A Somatic Approach to Combating Cybersickness when using Head-Mounted Displays

UNIVERSITY OF
LINCOLN

Jake Harrington

School of Computer Science

University of Lincoln

Submitted in partial satisfaction of the requirements for the
Degree of Master of Science by Research
in Computer Science

Supervisor Dr. Chris Headleand

17th July 2019

Acknowledgements

Firstly, I would like to thank my amazing parents for the unwavering love and support they have always provided through thick and thin. I am incredibly lucky to have you, and truly appreciate everything you do for me. I honestly wouldn't have been able to reach where I am today without you.

Additionally, I would like to thank my supervisor Chris - a great friend and an excellent academic who's motivation and charisma always drove me further, even when my own motivation was lacking. Furthermore, I'd like to extend this thanks to all of the University of Lincoln staff and research members I was fortunate enough to meet this year.

I would also like to thank Liam, an unlikely suspect at the start of my degree who quickly developed into an incredible friend. While you may have hindered the progress of my degree, you undoubtedly contribute to helping me grow as a person and bring entertainment with us wherever we go. So thank you, and I hope you never have to find out what's in the box.

To all the friends I have been blessed enough to make in my time at university, thank you all. You are some of the most inspiring and unique people, and I am massively grateful for the time we've spent together - hopefully plenty more to come!

Statement of Originality

The work presented in this thesis/dissertation is entirely from the studies of the individual student, except where otherwise stated. Where derivations are presented and the origin of the work is either wholly or in part from other sources, then full reference is given to the original author. This work has not been presented previously for any degree, nor is it at present under consideration by any other degree awarding body.

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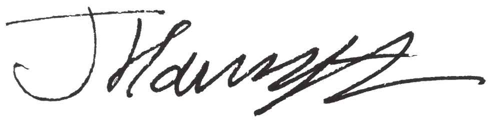

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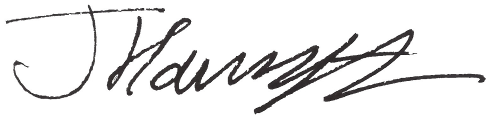

Jake Harrington

Abstract

This thesis presents a novel approach for reducing the risk of cybersickness during virtual reality locomotion in a 3D environment through the use of somatosensory feedback. This project looks directly at existing theories regarding the cause of cybersickness and describes the processes taken to develop, test and measure the efficacy of a solution. The solution proposed by this thesis builds on the concept of sensory misalignment, where the body struggles understand its state due to conflicting sensory feedback and consequently generates negative health symptoms and discomfort. As such, the studies in this project attempt to emulate the feedback of real movement during VR locomotion by artificially generating the passive airflow undergone whilst moving.

To evaluate the work, two studies are carried out where users drive a simulated car around a virtual environment, which in one condition is accompanied by the solutions dynamic airflow emulation equipment. Primarily, studies examine for cybersickness, however on-going discussions in the research community regarding the nature of correlation between sickness and presence present interesting insights that this project could contribute to. The project's pilot study failed to find conclusive results but provided a major amount of information about the correct strategies to use when investigating this exploratory area. A second study was far more successful, providing conclusive results showing that users felt less sickness and increased presence during the session supported by the somatic feedback extension. As such this work concludes suggesting somatosensory feedback has positive interactions with cybersickness, as per the project hypothesis regarding existing theories. Additionally, positive correlations with presence suggest somatic feedback can have an overall positive effect on VR locomotion.

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[1]Unity Technologies, 2018a.

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Chapter 1

Introduction

1.1 Background

The somewhat unnatural make-up of vehicular motion has persistently caused issues for the biological and nervous nature of some humans since its conception. This issue has largely been tempered but has manifested in alternate forms with the inception of vehicular and movement based simulators, and more recently, the advancements in virtual reality. The limited capability of the body to interpret these forms of movement often induce negative reactions in users who undergo it. For vehicular motion, these negative side effects are classified as motion sickness, with common symptoms of sweating, increased salivation, nausea and dizziness. It was once thought that the sickness during motion simulators was the same as motion sickness originating from vehicles, however research determined that the symptoms of motion sickness are similar to simulator and virtual reality sickness, but they are not the same. The severity of nausea and oculomotor factors vary significantly enough to have individual classifications for the different types of sickness (Bouchard, Robillard and Renaud, 2007; Stanney, Kennedy and Drexler, 1997).

