cyber/simulator sickness [29]. Hettinger et al. for example found that participants reporting vection were more likely to report cybersickness, thus stating a correlation between the two [29]. Ji, So and cheung did another study on the topic but concluded that Cybersickness can occur without the introduction of vection[16]. It must therefore be concluded that the relation between cybersickness and vection is possible. But is highly dependent on the participants individualism and ability to self-report correctly.

2.3.2.3.2 Self-Movement and Rotation Self-movement from a visual stimuli without any cues for the vestibular system causes a sensory conflict, it is also known to be a factor for inducing vection due to the visual stimulus dominance. Thus acceleration is an issue, acceleration occurs gradually over time until a determined speed limit is reached, this gradually change is detected in the vestibular system by the displacement of the fluid if it had occurred in e.g. a car. however locomotion in a VR does not provide this information if the user is stationary, hence visuals should rely on constants. A constant velocity would remove the acceleration and reach the speed limit instantaneously, the speed change is perceived in a pair of consecutive frames and limit the induced cybersickness [5] (illustrated in figure 2.2).

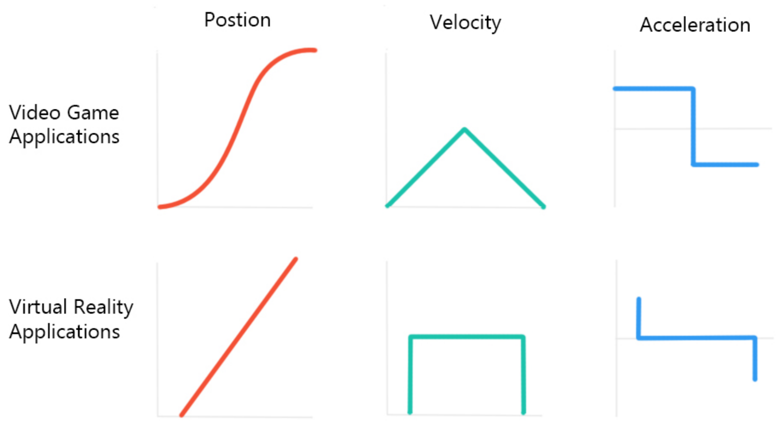


Figure 2.2: illustration of constant speed and acceleration in VR compared to video game application (inspired by [30])

Lo and So [31] did a study on rotation along different axis in VR using oscillation scenes i.e. pitch, yaw, roll or no oscillation. 16 participants were exposed to four 20min VR sessions, their nausea level was noted every 5min and pre- and post exposure simulator sickness questionnaire (SSQ) was used as self-reported measure. The results showed that the nausea ratings and SSQ increased significantly with the oscillation scenes, thus indicating rotational movement also induces cybersickness [31].

Similar studies were done by Dennison and D'Zmura which displayed a rotating virtual tunnel in VR at six different rotation speeds. The study was conducted as repeated measures with 15 participants, with the conditions of a standing and seated version, postural instability data and SSQ's were collected and the results showed that cybersickness increased with the rotation speed for both standing and seated conditions [32].

These complications are likely due to the vestibular system not detecting any change in yaw pitch and roll, but rather only the visual stimuli, it has therefore been suggested by Google VR Lab "Daydream" [30] to use discrete rotation, as opposed to a continuous smooth rotation for free locomotion implementation in VR. However a recent study by Ryge et al. compares these two implementation methods in a cybersickness study with 42 participants, found no significant difference in the self-reported SSQ between the two methods. though cybersickness rating was slightly higher for for smooth rotation, thus yields no definite suggestion that either is a viable long-term implementation [33].

2.3.2.3.3 Orientation Cues While moving around in a VE, the primary stimuli for orientation is the vision, which is why orientation cues of which way implies upwards direction is important for interpreting the gravity of a VE. Thus the lack of orientation cues may lead to disorientation and invoke cybersickness symptoms [2]. As the vestibular system may be sending conflicting information.

2.3.3 Measures for Detection of cybersickness

The most common method for measuring the level of cybersickness in research studies is the simulator sickness questionnaire (SSQ) developed by Kennedy et al. [34] in 1993. The questionnaire was based on 1119 pairs of pre- and post-exposure datasets from the Motion Sickness Questionnaire (MSQ) originally consisting of 28 questions [34]. The data was collected on-site from 10 Navy Simulators. The samples not containing any sign of simulator sickness induced symptoms were sorted out and the SSQ was formed from the remaining 600 observations. It was originally designed for military personal but despite this, it is still used as a supplement to determine alternative methods such as postural instability or physiological measures[2].

The questionnaire consist of 16 questionnaire items concerning the severity of each symptom, the severity is measured using a four point scale scores (0-3); none, slight moderate or severe. The responses are then grouped into the three categories; Nauseagenic (N), Oculomotor (O), Disorientation (D) (see figure 2.2 for an overview of the symptoms in each). The individual factors have their own weighting determining its influence on the SSQ scoring. The SSQ score is computed by adding up the ratings of all the items, and multiplying the item score with the assigned factor weight. The weights are 7.58 for oculomotor, 9.54 for nausea, and 13.92 for disorientation. The Total SSQ score is calculated by adding up the sums of N, O and D and multiplying the sum by 3.74, The result will show the collected severity of the simulator/cybersickness symptoms [34].

The SSQ is not perfect despite its popularity, due its generalization factors that appear in more than one category, making redundancies in two sub-scales while calculating the total score of sickness severity. Specifically the items General discomfort and difficulty concentrating are both assigned in the nausea and oculomo-

Table 2.2: SSQ distribution of symptoms in each category

Symptoms	Nausea	Oculomotor	Disorientation
General discomfort	1	1	
Fatigue		1	
Headache		1	
Eye strain		1	
Difficulty focusing		1	1
Increased salivation	1		
Sweating	1		
Nausea	1		1
Difficulty concentrating	1	1	
Fullness of head			1
Blurred vision		1	1
Dizzy (eyes open)			1
Dizzy (eyes closed)			1
Vertigo			1
Stomach awareness	1		
Burping	1		

tor sub-scales, which gives a conflicting image of the exact cause of the sickness [13].

Furthermore the fact that that the SSQ was based on and intended for a military demographic using simulators, leaves some researchers skeptical in its' validity in its the current factor structure and argue that it may not be adequate for research and treatment of cybersickness using HMDs on the general public. A recent study by Kim et al.[35] did a study to verify the SSQ' usage as a measure for Cybersickness in VR. The study used Gear VR headsets and had a total of 24 non-military participants (12 male and 12 female), the test lasted 90 minutes including breaks, where participants would perform target selection tasks. The study found that the SSQ's usage was verified using the data obtained from the experiment, as well as proposed a revised version; Virtual reality sickness questionnaire (VRSQ) [35].

2.3.3.0.1 Postural instability Postural instability is an alternative to the self-reported questionnaires as it offers an objective measure of cybersickness, as postural sway is connected to cybersickness. The swaying can be measured by its' amplitude, magnitude and frequency, the larger the swaying the more likely it is to cause cybersickness [17].

There are two types of floor based test methods used for measuring postural instability:

- Static postures - how long a person can hold a static posture.
- Dynamic test - perform a walking task.

These methods are subject to criticism regarding questioning the validity of them, as there is a general lack of precise uniform description of the tests should be performed. Many of the test were measured on the amount of time a participant could hold a static posture, the interpretations of these results rely on the criteria of failure but the description of what is considered a failure of the test is unclear, due to vague formulations e.g. foot moves or balance lost [27].

Kennedy et al.[36] therefore suggested a standardized video-based test consisting of recording a the body's displacement velocity on the x,y,z plane over a period of 30 seconds to get an accurate measure of the body sway [1, 36].

More recent studies have utilized the tracking data received from the HMD's and combined it with a Nintendo Wii balance board which has 4 sensors detecting a users weight distribution [32]. Dennison and D'Zmura did a study based on these measures with 15 participants. A baseline for the right balance and the individuals natural head position was established before the exposure. During the test samples were then captured to produce cross correlations between HMD position and balance board in the forward-backwards and right to left directions of displacement.

The results showed that A minority of the participants swayed during the VR exposure but the majority did not, in fact subjects with greater levels of cybersickness swayed less.These findings may suggest that postural instability may not be a defined condition for cybersickness [32], therefore other objective measures should also be considered.

2.3.3.0.2 Physiological measures The subjective measures provides the individual evaluation of their degree of sickness, and might not provide the full picture of when it occurs and how the body react. Therefore an objective measure could likely solve this complication as cybersickness is inherently the body reacting to a conflict, thus it should be measurable from a physiological state. However there are only few well documented objective symptoms associated with cybersickness [1].

Kim et al.[24] investigated the characteristic changes in the physiology of cybersickness. They had 61 participants go through a 9.5 min VR experience where they were required to detect specific objects within the scene. Sixteen electrophysiological signals were recorded before, during and after exposure in addition three self-reported questionnaires were obtained before and after the experiment. The physiological and subjective measures where compared for correlations, and the results suggest that cybersickness accompanies pattern changes in activities in the central and autonomic nervous system. The severity had a positive correlation with eye blink rate, heart period and EEG Delta waves and a negative in the EEG beta waves [24].

Ohyama et al. did another study with 10 participants in a within subject study, to examine the participants sickness symptoms and heart rate variability (HRV) during exposure to cybersickness in VR (CAVE system). The study showed an increase in low frequency HRV and no change in high frequency [37]. The participants were also given a self-reporting questionnaire which showed their symptoms worsened over time of exposure. however only a slight relation was found between participant self-reporting and the objective measures [37]. Given the previous studies within physiological measures it could indicate there is a connection between cybersickness and an increase in the cardiac sympathetic outflow [1].

The current established physiological measures can provide more detailed data on the specific events that occurred throughout the exposure and pinpoint the events of cybersickness. However EEG's and other equipment can be intrusive in their nature as they add up on the amount of equipment a participant need to wear and may limit their mobility. Davis et al. noted that physiological measures are expensive to perform and complex to analyze. Subjective measures on the other hand have a long history of validation and have shown to be reliable, so they may not be replaced quite yet [1].

2.4 Locomotion in VR

Virtual locomotion is the act the user moving from point A to point B in a scene it is also often referred as Virtual travel [38]. In this case Locomotion is used as it not only describes the act of moving but is also a term for a software mechanic in an implementation. A good locomotion mechanic is an important component in navigating and interacting with a virtual environment(VE) without inducing cybersickness which is an issue for the vast majority of VR users. Currently there is no real universal go to solution, but this section will list a few of the existing solutions, of how to tackle locomotion with limited cybersickness.

2.4.1 Room-scale

This technology allows the user to walk physically around in a physically space limited area, where the HMD and controllers' position are tracked and updated within in VE in a 1:1 mapping between the real and virtual walking path. This allows for a cybersickness free experience, as the user have physical movement and the vestibular system can react correctly on the information it is being provided with. However, this method gives a limited experienced as the locomotion in the

VE is limited to the confined tracked space which the sensors cover [**gepp _2017**].

2.4.2 Re-directed walking

Re-directed walking (RDW) is another technique utilizing the room-scale setup by re-directing the user to walk and stay within the confined tracking space using sense or orientation manipulation [39]. An ideal RDW implementation for a subtle continuous reorientation has all of these four criteria for-filled; the reorientation is imperceptible to the user, the redirection is within the safe space of the tracking field and prevents collision with physical obstacles, it can be applicable within any number of VE with any number of users; and it does not induce any signs of cybersickness [40].

2.4.2.1 Sense Manipulation

This relies on the fact that visual cues are usually weighted as more accurate in the sensory system and are therefore more important when determining orientation. This can be utilized to perform redirected walking techniques by manipulating the virtual camera based curvature an rotation gains. The users movement is mapped to the virtual camera within the VE and is then being dynamically updated in translation and rotation to keep the user within the confined tracking space [41].

One such implementation is attempted by Sun et al. who used an HMD with eye tracking utilizing a new method of detecting saccadic suppression and dynamically change the users direction during the temporary blindness in the visual system where the visual signals are not perceivable due to brain interpolation [42]. During the saccade they were able to alter the direction of the virtual camera away from obstacles and walls thus nudging the user (more on saccades in section 2.5.1.3). They were able to compress 6.4x6.4 meters of virtual space into 3.5x3.5meters of physical space using this redirection method [43] (see figure 2.3).

2.4.2.2 Scene Manipulation

Another way to redirect a user is to manipulate the scene and increase the compression factor of the VE thus manipulate the users to walk in certain directions. It works by overlapping elements or locations of the VE within the physical locations of a tracking space. while the user is in these overlapping locations the other parts or elements of the VE will be relocated without the users perceptual knowledge [41].

2.4.2.2.1 Change blindness This technique uses spatial compression in a different way, as it implements a system where specific tasks are designed to distract

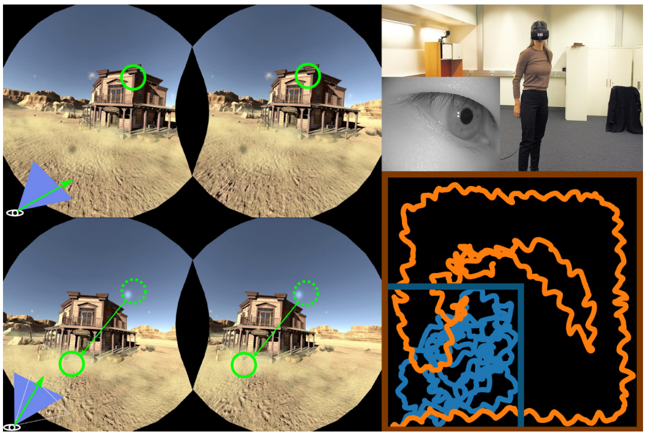


Figure 2.3: Redirected walking using saccades, blue path physical route and orange path is the virtual path [44]

the user so they will not notice large changes in the VE [41]. The method does not require any break to reorient the user nor does it cause any symptoms of cybersickness, due to the real-time mapping of virtual and physical motion [45].

Suma et al. conducted two tests on the effectiveness of the change blindness illusion, one where the participant would walk into a virtual room with a random object on a computer screen, and while distracted the door location would change several meters away from its' original position. In the other test they were simply told to turn on the monitors in the room. The results revealed that only one of 77 participants noticed a change in the scene across both studies [45].

2.4.2.2.2 Impossible Spaces The concept of impossible spaces relies on overlapping virtual architecture which violates the rules of euclidean space. Creating spaces that could not physically exist in the real world, but by utilizing this technique it is possible to produce a lot of walking space within a confined area [46]. The technique were tested out to explore the perception and experience of impossible rooms in two studies; the first experiment showed overlapping rooms of up to 56% before it became noticeable by the participants. The second test utilized the full 9.14x9x14meters work space and they were able to overlap up to 31% [46]. Vaslevska et al. combined change blindness and impossible spaces to produce procedural layout generations which would allow for an infinite walk based on the spatial manipulation of the architecture i.e. Flexible spaces [47].

2.4.3 Teleportation

This is common implementation in current VR experiences. The method works with the user pointing with i.e. a controller ray-casting a laser pointer to a new position in the VE and on button release the user is instantaneously transported to the new viewpoint location [5]. This provides a non-continuous motion and can be disrupting for the experience as it is an overt technique thus also reducing the sense of presence in the VE [48]. It does not induce cybersickness, however it can induce disorientation when teleporting around, as when the user jumps to a new position in the VE the users has lost the sense of spatial context of the surroundings while performing the virtual travel [48].

2.4.4 Joystick/gamepad

is the most common method of interaction in video games, and is naturally something to be transferred into a VR environment as it is a familiar interaction. However this is not at its' current state an optimal interaction method. It has high risk of inducing cybersickness due to the lack of physical motion. The technique also maintain a user spatial aware unlike the teleporation, and allows for more precise movement, but this does not seem to be enough to overcome the issue of cybersickness as a evaluation by Langbehn, lubos and steinicke concluded that users preferred RDW and Teleport over Joystick, the study evaluated the parameter of cybersickness spatial awareness, presence and their preference [49].

2.4.5 Experimental Locomotion for Comfortable VR

At Oculus connect 4 Tom Heath presented Oculus' Research Labs latest experimental software methods for producing comfortable VR locomotion i.e. methods for reducing cybersickness in VR. Two of the presented methods will be looked upon in this section. Both examples should be considered as training sessions before the actual experience and overtime be reduced [50].

2.4.6 Reducing the relevance of mismatch

This concept revolves around decouple the visual input from the vestibular senses which would otherwise cause a sensory conflict. The method uses disruptive visuals which would lead to tricking the brain into believing the visual input is not relevant for interpreting the sensation of motion, as the visual are contradicting its' normal reference point for perceiving motion [51]. In practice the it is multiple transparent overlays of the visual world rotating on the Z-Axis in opposite direction to each other, the visual in it self should not be uncomfortable as the brain already is at a state of mind it does not believe what the visual input communicates. Tom Heath has not conducted exact experiments on how long these sessions should be conducted before the the brain is at the disbelief of the visual input, and regular virtual locomotion can be introduced to the user with the result of no cybersickness in the continued experience [50]. Another example of reducing the mismatch is by reducing the field of view, this has been proven to reduce the sense of cybersickness, but also causes reduced sense of presence. A study by Ajoy and Feiner attempted to address this issue by implementing a dynamic field of view change, they found that the participants were unlikely to register it and that they tended to stay in the VE for a longer time[52].

2.4.6.1 Artificial tilt

Usually the notion concerning locomotion is not to rotate or tilt the users view point out of their control. However this experiment uses artificial head tilting as opposed to physical head tilting for locomotion which can cause fatigue and neck strains [50]. Implementing it artificially, should allow for a more comfortable acceleration and turning, by closing into the gravitational pull when turning. This method does produce some discomfort but the general idea is that slight discomfort is better than great discomfort [51].

2.5 The Eye

The eye is the human organ responsible for obtaining visual information about the world. But this information goes beyond what you see, it is processed and used to fine tune the balance system and to maneuver seamlessly giving mankind the possibility to act fast and precise without constantly having to think about where something is. The understanding and ability to measure the attributes of the eye is therefore of great use since most of them are involuntary and can therefore give an insight into the human cognition and perception without relying on self-reporting. As this study seeks to explore the connection between cybersickness and eye-movements it is therefore only reasonable that a general overview of the eyes physiology and movements will be presented as well as a general overview of the ways the eye can be tracked and the measurements of the eyes.

2.5.1 The Physiology of the Human Eye

The human eye is a complex mechanism that consists of many parts that work together to create the image of the world, that in turn is processed heavily by the brain in order to create the full and rich image that is finally perceived. In the following section the basic physiology of the eye will be presented, to create a fundamental understanding of what it is that is dealt with and what is measured when working with the eye.

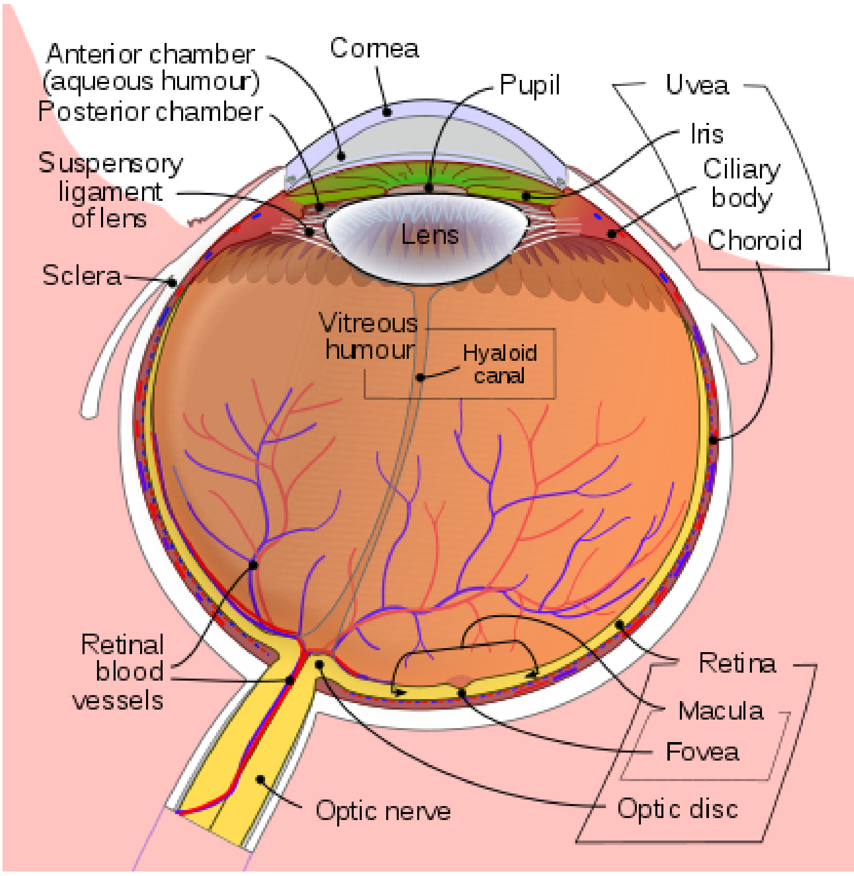


Figure 2.4: Illustration of the Human Eye [53]

2.5.1.1 From Cornea to the Retina

The eye consists of three visible elements, the white sclera, the colored iris and the black pupil. The sclera in conjunction with the transparent cornea work as a protective outer layer of the eye, hindering unwanted substances to enter the eye, as well as to focus the light through the cornea into the eye [5, 54]. After passing the cornea the light will pass through the aqueous humour which is a transparent gelatinous mass. Then the light enters the lens through the pupil for which the iris works like the aperture in a camera, controlling the size of the pupil, and thereby allowing more or less light to enter [5, 54]. The lens is controlled by muscles and can contrarily to the cornea change form in order to change focus on distance. The lens focus' the light through another transparent gelatinous mass called the vitreous humour, onto the retina. The retina is a membrane covering the backside of the eye on which the light sensitive photoreceptors are placed, for a visual illustration of the eye see 2.4 [5, 54].

2.5.1.2 Perceiving Light

As described previously the Human eye work by guiding light through a lens in the back of the eye, which then converges the light onto the retina. The retina consists of millions of photoreceptors that are all specialized in detecting a specific kind of light, two distinguishable types of photoreceptors exist, cones and rods. Cones are used to perceive details and color and require much light while rods need less light and are more sensitive, but cannot distinguish colors. There are 20 times as many rods as there are cones and they are more widely distributed across the retina compared to cones which are highly densed around the centre of the retina, an area known as the fovea. This density of cones around the center is what allows humans to see clearly at what they are looking at while having less sharp perception in the peripheral vision [5, 54]. The more widely distributed rods allow for the peripheral vision to be very good at perceiving motion as rods are more sensitive than cones and less information has to be processed, this may have been important on an evolutionary level as it have allowed humans to perceive possible dangers without seeing them clearly [5, 54].

2.5.1.3 Eye Movement

When talking about eye movement it is necessary to distinguish between how the eye is moved physiologically and the movements the eye makes in relation to perceiving the world.

The human eye is moved by six muscles, one on each side of the eye and two on the top and two the bottom[5, 55]. This allows for precise control of the eye and holds the eye in place while the counter pulling setup makes sure the eye cannot rotate too far in any direction. While the eye can theoretically move with three degree's of freedom(DOF) the movement on the z axis, also known as eye torsion is limited enough so that it is not easily visible and not really a full degree of freedom. Often this type of movement is ignored as pitch and yaw movement is much more common and the eye is much more free to move on these axis'.

The human eye have many types of movement, there are however six primary categories Saccades, Smooth Pursuit, Vestibulo-occular Reflex, Optokinetic Reflex, Vergence and a group of micro-movements [5, 55]. Each type of movement serves a specific purpose for the human vision and changing conditions for one or more of them could easily disturb the way things are perceived or create a conflict with other human senses.

Fixation Fixation is not an actual movement, but rather the lack thereof, it is when the eyes attempt to focus at a specific object and is typically linked with visual attention[55]. Even though it may seem like the eye is still when it fixates the eye still moves with many micromovements to keep the gaze steady [55], see more about this in paragraph 2.5.1.3. Though it is not a movement in its own right it is still necessary to understand in the context of eye-movement as this is as much about where the eye moves as it is about when the eyes are not moving.

Saccades Saccades are the rapid movement of the eyes when seeking something or scanning an image for points of interest. Saccades are movements with a speed of about 900 degrees per second and last less than 45 ms. During saccadic motions the eye is basically blind with the brain filling out the space between moments so that it does not seem like it, some cognitive functions related to vision have been proven to remain active during saccades, however these are subconscious and therefore the person is practically blind [5, 55]. Another type of movement, that is not entirely a type on its own is glissades, when the eye makes a saccade it will sometimes overshoot the intended target and make a quick correction back, this extra movement is called a glissade. Glissades are in their essence a saccade however it happens only after a saccade, and they are smaller and has a shorter amplitude.

Smooth Pursuit Smooth Pursuit in comparison to Saccades is the much slower movement made when following a specific object, this could be a ball or a person moving, this movement is only done at about 30 degrees per second and the vision remains active during the movement. However if something is moving faster than what the eye can steadily follow it will instead be using saccades to catch up[5].

Optokinetic Reflex The Optokinetic Reflex is used when something is moving fast by. The eye will find a point to fixate on and follow that point for as long as it remains in vicinity, then the eye will move back and find a new fixation point and so forth, this can be experienced by looking out of the window of a car on the highway or by looking at a train passing by a train station [5].

Vestibulo-occular Reflex The Vestibulo-occular Reflex(VOR) is used to stabilize the vision when moving, this reflex is a controlled by the eye muscles and the vestibular system together, to create a vision that is leveled and do not bounce up and down during body movement. Both yaw, pitch and roll is done when stabilizing the view, this is in contrast to most other eye motions that do not make use of the roll function known as eye torsional movement [3, 5].

Vergence Vergence is the movement used to fixate onto elements at a distance, by angling the eyes toward the same spot the brain can make an image of the world that both perceives depth and detail in the center. This movement is involuntary and is easily experienced if reading a book at a close distance and then taking it farther away, the eyes will then accommodate to the distance of the book, so that the focal point of the eyes is in the same spot [5].

Micromovements There are three types of movement in this subgroup, Microsaccades, Tremors and Drift, they are all characterized by working on a very small scale and often happening simultaneous with other movements. Drift is a type of movement that slowly brings the eye away from whatever it is focusing on, while microsaccades among other things correct for this drift. Microsaccades are similar to saccades in that it is a rapid movement of the eye, but it works on much smaller distances than normal saccades would do, beyond correcting the eye when it drift, microsaccades is connected to many other possible uses, however they are mostly related to the neurology of the eye [5, 55]. When the eye fixates it may seem that the eye does not move, however the movement tremor happens all the time, it is a small movements with a frequency of about 90Hz and their purpose is not fully understood, but they could be the result of imprecise muscle control or muscle tensions [55].

Rapid Eye Movements Rapid Eye Movements(REM) is a special type of eye movement that happens during sleep. But since it is an unconscious action that only takes place during deep sleep, known as REM sleep, they are not truly relevant for more general eye tracking studies [5].