To further classify the types of sickness it is important to appraise the difference in how they are induced. To do this, you can first segregate sickness variants into either “motion sickness”, or “visually induced motion sickness”. In this context, motion sickness can be thought of in the traditional sense, as it refers to scenarios when motion is felt but not seen, for example: sea sickness and car sickness.

Visually induced motion sickness refers to the opposite, where motion is seen but not felt, such as simulator sickness, and importantly cybersickness. While this analysis is simplified, understanding the difference in the conditions in which sickness is induced is essential to identifying a way to address it.

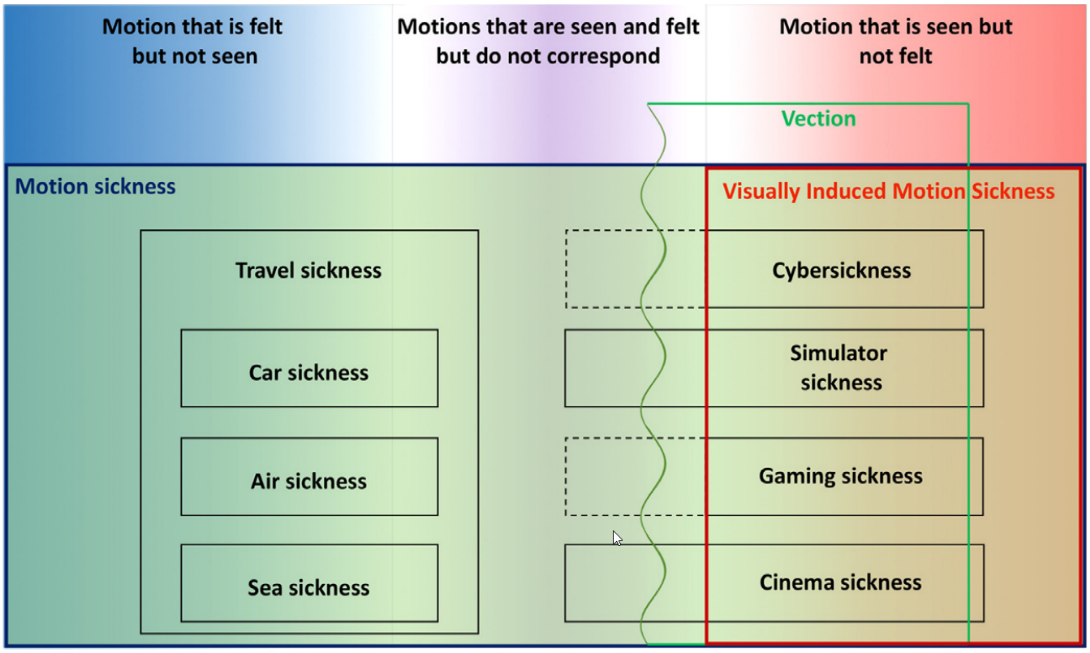


Figure 1.1: Classification for the types of motion sickness (Chang et al., 2018).

Virtual reality sickness, alternatively known as Cybersickness, has remained an obstacle, and an enduring inconvenience in the development and commercialisation of virtual reality research and products respectively. During very early stages of development, "3D games" were not actually 3D, instead using cleverly engineered environments to represent a 3D experience, however in doing so, caused significant motion sickness among players (LaViola Jr, 2000). Beyond this, the history of cybersickness is attributed to a combination of hardware having inadequate graphical capabilities and tracking accuracy (Vinson et al., 2012), along with software lacking proper design strategies such as frames of reference and restrictions on field of view (Whittinghill et al., 2015). There are proven countermeasures in design methods for developers to reduce VR sickness, as well as software specifically targeted towards addressing the causes of cybersickness (Kuchera, 2015). The variety of methods vary from the shade and pattern of textures, realistic scaling and physics, to discouraging particular movements or guiding the attention of the observer away from the imperfections of the motion simulation. Presently, as research has found that using virtual reality (VR) for extended periods increases the likelihood of experiencing cybersickness symptoms, users are often restricted to short, infrequent play sessions either to adhere to health and safety, or to avoid personal discomfort. To the same effect, commercial VR systems and developers for those platforms share regular concerns about the financial gamble of VR due to its recurring issue of sickness inducing content.