2.5.2 Tracking the Eye

Attempts to understand the movements of the eyes have been done for centuries, but only within the last 100 years have it become possible to track the eye precisely with electronic instruments. The first great leap on this part were achieved in 1922 when it was found that the corneo-retinal potential could be used to register the medical condition Ocular Nystagmus [56]. Since then several other ways of recording eye-movements have been developed, and eye tracking is today still used as a way of identifying medical conditions, but is also used as a tool in other industries, such as in UX design, where gaze patterns can be used to understand what a user sees and thereby help in designing more optimally for the user[55]. On a more basic level eye tracking can also be used to understand the physiology of the eyes in the sense that the patterns of movement used by the eye would hardly be known as well without tracking, as these movements happen so fast that they are difficult to track with the naked eye. A brief overview of the most prominent types of eye tracking will presented as to get an understanding of what the goal of an eye-tracker is.

Electrooculography As the oldest electronic way of measuring eye movements, this is based on the corneo-retinal potential, the fact that the eye has a positively charged cornea and a negatively charged retina. This means that by placing an electrode on each side of each eye, it is possible to use the difference in potential between the two electrodes to determine how the eye moves [56]. It has been widely used over the last 100 years as it is quite precise and relatively non-invasive and has no unintended side effects and does not limit the field of view [56].

Videooculography This method is also known as videobased eye tracking, it makes use of one or more infrared (IR) cameras, and one or more IR LED's to capture the image and reflections of the eye. The IR camera's capture the image of the eye which in turn is processed on a computer, to retrieve the desired information see more in chapter 2.5.2.1. During the last 30 years this way of tracking has become more popular as the size of cameras have become smaller and the processing power of computers have become stronger, this together with the fact that it is one of the few non-invasive ways of measuring eye-movement makes it ideal in many places [56]. There do exist methods that do not rely on IR light but instead uses natural light sources, they are less prone to interference from natural IR light, and may therefore be more suited for use outdoors, however natural light sources are more difficult to control, and may be more invasive as they are visible to the participant [57].

Infrared Reflection Oculography This method also uses infrared cameras, however instead of capturing the whole image and analyzing that, it is based the fact that the sclera reflects more light than the pupil and iris. By placing an IR camera on each side of the eye and comparing the amount of light reflected to the cameras, it can be measured where the eye is currently positioned [56].

2.5.2.1 Videobased Eyetrackers

Videobased eyetracking/videooculography as described in the previous chapter 2.5.2, depends on the use of IR cameras and IR lights to create an image of the eye. There are several ways to set this up, as the camera and the light sources may be placed in several positions. Holmqvist et. al describes three general types of videobased eyetracking setups Static, Head Mounted and Head Mounted with Head Tracking [55].

Static Eye trackers Static eye trackers come in two versions, tower mounted remote, tower mounted trackers are mounted in front of the user, often in combination with a screen. This allows for a less invasive way of tracking as the user is not required to strap anything to the head, however it requires the user to stay in place and keep the head still. It is not intrusive at all and do not pose any discomfort beyond having to sit in the same place for the duration of the test which makes it ideal for research regarding visual stimuli on a computer screen [55]. Remote controllers on the other hand are placed in order to track a participant from afar, this allows full freedom of movement for the participant, but potentially requires more cameras and the gaze estimation is much worse than with the more restrictive setups [55].

Head Mounted These are as the name says, mounted on the head of the subject, typically by some form of elastic band to make them more flexible, the advantage of this type of eye tracker is that the participant is free to move the head, since the cameras are attached to it. The downside is that it requires smaller cameras to not be uncomfortable and it needs to be tightly strapped to the head, so that it cannot detach during the testing period, and even small movement can render the calibration useless [55].

Head Mounted with Head Tracking This type of eye tracker has many of the same features as the normal head mounted eye tracker, however it uses headtracking to increase the precision of the gaze calculations [55].
Even though these are the general types of videobased eye trackers they come in many different versions and may incorporate several aspects from each of the general types in various ways.

2.5.2.2 Videobased Eye tracking in VR

In VR eye tracking currently has to be added separately. The general setup would fall into the category of headmounted eye trackers, ans since HMD's are already tracking the head the translation into gazepoints become easier.

Currently there are not that many companies producing publicly available eye trackers for VR. But it is expected to become integrated feature of HMD's in the future. For this project the open source produced eye tracker from pupil lab was used as it was the one available. The pupil lab eye tracker utilizes two infrared cameras that are mounted at the bottom of each lens in the HMD and several IR LED's which are placed around the lens to illuminate the eye.

2.5.2.3 Videobased Eye tracking Methodology

As explained previously videobased eye tracking is done by analyzing an image stream of the eye from an IR camera. In order to get to the end result, the image must undergo a series of analytic steps. The first step is image acquisition, this is to get a clear image of the eyes. In head mounted systems this is very simple as the cameras will always be focused on the eyes, however in remote systems, the eyes must first be identified from the rest of the image. The second step is image analysis here the information required for the next step is acquired, this could be the pupil, the pupils shape or the first Purkinje image [55].

There are four Purkinje images, these are four different reflections from the eye. The first is also known as the corneal reflection this is the reflection created by the IR light in the front of the cornea. This reflection is the one most interesting in relation to eye tracking as it is the clearest and most easily, when it is detected it can be used as a reference point, so that the position of the pupil can be calculated. The second Purkinje image is formed on the rear side of the cornea while the third and fourth Purkinje image are formed by the light reflected in the front and rear of the lens [58, 59]. The weakness of using these reflections in eye tracking is that glasses or contact lenses may create additional reflections and therefore make it more difficult to correctly assess the eyes' position [57].

There are two primary ways of identifying features of the eye, these are a shape-based and an appearance-based approach[57]. When using a shape based approach an algorithm attempts to identify the sought areas based on predetermined criteria, such as thresholds or gradients[55]. With an appearance based approach on the other hand the whole image is taken and attempts to align it with a model of how the eye should look is made, thereby identifying the features from the corresponding matches. Both methods have advantages and disadvantages, and it is quite rare that eye tracking companies make it publicly available information whether it is one or the other, it is even possible that they use some combination of the two in order to achieve a better result [55].

When all the information about the eye is ready, it has come to the last stage called gaze estimation, this part is essential as it is the part where the information about the eyes gaze position is calculated. Gaze estimation is basically about calculating a vector of the direction the gaze has or calculating a point at which the eye is gazing.

There are several methods to do this, but the most commonly used method is called feature-based. Common for all methods is that the participant will go through a calibration in which he or she will be asked to look at a series of points, this is done to determine parameters by which the point of gaze can be calculated [57].

The feature-based approach utilizes extracted local features of the eye to determine the point of gaze, such features could be the corneal reflection or the pupil. There are two approaches to doing this, a parametric method that is model-based and a non-parametric method which is interpolation-based. The model-based method is parametric as it is based on some basic assumptions, such as a spherical eyeball and the shape of the cornea [57].

The Pupil Lab Eye tracker used for this project does not in comparison with many other eye trackers use the corneal reflection, instead it uses the shape of the pupil to determine the direction in which the participant is gazing, it uses a parametric method as it attempts to fit ellipses onto the pupil to determine the current position. This method can be used as the camera is positioned very close to the eye, in an extreme angle, which means that the pupils will change form drastically depending on the angle. The strength of this method is that it is not affected by the participants use of glasses or contact lenses [60, 61].

A third method for determining gaze position could be the dual-purkinje method using the fourth purkinje image, the one reflected from the rear side of the lens. This can be used as its position will change relative to the first purkinje image on rotation but not on translation, though it is a precise way of calculating the eyes movement it has not become the most used method as the fourth purkinje image is only 10% the intensity of the first and therefore light sources needs to be very precisely controlled in order to make it clear enough for detection, and since it uses additional reflections it is even more susceptible if the participant is using glasses or contact lenses [57, 58].

2.5.2.4 Extracting Eye Movements

When information about the eyes positional data is available the only thing that remains is to identify the desired events, such events could be saccades, fixation or smooth pursuit. This is usually done by thresholding of specific characteristics, such as velocity, acceleration and duration. The registration of fixation and saccades are usually done with one of two methods, either a velocity based method or a dispersion based method. Velocity based methods are as the name said based on identifying saccades based on their velocity, typically the acceleration is used to register the onset and offset of saccades while the velocity peak is used to threshold the saccade candidate. Sometimes duration is added as it can be used to filter out microsaccades or glissades from saccades[62, 63]. Fixations are then typically identified as everything which was not saccades and then thresholded by duration, to identify what were and what were not fixations. The dispersion based method instead tries to evaluate based on the angular dispersion of the gaze, this requires access to the gazedata in the form of angular degrees, and first identifies fixations as periods of time over a certain threshold typically 80-150ms, in which the gaze do not move more than a certain amount of degrees typically 0.5°. Then everything else is identified as saccades. There exist several variations of the two mentioned here and they may be combined as well in order to identify more precisely [62, 63]. Nyström and Holmqvist suggest a more adaptive method of event detection in which saccades are first detected, after which glissades are detected separately, and then in the end fixations are detected[62].

2.6 Chapter Conclusion

In conclusion to this chapter it was found that the SSQ even though it has its faults, currently is the best way of measuring cybersickness, the overall understanding of cybersickness has been laid in order to possibly identify patterns in the results of the test to come. A basic understanding of the eye, its movements and the tracking of these have been founded, and even though this study does not aim at making algorithms for eye tracking, a basic knowledge of the equipment in use is necessary in order to understand the capabilities of the equipment and the limitations. This knowledge can then be used in the design of the experiment to avoid unforeseen complications.

Chapter 3

Research Problem

The research question and hypotheses, methods and scope of the study are presented in this chapter.Eye movement in relation to Cybersickness and Virtual Reality is not something that have been clearly enlightened before, and therefore the most reasonable way to approach the subject would be by using an exploratory research design. The focus of this would be enlighten whether there is a probable connection between cybersickness and the eyes movement.

3.0.1 Research Question

The primary goal of the study is to answer if there can be estimated a correlation between reported cybersickness and eye moving using gaze directional data from a head mounted display with built in eye trackers. This is something that has not been researched a lot, though theories of a connection between the body and eyes movement have been established; [3]. Only within the recent years have the advances of technology made it possible to combine HMD technology with eye tracking hardware along with the computing power to process the data, been available to researcher, which may explain the lack of research within the field.

> RQ; Is there a correlation between the degree of cybersickness and the way the eyes move, when moving virtually using a gamepad or physically walking using roomscale technology in virtual reality?

- Null hypothesis: There is no correlation between eye movement and cybersickness.
- Alternative hypothesis: There is a correlation between eye movement and cybersickness.

3.1 Research Method

The general methodology when researching exploratory is to start measuring many points of interest, thus using a quantitative approach and then use the quantitative data to identify specific areas of interest which will then be further explored qualitatively.

3.1.0.1 Exploratory Test Design

The goal of the test was to search for possible connections between cybersickness and eye movements, therefore an exploratory test design was used, with many measurements in order to provide enough information to clearly enlighten such connections if any were to be found. Several extra measurements of both position and orientation were recorded, together with the measurements of the eyes. The findings would then be held up against the findings in order to see if there were any unexpected discrepancies that could lead to further knowledge of the movement patterns of the eye VR. This is an exploratory design as it does not try explain already know connections in depth but rather tries to give a quantitative overview of possible connections which can then be analyzed and discussed. Opening up for further investigations into the specific connections.

3.1.1 Methods

The project revolved around a series of tests. First a pilot test to identify how the different measures worked and to iterate on the test setup, VE and to get a understanding of the general test procedure. This could hopefully reduce possible sources of bias in addition to make a more clean and purposefully designed VE. Then the primary test was conducted, which gave the necessary quantity of data in order to make an analysis based on general knowledge of the measurements and the acquired knowledge of the eyes movement and general movement physiology, see 2.5. The results of this analysis should then be used to determine if the change of movement control had any effect on the way the eyes moved during the test and whether there is any link to cybersickness. The goal was to enlighten the relation between eye movements, cybersickness and spatial movement in VR. The tests was performed as a within subject test, and the data gathered was a combination of self-reported questionnaire answers and physiological measurements in the form of gaze points.

3.2 Data gathering

Data was gathered in different forms as to determine the outcome from different angles. The eyes movement was measured to achieve and understanding of their movement, and the participants were asked to fill out a questionnaire in order to gather basic information and to determine their degree of cybersickness.

3.2.0.1 Measurements

In order to understand how the eyes move certain measurements are needed, the eye-tracker gives a set of coordinates in the form of X and Y values, combined they represent the current gaze position on the screen in a grid of normalized coordinates going from (0,0) in the bottom corner to (1,1) in the to corner. These gaze positions were the foundation for the measurements of the eye. In addition to basic demographic questions the participants would be confronted with the SSQ [34], and a small series of extra questions at the end of the test.

Saccades Saccades can be registered from the gaze data and can be further analyzed in order of providing information about the user's eye-movement behaviour at given points in time [55]. In this study the average duration of saccades as well as the average amplitude and average amount of saccades will be used to see if there is a difference in eye movement between test conditions [55]. The algorithm used for to register the saccades were a velocity-acceleration based method, using the acceleration to determine saccade-onset and offset, and evaluating the found saccades by thresholding on the maximum velocity. Normally the velocity would be described in °/s this was however not possible since the intrinsic values of the HTC Vive was unknown and the data given by the pupil software were in normalized coordinates. Instead the velocity was measured in pixels/s, where the calculation from normalized coordinates to pixels were based on the values used by the pupil software at calibration, pixels/s is a relative speed that depends on the distance to the screen, but in this case it was deemed sufficient to register saccades. The velocity threshold was determined by the researchers after analyzing a sample of visual gaze data. It was determined to be set to 1500 pixels/s as this was a clear difference between saccades and other types of movement, in addition it was deemed that the lack of noise in the data from pupil suggested that the data had been filtered, it was however not possible to neither prove nor disprove this assumption. Acceleration was determined in the same manner and set to 30000 pixels/s^2. Each of the thresholds were adjusted to see the effect on the result and graphs of the velocity and acceleration was analyzed to give a correct assessment see Appendix B for the Matlab Code used for saccade registration.

Fixations Fixations basically represent the periods of time when the participant is not moving the eyes, while fixations are normally used to identify areas of interest this study is less interested in what the participant is looking at, and more interested in how the participants eyes are moving [55]. This does however not make fixations unnecessary, as the lack of eye movement also tell something if they appear where they are not supposed to appear. Since the angular movement of the eye could not be determined it made it impossible to use the angular dispersion-based method and instead a velocity based method where anything not deemed a saccade would be assumed a fixation and then evaluated based on a duration threshold to determine if it was actually a fixation. This method is not as robust as a dispersion-based method but still sufficient to find fixations in the given context, see Appendix C for the Matlab code used for fixation registration.

Vestibulo-Ocrcular Reflex The vestibulo-occular reflex as described in 2.5.1.3 is a reflex and therefore is an unconscious act [5], it is difficult to register as it does not have any extreme movement features, but since the participants will be moving, it is expected that this movement will occur, and it should appear in the form of raw gaze movement or something that may seem like smooth pursuit or drift. This is difficult to detect directly, but by measuring the raw movement, it should be possible to see if this happened under one condition while not happening under another.

Rotation versus straight Walk There was differentiated between whether the participant were walking straight and when the participant was rotating, this was done in order to make an analysis of data based on the type of movement the participant was performing, and to make sure the data intervals were comparable as each person could move through the test at different speeds. By limiting it to rotation and walk the moments where a person is standing still is not counted in, nor is any irregular movement that cannot be classified as either. The movement was classified based on thresholds, with rotation being a change on the Y-axis of more than 90°however a clause that if a person rotated 80°for then not to rotate further in a period of time would also be classified as a rotation. This was done to avoid miss-classification in case a person walked to a corner from an angle and thus may not have rotated the complete 90°. Walk was classified as periods in which the person moved a certain distance on the (X,Z) plane while not rotating onset and offset was registered based on acceleration and velocity with a minimum duration for it to classify as a patch of walking see Appendix D and E for the MatLab code used to find rotaion and walk

3.2.0.1.1 Simulator Sickness Questionnaire Data collection of cybersickness was done through Kennedy et al. Simulator Sickness Questionnaire [34], as despite its' issues it is still the most validated and used subjective measure for cybersickness and simulator sickness. Participants would be given the Questionnaire right before the first experiment and immediately after each condition.

3.2.0.1.2 Follow up Questionnaire This questionnaire was aimed to get an insight in the participants SSQ answers, and obtain data on which parts of the VR exposure induced discomfort if any. and to identify a correlation in the specific movement types connected to the induced potential induced discomfort.

Question 1.
Did any of the scenarios make you feel more uncomfortable than the others?

a) Neither was worse
b) I did not feel any discomfort
c) Physically walk
d) Sitting with Joystick
e) Standing with Joystick
f) Standing and sitting with joystick was equally bad

Question 2.
Did any of these movement types induce discomfort?

a) None
b) Turning 180 degrees with controller
c) Turning 180 degrees while physically walking
d) Turning 90 degrees with controller
e) Turning 90 degrees while physically walking
f) Moving Straight with controller
g) Moving straight while physically walking

Question 3.
Did the discomfort increase or decrease after you took off the headset?

a) I didn't feel any discomfort
b) It increased
c) It decreased
d) I felt the same

3.2.0.1.3 Observations During the experiment the participants were observed. Their behavior in the different conditions was noted, The observers would log observations from the following guidelines of important factors:

- Behaviour during turning
- Physical signs of cybersickness
- Verbal signs of discomfort
- Technical issues

3.3 Scope and Limitations

As the study focuses on the visually induced cybersickness while moving and its' correlation to gaze direction, features such as sound, haptic feedback and interaction with the objects were excluded from the study.

To limit the amount of variables in each condition, the study movement types such as straight walking and rotation, vertical elevation was therefore not a part of the study due to its' complexity in implementation of a physical walking scenario. The experiment is also limited in the hardware used, as the eye trackers used only records at 120Hz which is below the recommended 250Hz [55], which means they will not catch every movement, but should be capable of giving usable information about general saccadic movement and fixations, initial tests also indicates they data acquired is filtered within the software itself thus not all data points are retrieved.

The data collection utilizes subjective questionnaires for evaluating induced cybersickness relying on test participants to report their symptoms and experiences. Eye tracking is used to measure gaze direction, however since there is no establish connection between the two, the study will rely on looking at correlation and comparisons of data trends.

3.4 Chapter Conclusion

Methods for interpreting the data gathered during the experiment has been presented and a foundation for the experiment has been laid out. Methods for detecting the relevant eye-movement events were found and methods for rotational detection and walk detection were presented as well. The SSQ remains the primary way of detecting cybersickness through self-report and as such it was concluded to be the chosen method. It was deemed that an extra questionnaire of a few relevant questions could be useful in order to provide extra information regarding the general experience of the type of movement.

Chapter 4

Experiments

In the following section the experiment as it was performed will be explained as well as the used implementations and applied methods. The purpose is to create an overview of the experiment on which to explain the findings.

4.1 Experiment Design

The experiment was designed with three independent variables; physical walking in roomscale, Standing with a gamepad and sitting with a gamepad. The study used a within subject design, where participants would be exposed to the visual stimuli from each of the three conditions, measuring the dependent variables of gaze direction and cybersickness symptoms using the Kennedy-Lane Simulator Sickness Questionnaire (SSQ) [34]. Counterbalancing was used to minimize the practice effect [64].

4.1.1 Experiment stimuli

The experiment took place at the Multisensory Experience Lab at Aalborg University Copenhagen. The lab features a Vive tracking space of 3m x 3m which was used as the setting for the experiment and therefore also was used as the basis for designing the VE of the experiment.

4.1.1.0.1 First iteration The initial design of the VE was focused around simplicity, with the general consensus that the VE should be a clean controlled environment with enough visual cues for orientation purposes.

The environment design contained no immediate walls at the tracking boundaries, but instead relied on the safeguard provided by steamVR which should stop the participants from walking out of the tracking space (see figure 4.1). The design featured objectives (cones placed at head height) in different colors in the

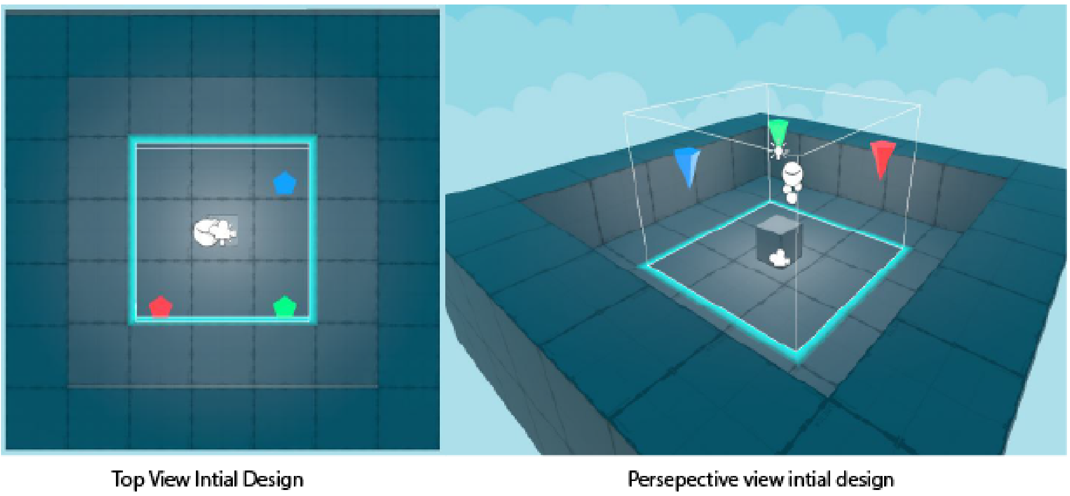


Figure 4.1: initial VE design

corners. The colors were different so the participants could be instructed to go to a specific target. This initial design showed several flaws in a small pilottest of the system carried out on 5 individuals who were present at the lab during implementation. The finding were: The steamVR safeguard was not apparent enough for users to stop before accidentally walking through it, and some thought the red colored cones meant they should stop walking, and the test design was too short to induce enough symptoms of cybersickness. A method for producing more walkable space was needed which would suit both the physically walking condition and the virtual locomotion conditions.

4.1.1.0.2 Second and Final iteration For the second iteration of the VE-design, utilized the findings from the first test to improve on the factors that could influence the experiment, in order to improve the experimental design. It was decided to use impossible rooms [46] and change blindness [41] to extend the amount of walking space within the tracking area. This was done by creating walls that could be dynamically activated and deactivated while the participant was looking in another direction, usually this would happen when the participant had to turn a corner or in the middle of a straight path, thus making it less likely for participants to look in a direction that would reveal the change, as the action of looking in that direction require a sudden change of direction during movement to look back. This method allowed for infinite walking space of corridors with overlapping architecture as seen in figure 4.3.

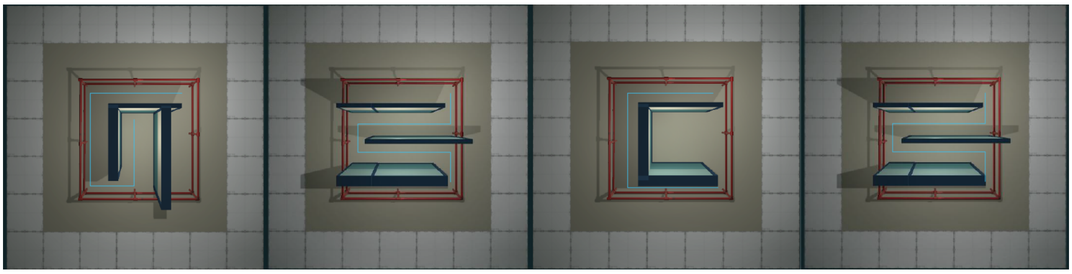


Figure 4.2: Final Test design top view; Blue line from the far left image to the far right indicate the path a participant would walk

The gamepad movement was implemented with an Xbox controller using only the left joystick to simplify the experience. Furthermore movement would always occur based on the forward vector of the head, meaning the virtual movement would always go in the direction of where the participant was looking. This was done to prevent a disconnect with the body and create unnecessary disorientation as no body-representation was implemented. Forward movement was implemented to be constant with no acceleration or deceleration this means that when moving forward the speed would change instantaneously to its' speed limit (as described in section 2.3.2.3.2). Collision between the walls and the virtual participant-collider was disabled to ensure no unintentional physics-glitches or unwanted movement occurring as a result of the Unity game engine. The participants were therefore not prevented from walking through walls, but were told during instructions not to do so.

All the 3D models in the scene were created within unity, using the ProBuilder prototyping tool which made it possible to create and edit meshes within the scene view. This approach ensured that one Unity meter corresponded to one meter in the real world, which in turn made the alignment with the tracking space easier.

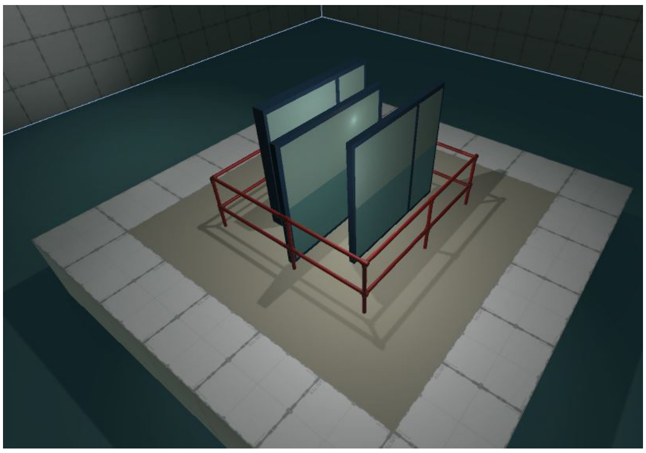


Figure 4.3: Final Test design; side perspective view

4.2 Eye-tracking implementation

Pupil Labs open source eye tracking software was used for the implementation. It is a combination of third-party standalone software and a plugin for Unity which takes care of the communication with the Pupil Labs eye tracking hardware that was modified onto the HTC Vive headset. The pupil software makes use of a message pack system that serialize the data into binary format that can then be accessed from other languages. The pupil HMD plugin for Unity then receives this information and deserialize it, so that it can be used within unity. In addition to making the data from pupil accessible in unity, commands could also be sent to the pupil software from Unity, this allowed for recordings to be started and general capturing instructions to be controlled from Unity. The plugin came with a set of scenes demonstrating the use of pupil-eyetracking in Unity, among these the calibration that was used in the experiment. At the end of the calibration the test scenario would be loaded in as a scene on top of the calibration scene, this meant that the calibration data and eye information were stored on top of the now seen Unity scene.