The massive collection of considerations that influence cybersickness can be broken into three overarching categories, each with several subcomponents. These factors are content, hardware and human factors. Within these categories, the most commonly occurring subcomponents have been reviewed repeatedly in research, such that there is a need for exploratory enquiries into new, but associated areas that could potentially address the persistent issue of cybersickness (Chang et al., 2018). One such overlooked area is feedback, which lies somewhere between the factors of content and hardware. Whilst visual, audio, and even haptic feedback have been examined as a means to alter the fidelity and immersion of VR content, any influence on cybersickness is often ignored. Given that the leading theory encompassing cybersickness is centred around varying feedback, it is surprising that every aspect of feedback is yet to be comprehensively examined, relative to other contributing components of cybersickness.

1.2 Motivation

At a macro level, the primary motivator for the investigation of cybersickness is driven by inconvenience and limitations it applies to the applications of VR by rendering movement driven games unplayable due to discomfort. If a method of reducing cybersickness could be operationalized it would aid in the utilisation of software that includes user locomotion within the virtual environment, and consequently broaden the range of potential applications using VR in the future.

In order to address the issue that is cybersickness, it is first important to understand what is believed to induce it. A few theories exist for what causes cybersickness, the most widely accepted theory being centred around sensory conflict. This conflict is found when visual stimulus does not align with vestibular stimulus in a manner that the body and brain can interpret correctly (LaViola Jr, 2000; Zielasko et al., 2017). The vestibular system is the nervous system which is the leading contributor to maintaining balance and spatial orientation of the human body. Additionally, it coordinates human movement and balance. In the case of desk-based VR, a user receives visual feedback without vestibular feedback, consequently the discrepancy in sensory information will likely induce discomfort in the user.

There has been moderate research into addressing the imbalance of feedback, with the existing solution being the addition of supplementary hardware into VR setups. In the case of standing VR systems, the solution is omnidirectional treadmills that allow for the user to move on the spot, but still carry out the action of walking, helping to emulate the vestibular feedback a user expects from walking (OculusOptician, 2016). For desk-based scenarios "six degrees of freedom" hydraulic chairs are the popular choice for emulating the body movement undergone during locomotion and are mostly commonly seen in dedicated vehicle simulator setups. These chairs angle the user to match their angle within the virtual environment and as a result amend the discrepancy highlighted in the sensory conflict theory. The downside to these solutions is their applicability to household consumers. The cost of such solutions will outweigh the price of a VR head mounted display (HMD) in addition to occupying a large amount of space.

By examining literature surrounding sensory feedback, balance and motion sickness it became apparent that there is another sensory system that could influence cybersickness, despite not being explicitly included in theorem behind it. From a physiological perspective, the somatosensory feedback nervous system is one of the three significant contributors to the central nervous system which is responsible for the bodies management of balance and posture (Fukuoka et al., 2001). The other two being vestibular and visual systems, already established as factors of cybersickness. The evidence provided from physiological research of balance and the commonalities found in cybersickness research justifies the investigation of somatosensory feedback as a solution to the highlighted issues. To further support this, there has already been some success in reducing cybersickness via the use of haptic feedback, a form of somatosensory stimuli where touch is used to provide users with physical feedback correlating to their position in the virtual environment (Lécuyer et al., 2004). The difficulty of haptics is that, without proper implementation it can be fairly invasive or can require user input that would not otherwise be involved in the system, detracting from the user experience. Additionally, desk-based VR systems are unlikely to be able to provide haptic feedback to consumers in the same degree that could be utilized in a standing experience or dedicated simulator systems.

The alternative somatic sense that this thesis will examine is the exteroceptive aspect of proprioception, which is the sense of the relative position of one's own parts of the body and strength of effort being employed in movement. The brain then integrates this with vestibular system to get an overall sense of body position, movement, and acceleration, with the result sometimes being labelled kinesthesia. Through the implementation of a non-invasive system of proprioceptive feedback during virtual movement, the resulting kinesthesia could be pushed towards a tolerable levels for users, and in doing so addressing the problem of cybersickness.

A potentially beneficial bi-product of additional sensory feedback is an improved sense of immersion and presence within the virtual environment among users. Presence is a term used to denote how involved and situated a user feels within a virtual environment and shows strong positive correlation with user experience in both 2D and VR contexts (Lee, 2004; Schuemie et al., 2001). In addition to benefiting user experience, links have been established between presence and cybersickness, and while the correlation has spurred some discussion in the research community, the consensus is leaning towards a negative correlation, although which is the causal factor is uncertain.

To summarise, the persistent issue of cybersickness for VR users has remained an issue for a long period, and despite the technological advancements in the field, improvements directed at the leading cybersickness theory are seen as compromises, sacrificing software content to avoid aggravating this fundamental issue. This thesis aims to provide insight towards addressing this issue from a proactive perspective and potentially broadening the prospects for virtual locomotion in desk based VR. An expected bi-product of implementing additional feedback is increased user presence within the virtual environment and consequently improved user experience. The possibility of improvement within two aspects of VR user experience is too great to ignore, and in combination with a novel method of approaching the issue, this research may be beneficial to both industrial and research advancements.

1.3 Research Hypotheses

This thesis seeks to address the following research hypotheses:

- An implementation of somatosensory feedback can effectively be incorporated into a head-mounted virtual reality experience, and users who undergo suitable somatosensory feedback during virtual reality locomotion experience less cybersickness than those without feedback..
- Users exposed a functional somatosensory feedback channel during virtual reality experience a increased degree of presence compared to users who do not have additional sensory feedback.
- A change in presence and cybersickness between conditions suggest that a correlation exists between the two.

1.4 Objectives

To achieve the requirements of this work, this thesis aims to:

- examine existing research relating to virtual reality sickness, and determine potential methods of addressing the issues identified;
- plan, design and implement an extension to a head-mounted virtual reality setup, addressing the determined feedback channel;
- perform user studies suitable for assessing the efficacy of the extension at combating the proposed areas; and
- analyse and discuss these results.

1.5 Thesis Structure

The chapter structure of this thesis is as follows:

- Chapter 2 reviews previous related work in virtual reality, focusing on the topics of virtual reality locomotion and its side effects, presence in virtual reality and physiological behaviours relating to these factors. Following this, the findings are summarised and a list of grand challenges are compiled.
- Chapter 3 presents a novel approach for potentially enhancing VR by reducing cybersickness and increasing presence. This chapter covers the design and implementation process behind a somatic feedback system and the virtual environment it supports.
- Chapter 4 covers the details regarding the methodology, strategy and procedure used to apply the artefact designed in chapter 3 to a study environment. This chapter also includes the finalized choice of measurement, and the risks and limitations surrounding the study.
- Chapter 5 looks into the numerical results of the first study that was detailed in the previous chapter, significance testing is applied and data is visualised. This chapter also includes a discussion for the study, where the results are evaluated such that meaningful findings can be extracted.
- Chapter 6 applies the findings and failings from the previous study in terms of design and implementation, detailing what changes are made to the artefact before the execution of another study.
- Chapter 7 lays out the details of the projects second study, examining the methodological components as seen in Chapter 4, using the new-found ideas gathered from evaluation of the prior study. While sharing a large number of similarities to the previous study, this iteration is backed by a much clearer understanding of the process, equipment, and research as a whole.
- Chapter 8 looks at the numerical results of the projects second study, and explains the mathematical process to determine whether findings are significant. Additionally, this chapter contains a brief thematic analysis report of qualitative data gathered. Finally, quantitative and qualitative data are then evaluated and discussed.

- Chapter 9 appraises this project as a whole, summarising and discussing findings across both studies with respect to this theses review of existing work. The limitations encountered during the project as well as the constraints of the findings are looked at to help place this research in the field, and to highlight areas that warrant further exploration. The chapter concludes with a brief personal summary of the entire process.

1.6 Contributions

This thesis contributes to the domain of virtual reality, in the field of computer science. Primarily, it explores a novel implementation of somatosensory support for a desk-based virtual reality setup, to act as a solution to cybersickness among users. Additionally, the use of somatosensory feedback as a means to enhance user presence is appraised, taking into consideration the practicality and efficacy of the addition to the VR system.

This novel application of technique has potential contributions in the game and simulator development industries, and academia where it can be expanded upon, or further refined to improve applicability as a viable extension to virtual reality systems. Secondarily, this contribution can also further homogenise the variety among cybersickness theories with the goal of understanding explicit causal effects in the future.