The 2D Calibration was used as it was the one recommended by the support in pupils discord channel. Since it supposedly should be more reliable when using VR. This is due to the angular distortion of the lenses which makes the exact calculation of the 3D calibration unreliable [65]. In addition the plugin came with a capturing implementation that allowed for both capturing the frame into a video format and the gazedata along with unity data into a .csv file. Some modification of this was needed as data was recorded onto the hard-drive in real-time, heavily influencing the framerate of the scenario. The video recording had to be cut out completely as there was not time to write a new capturing script that could capture the frame in real-time without severely hampering performance. The writing of the .csv file also had to be modified, as this alone reduced the framerate to about 60 frames per second, significantly lower than the recommended 90 frames pr. second for VR. The solution was to write the data into C# Lists and then at the end of the session write the lists into the .csv file in iterations. This resulted in a major lag spike at the end of the session, however the recording would be stopped before this, and the writing of the .csv file could be done while the participant filled out the questionnaire.

The resulting .csv file contained the following information:

- Timestamp in seconds from the Pupil Camera
- Eye ID
- Confidence, used to filter out unreliable data
- Gaze X position

- Gaze Y position
- Unity Position as a vector x,y,z
- Unity Rotation in Euler Angles

The following piece of code shows the implementation of lists as the way of recording data at runtime in order to save performance. The method AddToRecording was a part of the pupil plugin code, the code was then modified to save the data into lists rather than saving it directly to the hard drive.

```
private static void AddToRecording( string identifier,
   Vector3 position, bool isViewportPosition = false )
        {
        var timestamp = FloatFromDictionary(gazeDictionary,
           "timestamp");

        var confidence = FloatFromDictionary(gazeDictionary,
           "confidence");

        if (isViewportPosition)
            unityWorldPosition =
               Settings.currentCamera.ViewportToWorldPoint(position
               + Vector3.forward);
        else
            unityWorldPosition =
               Settings.currentCamera.cameraToWorldMatrix.MultiplyPoint3x4(posi

        cameraWorldPosition = Camera.main.transform.position;
        cameraRotation =
           Camera.main.transform.rotation.eulerAngles;

        if (!isViewportPosition)
            position.y *= -1;

        timeStampList.Add(timestamp);
        confidenceList.Add(confidence);
        identifierList.Add(identifier);
        positionList.Add(position);
        unityWorldPosList.Add(unityWorldPosition);
        cameraWorldPosList.Add(cameraWorldPosition);
        cameraRotationList.Add(cameraRotation);
```

```
        dataPoints = timeStampList.Count;
        }
```

The next piece of code describes the process of enabling and disabling the objects used in the process of creating the impossible rooms. By placing this script on two trigger boxes, the setup could be switched whenever the participant walk through that collider, thereby creating an infinite walkingspace.

```
public class ActivateSetup2 : MonoBehaviour
{
    [SerializeField]
    public GameObject DisableState;
    public GameObject DisableState2;
    public GameObject EnableState;
    public GameObject enableCone1;
    public GameObject enableCone2;
    public GameObject cornerCone;
    public GameObject triggers;
    private List<GameObject> triggerList;

    void OnTriggerEnter(Collider other)
    {
        if (other.gameObject.tag == "MainCamera")
        {
            if (DisableState.gameObject.activeSelf == true)
            {
                DisableState.gameObject.SetActive(false);
            }
            if (DisableState2.gameObject.activeSelf == true)
            {
                DisableState2.gameObject.SetActive(false);
            }

            EnableState.gameObject.SetActive(true);
            enableCone1.SetActive(true);
            enableCone2.SetActive(true);
        }

    }
}
```

4.3 Tasks

The visual task design was inspired by a locomotion comparison study by Langbeh et al. [49] who used clear visual targets which the participants should move towards. This was implemented by add brightly colored cones which the participant would walk towards and once within close proximity the cone would be deactivated and the participant would walk towards the next cone. The cones were place in at head height to provide a fixation point for the participant, once 10 cones (objectives) were reached the visual stimuli would stop.

The walking task was focused on straight lines and turns these were largely inspired by a study by Imai, more Raphan and cohen [3] who measured the interaction of the body head and eye during walking and turning. Though this experiment only focuses on the interaction of the eyes while walking and turning. To ensure the participants did not only use head rotation during virtual locomotion a series of 180 degree turns was also added, forcing participants to use the joystick on the gamepad for rotation.

4.4 Apparatus

The experiment is carried out using a modified HTC Vive with display resolution of of 1080x1200 per eye (2160x1200 combined pixels). The HMD has implemented binocular eye-tracking from pupil labs, each camera records at 120Hz, and around the lenses were a ring with IR illuminators. The software application was developed in Unity and ran on a high-end PC (i7 Processor, Nvidia GTX 1070 graphics card, 512gb SSD) to ensure stable performance through out the testing (90fps or above). An Xbox one controller was used for the virtual locomotion using left joystick. Furthermore a questionnaire was used using Google Form and was filled out by the participants on a laptop.

4.5 Participants

A total of 27 participants (8 Female and 19 male) between the ages of 19-30 (M= 24.6, SD = 2.2) took part in the study. The participants were mostly collected through convenient sampling, 20 were university students, and 7 had occupations elsewhere. The participants were asked to rate their experience with VR where 10 claimed high experience, 7 with medium experience, 9 with low experience and one had not tried VR before. The participants where not offered any reward for their participation. 9 participants reported having visual impairments one reported astigmatism and the remaining 8 reported near slightness or farsighted but where all compensated for by visual aid.

4.6 Procedure

The independent variables were counterbalance in sequence: A,B,C (walking, sitting, standing), CAB, BCA. The procedure is explained for sequence ABC, but can be applied in for all with the corresponding order change.

4.6.1 Participant procedure

upon arrival the participants were handed a consent for to sign (see Appendix A) allowing the researchers to gather eye-tracking information and questionnaire data as well as briefly explaining the experiment. A questionnaire about their experience with VR, visual impairments and general demography, was presented before being asked to fill out the pre-simulator sickness questionnaire.

The participants were then instructed to go to the center of the tracking space, and face towards the computer. They were then instructed on the calibration scene of the eye tracking i.e. look with the eyes on the white dots appearing on screen, once the calibration completes the test environment would appear and they were told not to walk through walls and follow the path. Once instructed they would be equipped with the HTC Vive headset, making sure it was positioned comfortably and the eyes were visible on the computer screen. The researchers would then enter order and participant number, and start the calibration scene. Another researcher would hold the wire for the participant so they would not be restrained by it or or bump into it while they were walking. Once 10 objectives were hit the visual stimuli would stop and they were instructed to take off the headset and fill-out a post-SSQ. Meanwhile the researcher would place a chair in the center of the tracking space for the next task. The participant were told to sit on the chair (setup see figure: 4.4), instructed that the calibration scene would take place again and they would enter the same virtual environment but would move with a gamepad this time (Xbox one controller,using left joystick), and they were instructed how to use it and told to not move through the walls. Another Post-SSQ was this presented to the participant after the 10 objectives were hit, and the chair was removed from the tracking space. The participant were then told to stand up right, towards computer and not physically move but move using the left joystick. If the participants moved by turning their body during the exposure they were told to use the joystick on the gamepad. After the final session they filled out a post-SSQ and answered some predefined questions about the experience in regards to cybersickness (e.g. if there was any condition that induce sickness or certain movements that induced it, and whether or not if any sickness, increased, decreased or stayed the same after taking off the headset). The entire test including questionnaires took approximately 15 minutes.

4.6.2 Researcher procedure

In order to log the data and facilitate the experiment smoothly, the researched followed their own procedure in regards to making sure all data was logged. Once the participant was equipped with the HMD, the researcher with the participant would signal to the other researcher by the computer that everything was ready. The unity scene containing room scale capabilities would be started, before the calibration the researcher would start with entering the number of the participant and which condition the participant was going to experience. Then the Windows screen recorder would be started to capture the computer screen of what the participant is seeing in the HMD, once this was recording, the calibration scene would start. When entering the test environment the two eye-tracking cameras would start recording automatically as well as logging the gaze data points to the memory. Once the participant hit the 10th objective the VE would stop and the computer would start writing the gaze data points to the hard drive, thus freezing the Unity application until completion. The Screen recording would also be stopped, and the video file would be place in the correct folder generated from the information about participant number and test condition in the beginning of each test. The process would the repeat itself for the next condition just with room-scale turned off, so it would load the controller based version of the scene.

4.7 Chapter Conclusion

The Experiment was presented, in regards to test design how we implemented it and the solutions to problems that was discovered during implementation, as well as an overview of the task design, participants and procedures used to conduct the experiment. This is used to get an understanding of the work that went into the experiment before the presentation of the results.

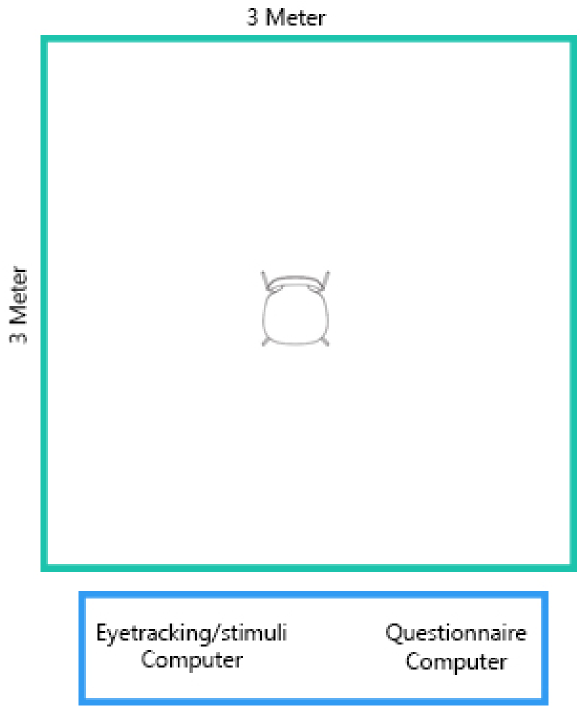


Figure 4.4: Test setup in the Lab, green square represents the 3x3meter tracking space with the chair place at the center spot. the blue square represent the table with the computer controlling the stimuli and the one used for questionnaires

Chapter 5

Results

In this chapter the results from the data analysis of the subjective measures and the data analysis of the eye tracking data will be presented along with their individual findings.

5.1 Simulator sickness questionnaire

SSQ ratings were scored and weighted as described in Kennedy et al. (1993) study [34]. Thus the total severity scores were used for the data analysis. The analysis had two objectives; Determining an increase in cybersickness when comparing pre and post exposure (TS)scores of the SSQ between them using the repeated measures data from the 27 participants. The second objective of the analysis was to determine whether the three conditions yielded a significant increase in cybersickness between each other using the total difference scores.

A Kolmogorov-Smirnov test was performed to determine the assumption of normality in the pre and post scores of the individual conditions. The walking condition showed that it was not significantly different from a normal distribution, and can therefore be analysed using parametric test, while the sitting and standing conditions rejected the similarities to the normal distribution, and non parametric test should be performed on those two conditions. A dependent t-test was performed on the walking condition which showed a significant increase in cybersickness from pre and post at a p value = 0.0003. A Wilcoxon signed-rank test was used on the non-parametric data and showed a significant increase of cybersickness in both conditions from pre to post exposure scores (sitting; p= 0.001, standing; p = 0.0006). A further investigation was done into the individual post scores in form of descriptive statistics as seen in figure 5.1. It shows that the mean values rises in all three conditions even for the individual categories. Therefore the total difference scores was calculated between each pre and post exposure score in each condition (TSdiff = TSpost – TSpre). Then a Kolmogorov-Smirnov test was used to determine the assumption of normality, the results showed that normality was violated in all three conditions, thus non-parametric test where used. The Wilcoxon signed-rank test revealed no statistically signicant median increase in total difference score between the individual conditions (walking/sitting; p = 0.711, walking/standing; p = 0.469, sitting/standing; p=0.562).

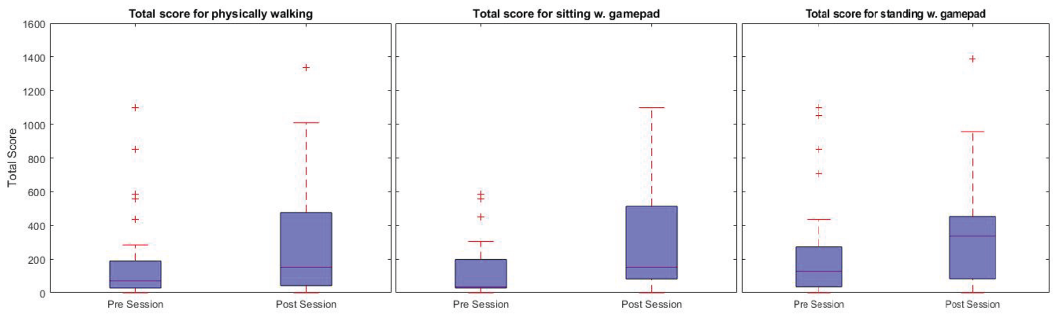


Figure 5.1: Boxplots presenting the medians, interquartile ranges, minimum and maximum ratings, and outliers related to total scores for physically walking (left), Sitting with gamepad(middle) and standing with gamepad (right).