1.7 Nomenclature

cybersickness - the collective negative health symptoms as a result of using Virtual Reality

oculomotor - relating to the eye

somatosensory - relating to or denoting a sensation (such as pressure, pain, or warmth) which can occur anywhere in the body, in contrast to one localized at a sense organ (such as sight, balance, or taste)

sensory feedback - information targeted at a sense that is returned to a user based on their actions

telepresence - the sense of being in an environment, generated by natural or mediated means. (Steuer, 1992)

vection - sensation of self-motion produced by visual stimulation. For example, when one is in a train at a station, and a nearby train moves, one can have the illusion that one's own train has moved in the opposite direction.

virtual environment (or VE) - the digital world the user experiences within Virtual Reality

virtual reality (or VR) - A "virtual reality" is defined as a real or simulated environment in which a perceiver experiences telepresence. (Steuer, 1992)

Chapter 2

Related Work

The purpose of this chapter is to review literature related to this thesis and in doing so, identify strategies for artefact development as well as potential limitations and concerns that cybersickness brings. With this, the first objective of this thesis can be satisfied.

The inspection of this literature is enacted by first reviewing cybersickness as a whole, including its history, cause, symptoms, and effects on user experience. From this, physiological literature is examined to consider exploratory means of addressing cybersickness. With the primary issue of the thesis covered, the pertinent areas of presence and VR design are investigated. The challenges identified by the review are then presented, followed by a brief summary of the reviews findings.

2.1 Cybersickness

Cybersickness is a potential by-product from the use of virtual reality, with many different factors contributing to its induction including content, hardware as well as human factors. The following sections provide a short assessment of this subject.

2.2 Motion Sickness

Motion Sickness has a wide variety of reported symptoms but is typically associated with nausea and vomiting. Reason examines the causal effect of motion sickness by investigating the *sensory rearrangement theory* (Reason, 1978). This theory proposes two hypotheses, the first of which is that a situation where visual, vestibular and non-vestibular proprioceptive systems all receive stimulus, however these stimuli are at variance with one another, and consequently with what is expected of the actions in the environment (Reason and Brand, 1975). The second, is that the vestibular system must be involved for motion sickness to occur, regardless of other sensory systems. As a result, Reason identifies that effective motion stimulus must involve a changing velocity component, since vestibular receptors are only responsive to angular and linear accelerations.

One concern regarding this theory is the lack of explanation as to why a sensory difference can make someone sick (LaViola Jr, 2000), which Treisman attempts to address in *Motion Sickness: An Evolutionary Hypothesis* (Treisman, 1977). The premise (similar to the sensory conflict theory) is that the cause is not a difference in the present sensory input and past experience, but in the occurrence of a scenario where two associated spatial reference systems (visual and vestibular, or vestibular and proprioceptive) undergo unpredictable perturbations to the previously established correlation. From this, it is argued that the human body has evolved to react to the misalignment as symptomatic of ingested toxins, and the appropriate steps must be taken to expel them from the body which includes nausea and vomiting. While it lacks proper justification for other motion sickness symptoms, this hypothesis is a potential explanation for the human reaction to motion sickness.

Cybersickness is often assumed to be the same as motion sickness due to the similarities in their symptoms, however they are not necessarily the same thing. In *A Discussion of Cybersickness in virtual Environments*, LaViola Jr clarifies that for the former, vestibular motion alone can be enough to prompt motion sickness, although visual factors can also contribute (LaViola Jr, 2000). With cybersickness, visual stimulation without vestibular motion is the most common reason for its occurrence, however it is argued that there is no one exact cause, and is even described as polygenic. The lack of motion with the induction of cybersickness cements the independence between the different types of sickness, as motion sickness cannot occur in static conditions (Bos, 2007).

2.3 Theories of Cybersickness

While it is established that there are many contributing factors to cybersickness in hardware, VR content and human variability, the explicit cause of cybersickness is still speculative and a lot of the underlying physiological reactions are uncertain. There are however, leading theories for the root of cybersickness; the sensory conflict theory, the poison theory and the postural instability theory. Each of these are somewhat derived from motion sickness theories, but are revised with respect to Virtual Reality.

2.3.1 Sensory Conflict

The sensory conflict theory is the most commonly accepted of the cybersickness theories. Using a derivation from the sensory rearrangement theory mentioned in the previous section, it is based on the discrepancies between the vestibular sensory system and visual stimuli. These systems provide information about an individual's orientation and perceived motion, which, when in a virtual world, can regularly mismatch (Davis, Nesbitt and Nalivaiko, 2014). One example used by Davis et al is a driving simulator in which the user senses the optical flow patterns of the environment in their peripheral vision as they move, thus creating a sensation of movement. However the vestibular system fails to detect the corresponding sensation of linear and angular motion, creating conflict. Some issues surrounding this theory include why the body cannot process the information and why some individuals are affected by it more frequently or severely than others given identical stimuli (LaViola Jr, 2000).

The findings of Vinson et al largely supports previously highlighted areas, however notes that for applications rooted on a desktop system, the issue changes from a sensory mismatch, to a nearly complete limitation in vestibular movement and sensations due to a seated user (Vinson et al., 2012).

2.3.2 Postural Instability

A secondary cybersickness theory covered in LaViola Jr's *A Discussion of Cybersickness in virtual Environments* is the postural instability theory, originally presented by Riccio and Stoffregen (1991). The theory suggests that prolonged instability and lack of control accumulates from a variety of factors such as low-frequency vibration, weightlessness, changing relationships between the gravitoinertial force vector and the surface of support, and altered specificity. Riccio and Stoffregen (1991) Cybersickness is classified as altered specificity, due to the optically specified accelerations and rotations that are unrelated to the constraints on control of the body, postural control strategies for gaining postural stability will not work. One example is using muscular force to resist to the acceleration interpreted visually, creating a subconscious diversion from a stable position. This occurring repeatedly on a subconscious and micro level has been found to cause sickness. It is even argued that the sensory conflict theory cannot be applicable for motion sickness and cybersickness, stating that when the vestibular and visual system are in agreement they are receiving redundant information. So, if the two systems are not in agreement, then there exists non-redundant information. In many cases, this non-redundancy does not induce sickness and the sensory conflict theory has no explanation for why (LaViola Jr, 2000). The postural instability theory however lacks validation, and falls into the same pitfalls as the sensory conflict theory, accounting for the existence of symptoms but not their nature (Riccio and Stoffregen, 1991). The postural instability theory does have more predictive power than other theories however, as demonstrated by Munafo, Diedrick and Stoffregen (2017), where instability before exposure to VR correlated to the occurrence of sickness symptoms.

2.3.3 Poison Theory

The poison theory is the third of the most prevalent theories in assessing the cause of cybersickness and has received some supporting research (Money, 1990). In some virtual environments, the nature of the visual stimulation and the likely lack of vestibular feedback can be misinterpreted by the nervous system as a form of hallucination (Davis, Nesbitt and Nalivaiko, 2014). In this situation, an emetic response may occur as the body attempts to remove the hallucinogenic or sense impairing toxin from the body (LaViola Jr, 2000). While this theory is unique in that it has some justification for the induced symptoms, it still falls into the same pitfalls, it fails to explain the volatility of the reactions among participants given identical stimuli. It can also be argued that the inability to explain the complete set of symptoms is of detriment to the validity of the theory.

2.4 Measuring sickness

The most widely used method of "measuring" the degree of sickness induced among participants is the *Simulator Sickness Questionnaire* (SSQ) (Kennedy et al., 1993), compiled based on the Pensacola Motion Sickness Questionnaire (MSQ) (Kellogg, Kennedy and Graybiel, 1964). The SSQ was adapted to specifically identify negative health side effects in simulators and to provide improved diagnostic capability (Kennedy et al., 1993), prompted by the difference in the stimuli and the different symptoms as a consequence. The SSQ ultimately generates sub-scores for nausea, oculomotor and disorientation related symptoms, as well as a "total" representing the overall severity of discomfort experienced by the user (Davis, Nesbitt and Nalivaiko, 2014). The isolated symptoms mostly align with the understanding of cybersickness used by a large number of studies, however it has been argued that simulator sickness is sufficiently different from cybersickness in terms of symptoms and severity to be treated differently, but both are still considered to be strains of motion sickness (Stanney, Kennedy and Drexler, 1997). Some studies dispute the categories of items which the questionnaire addresses with the consensus that nausea and oculomotor are the more significant factors

(Bouchard, Robillard and Renaud, 2007). This lead to the French-Canadian validated revision of the SSQ, which included the aforementioned change to scoring in order to limit items to either nausea or oculomotor categories (Bouchard et al., 2011).