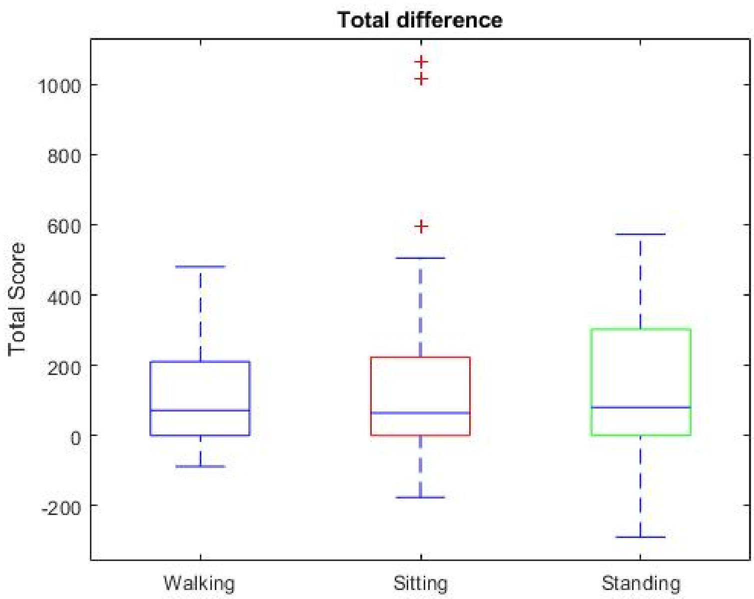


Figure 5.2: Boxplots presenting the medians, interquartile ranges, minimum and maximum ratings, and outliers of the total difference scores for physically walking (left), Sitting with gamepad(middle) and standing with gamepad (right).

Table 5.1: Simulator sickness questionnaire (SSQ) analysis results (Physically walking, A; Sitting w. gamepad, B; and standing w. gamepad, C).

		SSQ Post Scores (Weighted)			
		Mean	Standard Deviation	Minimum	Maximum
Total	A	302.69	341.55	0	1335
	B	314.88	329.63	0	1098.6
	C	387.46	397.93	0	1625.3
Nausea	A	22.61	21.03	0	76.32
	B	23.67	23.72	0	95.40
	C	29.68	28.66	0	133.56
Oculomotor	A	19.65	24.9	0	133.70
	B	21.33	22.05	0	83.38
	C	24.42	28.77	0	113.7
Disorientation	A	38.66	49.64	0	167.04
	B	39.18	48.07	0	153.12
	C	49.49	54.37	0	194.88

5.1.1 Findings

The tests for a significant increase in cybersickness between pre and post scores was found in all conditions, a visible increase in median was also seen in the boxplot figures 5.1. However no statistical significance was found in the total difference score between the conditions.

5.2 Post experience questionnaire data

In conjunction with the SSQ, the participants were also asked a series of question in regards to what affected them during the session. It is also worth nothing that only two scored 0 in the SSQ out of the 27 participants. 22 reported that the discomfort for the exposure decreased after the took off the headset, three felt the same and one reported the discomfort increased after removal of the headset. 12 reported that the standing condition made them feel more uncomfortable than the others, 7 reported sitting to be worst while 4 reported sitting and standing to be equally bad. One of the two who reported not having any discomforted reported that the physically walking condition was the most uncomfortable. Lastly the participants were asked if any movement types induced any discomfort. 22 participants reported either 180 degrees and 90°rotation with controller to induce discomfort while two reported moving straight with controller, two reported none and nobody reported physically walking to induce any discomfort.

5.2.1 Findings

The questionnaire showed an insight into the participants discomfort, it was clear that the participants were more sick during rotational movement using virtual locomotion compared to physically walking. It was also clear that the discomfort decrease after taking off the headset.

5.3 Observations

During the experiment observations of the participants performance and behaviour was noted. It was apparent that there was a trend in the physically walking condition for the participants to look down at every turn despite not having any body representation to look at (16 out of 27 participants). It was also noted that one participant showed extreme postural instability during the standing condition swaying more and more from start to finish. Five verbally expressed discomfort during the sitting condition ("uuugh is it over soon!", "I don't wanna move"), two expressed heavy breathing during the standing condition. Three were a bit cautious while walking physically, while five participants rotated with smaller increments during corners instead of using a smooth movement. Two participants experience technical difficulties, one where the strap loosened during standing condition but was immediately fixed, while another experience software issues between tests which resulted in a bit of cool-down time before the next condition.

5.3.1 Findings

The observations showed potential complications which could have an effect on the recorded data, such as the fact that people had a tendency to look down while walking around corners in the physical condition but did not during both of the virtual locomotion conditions. Furthermore some did not use a smooth rotational movement through corner but rater took it in increments and some even had breaks in between, which might have influence their perception on induced cybersickness.

5.4 Eye Data

The results from the eyedata collection will be presented in three groups, first the results of the raw eye movement then the results of the saccades and finally the fixations. The data gathered was sorted based on complete sets of data, that is if a participant had one set of data with a confidence of less than 0.85 they would be sorted out. This gave complete results for 20 of the 27 test participants. Each type of movement is described in two groups, one for the results gathered during walk and one for the data gathered during rotation. The data is compared statistically by testing for normality and a subsequent analysis for a statistical difference. By limitng the temporal frame of the eye data that is compared, it was deemed that the data should be statistically comparable. In addition the data came from the same participants during each condition and thus each participants individual eye-movements were present under each condition.

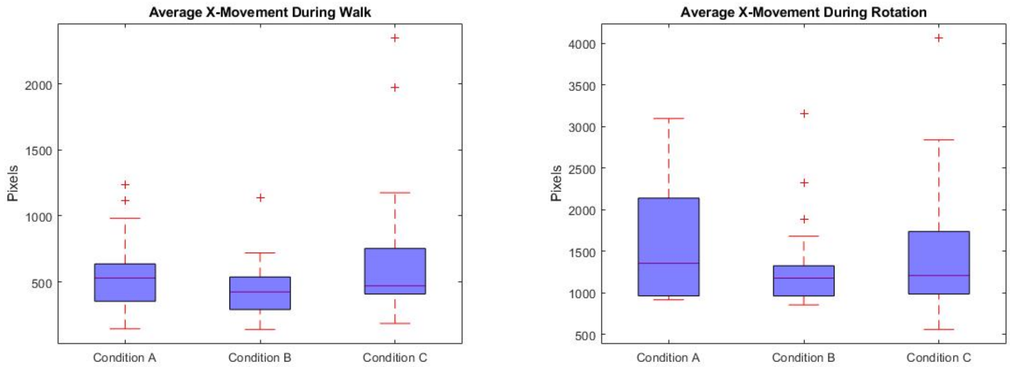
5.4.1 Raw Eye Movement

The raw movement of the eye was calculated point to point as a distance for a general analysis of how much the eyes moved during the test. The data was gathered and measured as the distance, on each axis independently for both eyes and then averaged.

In figure 5.3a it is seen that there is a slightly higher amount of movement under condition A(physical walking), while condition B(Sitting with gamepad) and C(standing with gamepad) are close to each other, though there are more outliers under condition B. Figure 5.3b shows a mostly identical pattern to figure 5.3a however in this case condition C(standing with gamepad) has more outliers. The data was tested for normality using a Kolmogorov-Smirnov test and was found to not be normally distributed, then the samples were compared in the following order A-B, A-C and B-C using a Wilcoxon signed rank test, all tests failed to reject the null hypothesis see table 5.2. This indicates that there were no significant difference in the amount of movement made by the eyes on the X-axis during neither walk or rotation.

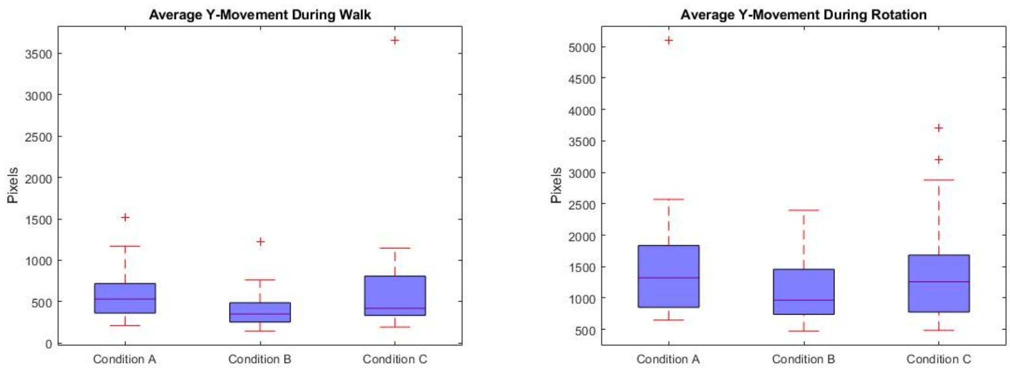
Table 5.2: The p-values of the Wilcoxon signed-rank test performed on the eye movement of the x-axis during rotation and walk

x-Axis Rotation	*p-value*	x-Axis Walk	*p-value*
Condition A-B	0.179	Condition A-B	0.2627
Condition A-C	0.3905	Condition A-C	1.0000
Condition B-C	0.8519	Condition B-C	0.1169



(a) **(b)**

Figure 5.3: Boxplots presenting the medians, interquartile ranges, minimum/maximum and outliers of the average distance moved on the x-axis for rotation(left) and for walking(right). Each figure present the results for each of the three condition, physically walking (left), sitting with gamepad(middle) and standing with gamepad(right).



(a) **(b)**

Figure 5.4: Boxplots presenting the medians, interquartile ranges, minimum/maximum and outliers of the average distance moved on the Y-axis during rotation(left) and during walking(right). Each figure present the results for each of the three condition, physically walking(left), sitting with gamepad(middle) and standing with gamepad(right).

The method used to analyze the raw movement on the x-axis was also used to test the movement on the y-axis, figure 5.4a shows how the amount of movement closely resembles itself under each condition with only a few outliers being much different from the main portion for the data. In figure 5.4b it seems that the data is slightly different during each condition, particularly during condition B, however when comparing these results with a Wilcoxon signed-rank it again failed to reject the null hypothesis (see table 5.3), and there the results cannot be said to be significantly different from each other.

Table 5.3: The p-values of the Wilcoxon signed-rank test performed on the eye movement of the y-axis during rotation and walk

y-Axis Rotation	*p-value*	y-Axis Walk	*p-value*
Condition A-B	0.1084	Condition A-B	0.0251
Condition A-C	0.9702	Condition A-C	0.5016
Condition B-C	0.2471	Condition B-C	0.0228

5.4.2 Saccadic Movement

The saccadic movement were detected offline and analyzed further in relation to the type of movement (walking or rotating) that were done at the time of the saccade. In figure 5.5 the total amount of saccades during the tests are presented, these numbers are mostly to get a scale of the amount of saccades registered during the test, since they are not directly comparable as they are not normalized according to a time frame and thus some participants may have spent more time and thus gained a higher number than those who took less time, see figure **??**

Table 5.4: The p-values of the Wilcoxon signed-rank test performed on the duration of the saccades

Saccade Duration Rotation	*p-value*	Saccade Duration Walking	*p-value*
Condition A-B	0.0005	Condition A-B	0.0674
Condition A-C	0.0090	Condition A-C	0.0333
Condition B-C	0.1560	Condition B-C	0.8228

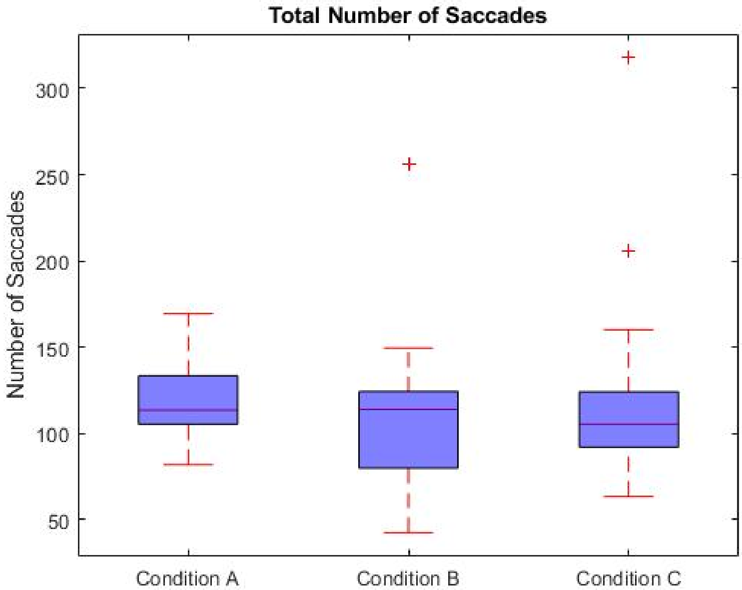
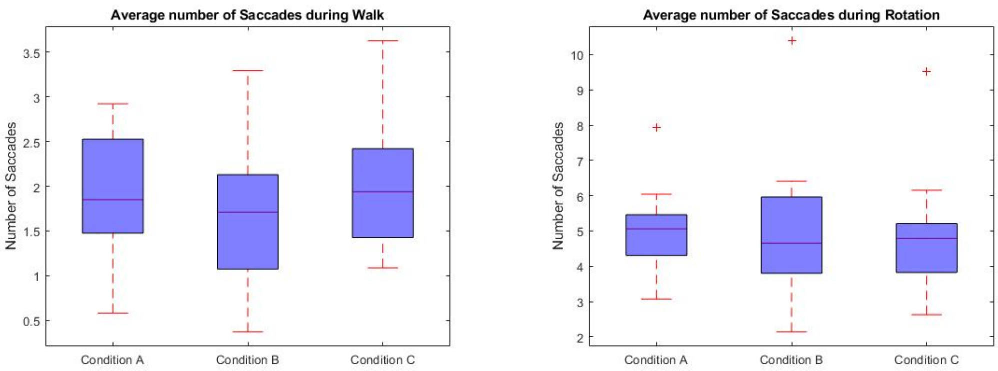


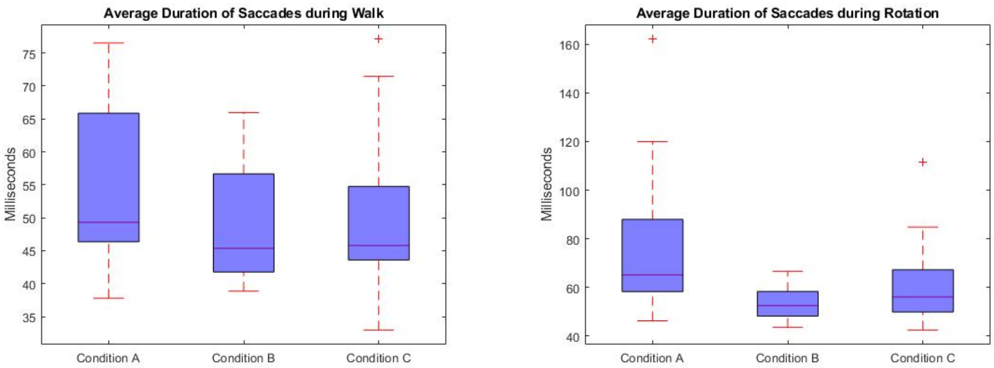
Figure 5.5: Boxplot presenting the median, interquartile range, minimum and maximum rating, and outliers of the total amount of saccades, for each of the three conditions, physically walking(left), sitting with gamepad(middle) and standing with gamepad(right).