Despite the frequency of the SSQ being used with virtual reality studies, an alternative, cybersickness specific questionnaire exists. Ames, Wolffsohn and Mcbrien, 2005 compiled a series of questions targeting the most frequently reported symptoms of cybersickness as the *virtual reality symptom questionnaire*, which was developed specifically for use with virtual reality and was tested on head-mounted displays, however it lacks the validation of other approaches and so far has not been as widely adopted.

Some authors have warned that self-reported check-lists are vulnerable to fabrication and subjective opinions, however they have found that questionnaire data is "probably twice as reliable as the objective measures developed to replace them" as they accommodate variations in participants reactions, as not all people have identical physiological responses, for example paleness is not a prerequisite for vomiting among all people (Kennedy et al., 2003). On the other hand, it has been suggested that psychological factors play a role in inaccurate reports from participants. When looking at male participants and health concerns, it is suggested that men will report reduced severity and occurrence of symptoms to appear "macho" (Hill and Howarth, 2000). At the other end of the spectrum, Hill et al, note the expectation of cybersickness could result in exaggerated symptoms due to the suggestibility of participants after being primed before a study. Another similar, yet opposite psychological element to be considered during measurement is the placebo effect, where by participants can be suggested to favour a particular study condition on the belief that it will be better. When placebo effect has been examined in the application of virtual environment studies, no relationship was found between placebo conditions and cybersickness (Kim et al., 2008). A study that controlled for the administration of the Simulator Sickness Questionnaire before using a virtual environment found that participants who completed the pre-exposure questionnaire reported a significant increase in discomfort post-exposure (Young, Adelstein and Ellis, 2007). While the authors highlight a number of limitations and possible justifications for this outcome it ultimately confirms the inconsistency between studies in measuring for sickness outcomes.

2.5 Cybersickness Components

Outside of the primary cybersickness theories, a significant number of additional contributing factors have been noted over the history of virtual reality (Chang et al., 2018). These additional contributing factors can be sectioned into Content, Hardware and Human Factors which are covered below.

2.5.1 Content

Content encompasses the factors that relate to what is contained within the virtual environment, and how the user interprets it.

2.5.1.1 Optical Flow and Vection

Optical flow is the movement pattern of VR content (Chang et al., 2018). This includes velocity of VR content, the number of axes the movement is on and background complexity, all of which influence optical flow which in turn has been found to increase cybersickness. In early virtual reality studies centred on vehicular simulation, it was found that self movement should be at high altitudes above the terrain and/or at low speed to reduce optical flow and consequently reduce sickness (Kolasinski, 1995; McCauley and Sharkey, 1992).

A study looking into the effects of movement on varying axis in a virtual environment found that the effects of cybersickness were significantly worse when pitch and roll movements were combined to when they were demonstrated individually (Bonato, Bubka and Palmisano, 2009). Bonato et al hypothesised that as well as the number of movement axis, the speed and rate of rotation played a significant role in the induction of cybersickness, supporting the idea that gradual rotation is a less risky method of turning a player in VR by considering optical flow (Vinson et al., 2012). An additional element suggested by Vinson et al to affect the severity of cybersickness is the sharpness of the turn, suggesting gentle turns on long arcs cause less sickness than sharp rotations on the spot. Similarly, increasing navigation speed results in increased vection sensation and sickness symptoms, especially in the first ten minutes of exposure, becoming insignificant as time passes, such that evidence suggests navigation speed is a primary factor in the onset speed of cybersickness but will not accelerate the rate of increase with increased duration. (So, Lo and Ho, 2001)

Optical flow is also believed to be the primary contributor to the illusory sensation of vection. Vection is a term for the false sensation of self motion and can be induced by viewing representations of motion in any of the linear or rotational axis of the body. The optical flow rate will also alter the induction of vection since a faster flow rate will increase the perceived speed, thus making the sensation more severe (LaViola Jr, 2000). The most common real-life example of vection occurs as a train passenger, where seeing the movement of an adjacent train creates the sensation that one's own stationary train is moving (Keshavarz et al., 2015). In standard self motion, the spatial components visualised would be accompanied by vestibular information, but during vection, that information is not present or is governed by optical flow patterns (Kennedy, Hettinger and Lilienthal, 1990). This relationship between visual and vestibular information can then be tied back as the foundation of the sensory conflict theory in Section 2.3.1.