(a) **(b)**

Figure 5.6: Boxplots presenting the medians, interquartile ranges, minimum/maximum and outliers of the average amount of saccades during rotation(left) and during walk(right). Each figure present the results for each of the three conditions, physically walking(left), sitting with gamepad(middle) and standing with gamepad(right).

In figure 5.7a the average duration of saccades during walk can be seen along with the average duration of saccades during rotation in figure 5.7b. These show that the saccades had a longer duration during walk under condition A compared to B and C, and quite a lot more during rotation under condition A. The Wilcoxon signed-rank test was also performed between these samples and they confirmed the visual findings in succeeding to reject the null hypothesis in 3 of 4 cases between condition A and the two others while not being able to reject it between condition B and C, see table 5.4.



(a) **(b)**

Figure 5.7: Boxplots presenting the medians, interquartile ranges, minimum/maximum and outliers of the amplitude of saccades for rotation(left) and for walking(right). Each figure present the results for each of the three condition, physically walking(left), sitting with gamepad(middle) and standing with gamepad(right).

5.4.2.1 Amplitude

The saccadic amplitude represents the total distance moved by the eyes from the beginning of a saccade until the end of a saccade. This distance were calculated and categorized based on the movement type (rotating or walking) see chapter 3.2.0.1. As seen in figure 5.8 the overall average amplitude of saccades were about the same for each test condition, this was also the case for saccades during rotation as well as walking see figure 5.9b and figure 5.9a. All samples were tested for normality, using Kolmogorov-Smirnov test and found not to be normally distributed, then they were compared between conditions with a Wilcoxon signed-rank test, none of the tests could reject the null hypothesis and the result was therefore that there were no significant difference between the amplitude of saccades between either of the conditions, see table 5.5.

Table 5.5: The p-values of the Wilcoxon signed-rank test performed on the duration of the saccades

Saccade Duration Rotation	*p-value*	Saccade Duration Walking	*p-value*
Condition A-B	0.0674	Condition A-B	0.5503
Condition A-C	0.5257	Condition A-C	0.9405
Condition B-C	0.4781	Condition B-C	0.4115

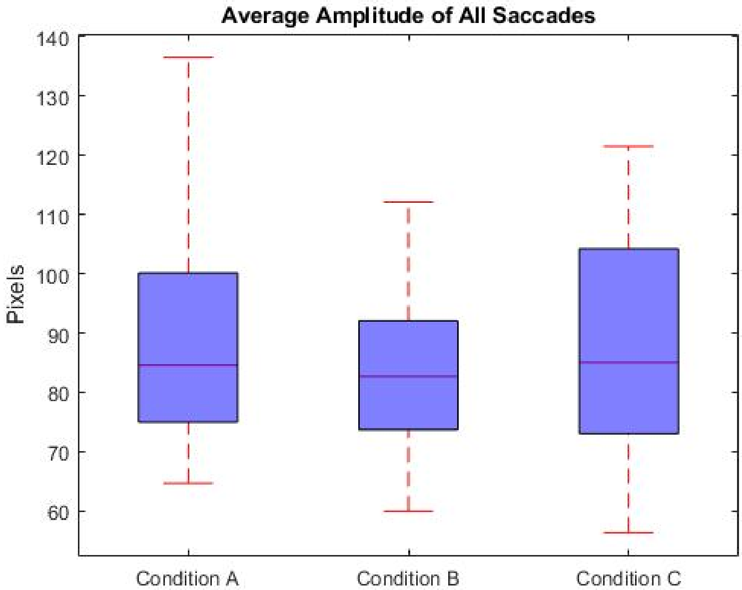


Figure 5.8: Boxplot presenting the median, interquartile range, minimum/maximum and outliers of the overall average of amplitudes of the saccades registered for each of the three conditions physically walking (left), sitting with gamepad(middle) and standing with gamepad (right).

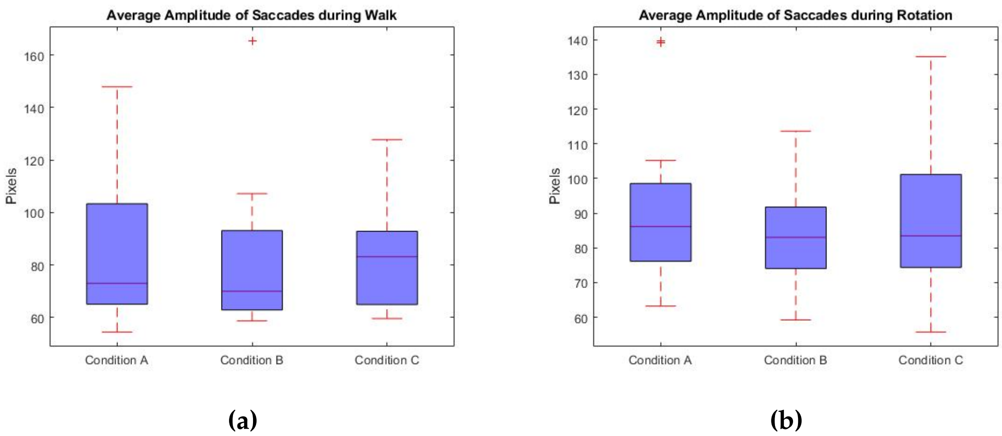


Figure 5.9: Boxplots presenting the medians, interquartile ranges, minimum/maximum and outliers of the average duration of saccades during rotation(left) and during walk(right). Each figure present the results for each of the three condition, physically walking (left), sitting with gamepad(middle) and standing with gamepad(right).

5.4.3 Fixations

Fixations were defined as time periods with no saccades and a duration of more than 80ms, for more about fixation registration see 3.2.0.1. The fixation registration algorithm registered several fixations, however only very few of these found place during walk or rotation, which means that no meaningful results could be gathered about this behaviour as it was absent in the specified time-frames.

5.4.4 Within Sample Test

Within the sample it was tested if there were a difference between the findings during rotation and the findings during walk. This was done by comparing the average amplitude of saccades, the duration of saccades as these were the most comparable measurements as they were independent of the time the user had been in the test or the duration of the rotation/walk. It was found that there was a significant difference between the duration of saccades during rotation and walk, however no significant difference in amplitude was found see table 5.6.

Table 5.6: The p-values for the Wilcoxon signed-rank tests made between the duration of saccades during rotation and walk and the test made on the amplitude of saccades during rotation and walk, both tests performed for each condition

Duration of Saccades	*p-value*	Amplitude of Saccades	*p-value*
Condition A	0.0001	Condition A	0.1913
Condition B	0.0365	Condition B	0.3317
Condition C	0.0045	Condition C	0.4552

Chapter 6

Discussion

It was found that the participants tended to be more sick post test, however it was not proven that there were a significant difference between the conditions. The eye-tracking gave varied results, but overall there were mostly not found any difference between the eye movements under each of the different conditions.

6.1 Bias

Bias in this experiment is more easily described in two parts, the human side and the computer side. When working with self-reporting and questionnaires there is always a human factor involved, may that be the participants seeking to answer in a "correct" way or simply misunderstanding the questions of the questionnaire. Especially the SSQ can be prone to the second of the two, as many people may have a difficulty understanding what the difference between vertigo and nausea is, and many of the items of the SSQ may be difficult to rate on a scale as awareness of the things tend to be low unless they are a problem. Furthermore more the experiment has a majority of male participants, which has shown to be a population which are less susceptible to cybersickness compared to a population of female participants, but also the fact that men have shown a tendency to self-report their symptoms lower than the actual amount [25]. However the SSQ is the most validated way of testing cybersickness as of now, and therefore in spite its shortcomings, the results are the best we can get. Worth mentioning though is the time of the test, the short amount of time spent in the VE could have affected the degree of cybersickness experienced by the participants, and a longer test would likely have caused participants to get more sick [15, 27]. This short amount of time within the VE in a repeated several time may also have decreased the participants susceptibility of cybersickness as reported by Davis and Kolasinski [1, 12], that short exposures times in VE may increase the speed of adaptation. However a longer test would have come with other complications and the layout of the test would likely have to be changed in order to accommodate this, as the current design would likely have become very repetitive if walked through another 10 times.

On the computer side there were also some possible causes of bias, first of all the missing intrinsic values which made it impossible to calculate and angular velocity, this caused that the eye results could not be compared to findings of other researchers in regards of velocity and acceleration. This would have been an advantage in order to set the threshold based on that of previous findings, and in order to directly implement more robust algorithms such as a dispersion based algorithm for fixation detection [55, 62, 63]. The values could possibly be calculated using the calibration to do so, however this would have to be recorded separately during the test, and would require further analysis of the pupil source code to extract the necessary information about their calibration procedure.

As described in chapter 2.5.2.1, headmounted eye trackers can move during the experiment and thereby contaminate the eye tracking results. The pupil labs eye tracker in the HMD, could be regarded as such an eye tracker and therefore is susceptible to this as well. However it is unlikely to be the most profound bias in this study, as the study does not directly involve what the person is looking at, and instead would mostly related to momentary noise in the registered movement of the eyes. The algorithms for detecting saccades and fixations could also cause some bias. But since no relevant fixations were found, this seems an unlikely candidate, and the saccade registration seemed consistent even though no angular dispersion could be measured, and since both algorithms were consistent in their registered events it must be assumed that the results they created are comparable, even if some events may have been either false positives. The greatest problem was that the algorithms were difficult to compare directly to similar algorithms due to the difference in the way the distance was measured.

Furthermore it was observed during the tests, that people tended to look down a lot, this could have an effect on the eye-movement since it could affect the change in field of view during movement and decrease the change in the visual field on the Y-Axis. This action were very particular for roomscale movement and was not observed during virtual movement. Therefore the results could have been affected by this. The current HMD's need to be calibrated to the individuals interpupillary distance as described by Davis[1], this was however not done and may have affected the results of the experiment as this can cause eyestrain if the lenses of the HMD are placed either to close or to far from each other, thereby contributing to a sense of cybersickness.

The use of redirected walking in this study was deemed necessary, however redirected walking can cause disorientation which in turn is one of the major causes of cybersickness see section 2.3.1, it was not observed among any participants that they felt disoriented nor did any indicate this. But it cannot be dismissed that some may have been affected by the redirected walking in a negative manner.

6.2 Simulator Sickness Questionnaire

The SSQ confirmed that people did get sick by the experience, however the statistical findings were that there were no significant difference between the degree of sickness in between the conditions, this contradicts previous findings that roomscale movement supposedly should make people less sick than virtual movement with a gamepad, if the scores of the SSQ are inspected it is also clear that the roomscale walking scored the lowest, however the difference may simply be too small for a statistical difference. The duration of the test could be used to question these findings as the amount of cybersickness does depend on the time spent in VR and thus the amount of time spent in this VE may have been enough to provoke cybersickness in general, but not enough to provide sufficient information for a statistical difference between the conditions[15, 27]. The post experience questionnaire supports this as most people either rated the standing with gamepad or the sitting with gamepad as the most uncomfortable which would support this general theory. Therefore it should likely be disregarded that there was not found a statistically significant difference between the conditions and instead focus should be set on the fact that people did get sick from all conditions.

6.3 Eye Tracking

The results of the eye tracking seem to indicate that there is no difference in how the eyes move based on the way a user moves in virtual reality. This would contradict with the results of Takao Imai et al.[3] as their experiment indicated a close relation between body movement and eye movement. This could indicate several things. This could be due to biased data as discussed in section 6.1, but if we assume that this is not the case, why would the eyes not move in relation to the body when walking in VR, but with room-scale movement? The answer could have something to do with the HTC Vive's representation of the virtual environment is not 100% correct, the HTC Vive uses a grid of light to track the position of the HMD, previous research has shown that inaccuracy of the HTC Vive is not purely speculative Niehorster, Li and Lappe discusses the implications that the inaccuracy of the HTC Vive could have on experiments in which visual stimulation and self motion are involved, here they mentioned that the virtual plane is tilted in respect to the physical plane[66]. This means that roomscale walking is not actually comparable to real world walking as the visual feedback during walk with the HTC Vive is not the same as the visual feedback of walking straight forward in reality. In relation to this study this could have affected the Vestibulo-Occular Reflex as the visual stimuli may have moved differently on the y-axis depending on where the user walked, since the participants walked the same path each time and the grid was calibrated in the same way each time, this offset should be the same for all participants. In relation to cybersickness this could indicate that the incapability of the HMD's to give an accurate representation of movement in the VE relative to the real world is still contributing to Cybersickness, as it is decribed how the descrepancies can cause cybersickness by Laviola[6].

One of the points that was found to be different were the duration of saccades during rotation and in one case also during walk, this is interesting as the amplitude was not significantly different and one would assume the two were connected, the best explanation to this would be that the velocity under one condition was higher than under the other, but this proposes the question of why the eye would move faster under one condition than the other. To answer this question the speed of which rotations were done could be brought up, while rotations made with a gamepad were at a constant speed, the rotation of a natural head is not at a constant speed, therefore it could be hypothesized that the rotational speed of the head affects the speed of the saccades made during this rotation. Which in turn could lead to saccades of the same amplitude but of different duration. Whether this in itself affect cybersickness would require a very specific test in which several test groups would experience rotation at different speeds. Another possible explanation to the increased duration of saccades during rotation and walk could be that the glissades were registered as a part of the saccade and that glissades were more profound during roomscale movement. The detection algorithm should however not be likely to incorporate glissades into the saccades, as the end of a saccade were detected by a fall in acceleration, which would happen in between a saccade and a glissade. But if the threshold were placed too low this may have happened.

Fixations were registered to see if they took place during walk or rotation during one condition while not during another, this was not the case, as so few fixations were found to take place during rotation or walk for either of the conditions that it must be deemed that those few that were, are more likely a result of the fixation detection algorithm not taking angular dispersion into account, rather than actual fixations. In any case the vast majority >80% of participants were reported to have no fixations during rotation or walk. The classification error the fixation algorithm would have been most likely to make was a false positive, thus finding a fixation where there was none, and it is quite unlikely to make a true false negative, thus not to find a fixation where there were one, see section 3.2.0.1. Therefore the result that there was found near to none during walk and rotation is actually interesting. This fits the theory quite well as the gaze should be constantly changing during walk and rotation, however it would be interesting to see a comparison of how the gaze moved during walk compared between each condition[3]. The eye movement could be analyzed in other ways than it was done here, this study went with a quantitative statistical analysis of the results while a more qualitative oriented analysis of scanpaths and vestibulo-occular reflex could lead to further understanding of the eyes movement.

6.4 Cybersickness and eye movement

The missing link between the eyes movement and the way people moved does pose an interesting approach to the discussion of how eye movements affect cybersickness. Since it was found that people got sick during each of the three conditions and there was a lack of difference in the eye movement where it would be expected that such a difference were present, it could indicate that eye movement during movement in VR does not match up to the movement of the eyes during movement in reality, and that this discrepancy in movement could be a cause of cybersickness. Even though there are several sources of possible bias, there is also a consistency in the findings, only the duration of saccades were significantly different and while it was not possible to statistically prove that people got more sick during movement with the gamepad, it is likely that they would have become more sick in the long term, based on the observations, previous findings and the post SSQ questions. And it would also be wrong to say eye movement is the only cause of cybersickness, however nothing in this study indicates that it does not affect cybersickness, on the other hand it is confirmed that in the situations where people get cybersick, the eyes does not move in a way you would expect. The increased duration of saccades during roomscale walking cannot really be connected to any cybersickness as such, but it is curious that it is so clearly found compared to the other factors that was so clearly rejected. Mostly since all the eye findings depend on the same movements and thus are merely different descriptions of the same actions, this could indicate that there is a difference, but it is the only factor that indicate there is a difference, and this difference could be explained by the increased speed at which the vision rotates during roomscale walk. Therefore the most likely conclusion is that there is no difference between the conditions in regards of eye-movement. In relation to cybersickness it supports that there could be a relation between eye movement and cybersickness as it is not possible to reject that there is not. The degree of cybersickness between the conditions could be argued to be larger for condition B and C however this is not possible to statistically prove, which may very well be due to the short amount of time spent in the VE.

One thing that the study is not capable of defining with certainty is whether the movement of the eyes during the test matched or were different from the movement the eyes would have done during natural walk in reality. However, it must be assumed that they did not match natural eye movement as there were no vestibular input by which to control the vestibulo-ocular reflex during condition B and C and there are previous research indicating that eye movements depend on the body's movement[3].

Chapter 7

Conclusion

A setup consisting of an HTC Vive with an added Pupil Lab eye tracker was used to observe 27 test participants moving through the same VE made in Unity during three conditions in a within subjects design, where the only differentiating variable were whether they were walking in a roomscale setup, moving with a gamepad while standing or moving with a gamepad while being seated. Cybersickness was measured using the SSQ and eye movements were detected utilizing the Pupil Lab eye tracker. The purpose of this setup was to track the eye movements and correlate these to the degree of cybersickness that the test participants felt during each condition, with the goal of enlightening how eye movements affect cybersickness.

It was found from the SSQ that the participants had a significant increase in induced cybersickness during all conditions and no significant difference in the degree of cybersickness between the conditions were found. It had been expected that the eyes would move more during roomscale walking since the movement up and down as well as tilting to either side would assumably be greater in this scenario, and thereby cause increased amount of eye movement due to VOR. This was not found however and several aspects as to why were discussed, also the finding that participants showed symptoms of cybersickness during each of the conditions without a significant difference between the the conditions, arose questions. It was deduced that it could be due to the HTC Vive's incapability to reproduce movement correctly that could lead to the indifference in eye movement between the three conditions. This result corresponded to the finding that people who experiences cybersickness during each condition and thus it was not possible to reject the null hypothesis that there was no difference between the conditions.

The interesting thing about this result is that a difference would have been the expected result, thus the inability to reject that there is no difference, indicates that something may be wrong in the way the VE's are portrayed, since a perfect replication of reality in a VE presumably should invoke the same physical reactions as reality would.

The conclusion may be that it was not possible to reject that there is any difference, however it is assumed that the eyes do not move as in reality, since there were no vestibular input present during two of the conditions. It cannot however be ruled out that the eyes are in fact moving like they would in reality under all three conditions, since there is no real-world walk condition present. Such a condition would require completely different equipment and was outside of the scope of this project.

A future study should consider adding a real-world walk condition in which the participants eyes in reality would be measured to create a baseline for the movements that the human eyes make while rotating and walking, which are directly comparable to the results of the study itself. In addition enhancements on the registration of events could be made by calculating the angular movement of the eye using the calibration data as a baseline for this.

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Appendix A

Consent Form

See next page.

Participant consent form

Research Details:

You will play through the same scenario 3 times in different real world positions. During this session, you may encounter slight discomfort and nausea. Eye tracking, video and gameplay POV will be logged throughout the session, Between each session you will answer a set of questions, your answers will be saved anonymously.

Please tick the boxes

1. I confirm that I have read and understand the information sheet for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily. ☐

2. I understand that my participation is voluntary and that I am free to withdraw without giving any reason. ☐

3. I understand that the Eye Tracking data will be anonymously logged. ☐

4. I understand that the anonymously collected data from the experiment, may be in any write up, presentation or publication of this study. ☐

5. I understand that all personal information will be anonymised and treated confidentially. ☐

6. I agree to take part in the above study. ☐

Signature ………………………………………………..… Date ……………………………..

Appendix B

Saccade Classifier

See next page.

```
function [output1,output2,output3,output4,output5] =
 SaccadeClassifier(eyeData,timestamps,makePlots)

length = size(eyeData,1);

distanceArr = zeros(length,2);
velocityArr = zeros(length,3);
accelerationArr = zeros(length,1);

velocityThreshold = 1500;
timeThreshold = 0.01;
accelerationThreshold = 30000;

calibrationAreaWidth = 1000;%in Pixels
calibrationAreaHeight = 1000;%in Pixels

%convert normalized points to pixels

for i = 1 : length
    eyeData(i,1) = eyeData(i,1)*calibrationAreaWidth;
    eyeData(i,2) = eyeData(i,2)*calibrationAreaHeight;
end
%Calculate Distance, Velocity and Acceleration
for i = 1 : length
    if(i-1 > 0)
        distance = sqrt((eyeData(i,1) -
 eyeData(i-1,1))^2+(eyeData(i,2) - eyeData(i-1,2))^2);
        distanceX = sqrt((eyeData(i,1) - eyeData(i-1,1))^2);
        distanceY = sqrt((eyeData(i,2) - eyeData(i-1,2))^2);
        velocity = distance / (timestamps(i)-timestamps(i-1));
        velocityX = distanceX / (timestamps(i)-timestamps(i-1));
        velocityY = distanceY / (timestamps(i)-timestamps(i-1));

        distanceArr(i-1,1) = distanceX;
        distanceArr(i-1,2) = distanceY;

        velocityArr(i-1,1) = velocity;
        velocityArr(i-1,2) = velocityX;
        velocityArr(i-1,3) = velocityY;

        if(i+3 <= length)
            time = 0;
            for j = 1 : 3
                distance = distance + sqrt((eyeData(i+j,1) - eyeData(i
+j-1,1))^2+(eyeData(i+j,2) - eyeData(i+j-1,2))^2);
                time = time + (timestamps(i)-timestamps(i-1));
            end
        end

        acceleration = distance / time^2;
```


```
        accelerationArr(i-1) = acceleration;
```

Appendix C

Fixation classifier

See next page.

```
function [output1] =
 FixationClassifier(saccadeArr,eyeData,timestamps,makePlots,velocity)

length = size(eyeData,1);

calibrationAreaWidth = 1000;%in Pixels
calibrationAreaHeight = 1000;%in Pixels

for i = 1 : length
    eyeData(i,1) = eyeData(i,1)*calibrationAreaWidth;
    eyeData(i,2) = eyeData(i,2)*calibrationAreaHeight;
end

timeThreshold = 0.08;

j = 1;
fixationOn = 0;
fixationOff = 0;
%Find Fixation onset and offset
for i = 1 : length
    if(i < length)
        if(saccadeArr(i) == 0 && fixationOn == 0)
            fixationOn = 1;
            fixationOnset = i;
        elseif(fixationOn == 1 && saccadeArr(i) < saccadeArr(i+1) || i
+1 > length)
            fixationOff = 1;
            fixationOffset = i;
        end

        if(fixationOff == 1)
            tmpTimestamps(j,1) = fixationOnset;
            tmpTimestamps(j,2) = fixationOffset;
            temporalStamp(j,1) = timestamps(fixationOnset);
            temporalStamp(j,2) = timestamps(fixationOffset);
            j = j + 1;
            fixationOn = 0;
            fixationOff = 0;
        end
    end
end

fixationDurations = temporalStamp(:,2) - temporalStamp(:,1);
fixationCount = 0;

for i = 1 : size(fixationDurations,1)
   if(fixationDurations(i) >= timeThreshold)
       fixationCount = fixationCount + 1;
   end
end

fixationTimestamps = zeros(fixationCount,4);
```

Appendix D

Find rotation data

See next page.

```
function [output1,output2] = FindRotations(diffArr,timeStampArr)

length = size(diffArr,1);

rotationArr = zeros(length,1);

currentRotation = 0;
rotationIsStarted = 0;
rotationAtStart = 0;
frp = 0;

%Find rotations based on a threshold of 90 degrees and a 10 degree
 buffer
for i = 1 : length
    currentRotation = currentRotation + diffArr(i);

    if(currentRotation ~= 0)
        if(rotationIsStarted == 0)
            rotationIsStarted = 1;
            frp = i;%first rotation point
            rotationAtStart = currentRotation;
        elseif(or(and(rotationAtStart < 0,currentRotation >
 rotationAtStart),and(rotationAtStart > 0,currentRotation <
 rotationAtStart)))
            rotationIsStarted = 0;
            rotationAtStart = 0;
        else
            if(or(currentRotation > 90,currentRotation < -90))
                erp = i;%end rotation point
                rotationIsStarted = 0;
                currentRotation = 0;
                for j = 1 : length
                    if(and(j >= frp,j <= erp))
                        rotationArr(j) = 1;
                    end
                end
            elseif(i+50 <= length)
                if(or(and(currentRotation > 80,sum(diffArr(i:i+50)) <
 10),and(currentRotation < -80,sum(diffArr(i:i+50) > -10))))
                    erp = i;%end rotation point
                    rotationIsStarted = 0;
                    currentRotation = 0;
                    for j = 1 : length
                        if(and(j >= frp,j <= erp))
                            rotationArr(j) = 1;
                        end
                    end
                end
            end
        end
    end
end
```

Appendix E

Find walk data

See next page.

```
function [output1] =
 AnalyzeSpatialMovement(movementArr,timestamps,rotations,makePlots)

factor = 1;

uVThres = 5;
uAThres = 100;

length = size(movementArr,1);
movement = zeros(length,3);

movementArr = movementArr * factor;
%Calculate Velocity and Acceleration of the movement
for i = 1 : length
    if(i > 1)

        distance = sqrt((movementArr(i,1) -
 movementArr(i-1,1))^2+(movementArr(i,3) - movementArr(i-1,3))^2);

        movement(i-1,1) = distance;

        velocity = distance / (timestamps(i)-timestamps(i-1));
        if(velocity > uVThres)
            velocity = uVThres;
        end
        movement(i-1,2) = velocity;

        if(i+3 <= length)
            time = 0;
            for j = 1 : 3
                distance = distance + sqrt((movementArr(i+j,1)
 - movementArr(i+j-1,1))^2+(movementArr(i+j,2) - movementArr(i
+j-1,2))^2);
                time = time + (timestamps(i)-timestamps(i-1));
            end
            acceleration = distance / time^2;
        end
        if(acceleration > uAThres)
            acceleration = uAThres;
        end
        movement(i-1,3) = acceleration;

    end
end

%Plot a sample of movement
if(makePlots == 1)
    sampleStart = 500;
    sampleEnd = 2500;

    x = timestamps(sampleStart:sampleEnd);
    y = movement(sampleStart:sampleEnd,2);
```