In a review of the relationship between vection and visually induced motion sickness when using VR, Palmisano, Mursic and Kim (2017) explains that early findings that used fixed-base simulators rather than HMDs, suggest vection could be a requirement for visually induced motion sickness. Palmisano et al also express that other studies however suggest a negative relationship between the phenomena, and still others struggle to find a significant relationship. Beyond this, Palmisano et al explain that when wearing HMDs, head and some body movements will contribute to the experience of self motion by stimulating the vestibular system as well as indirectly altering the visual scene, which in turn may reduce cybersickness via the sensory conflict theory.

In *Circular, linear, and curvilinear vection in a large-screen virtual environment with floor projection*, Trutoiu et al. (2009) highlight ideal scenarios for a motion based driving simulator. Principally, the illusion of vection would be rapidly induced and long lasting, meaning minimal "stop-starting" where possible once motion was under way. A secondary component that the authors suspected to improve vection is motion parallax, where by distant objects appear to move slower than nearby objects during linear motion due to an inverse relation between angular change and viewing distance. While the authors' study found that the level of discomfort on varying trajectories had little variance, the horizontal linear motion was rated to be the least convincing by participants. In a head-mounted virtual environment rather than a projected environment, this lack of convincing movement will most likely create a misalignment of visual and vestibular senses among participants reducing the quality of vection and initiating cybersickness.

2.5.1.2 Virtual Reality Fidelity

VR fidelity alludes to the level of realism and the scene complexity of the virtual environment. McMahan et al. (2012) separates fidelity into degrees of display and interaction.

McMahon's findings suggest that higher levels of interaction and/or visual fidelity result in higher levels of presence, engagement and usability. While this may seem massively beneficial to user experience, high fidelity virtual environments with large amounts of movement have been reported to induce greater levels of cybersickness compared to low fidelity environments (Davis, Nesbitt and Nalivaiko, 2015). The increase in sickness is believed to be connected to the resulting increase in visual flow, which is initiated through the fast paced changing of detail. Despite this, Davis' study included several other aspects that may have been greater influences than high fidelity, including environment configuration, velocity and placement of reference objects. This is far from certain however, as the relationship between presence and cybersickness has had many mixed outcomes, with some taking the opposite stance to Davis, suggesting a negative correlation between presence and cybersickness (Witmer and Singer, 1998; Zielasko et al., 2017), which is is examined in more depth in Section 2.7.

When looking at task performance specifically, two conditions of McMahon's were strongly favoured: low-display, low-interaction fidelity (representative of traditional FPS games) and high-display, high-interaction fidelity (similar to the real world). A scenario where a users hand or body movements directly control the input of an application, would be considered high-interaction fidelity (if implemented accurately), and as such McMahon's results suggest that they would be best paired with high-display fidelity.

2.5.1.3 Rest Frames

Rest frames are a concept based around the idea of frames of reference, which provide the observer with spatial information of stationary objects, as well as their own position and orientation with respect to the rest of the environment. According to the hypothesis of (Chang et al., 2013), the human nervous system uses a rest frame in the environment to maintain spatial representation, but in the scenario where a consistent rest frame is difficult to determine, it can result in sickness. When this is applied to VR specifically, if a user has trouble determining a rest frame, they will have conflicting information on what is stationary within the virtual environment, and what is mobile, resulting in negative side effects. Prothero (1998) tested a hypothesis of removing discrepancies which caused conflicting rest frames in virtual environments, finding that using an independent visual background which is in agreement with inertial cues can reduce cybersickness symptoms.

An alternative to using the environment as a source of reference is to use ones self as the frame of reference. Often, the users hands are visualised during use of a system with hand detection capabilities. These features are not always available, and one solution found the use of a "virtual nose" effective at combating cybersickness, attributing its success to the ability to grant the user positional reference based on real-life experience (Whittinghill et al., 2015).

2.5.1.4 VR Design Practices

There are some additional design considerations to make during the creation of virtual environment, that are unique to virtual reality. Not only is this to be aware of sickness inducing design principles, but to also improve usability. To address new and variable parameters introduced by VR, developers of head-mounted displays have released guidelines with recommended specifications for software designers in order to combat sickness, for example Oculus and Vive both use 110 degree displays, but encourage use of lower fields of view. (OculusOptician, 2016)

Zielasko et al. (2017) in *Remain Seated: Towards Fully-Immersive Desktop VR* declares cybersickness to be one of the "major challenges" in determining a platform to work productively in. They highlight the development trend of replacing continuous movement with teleportation mechanics to reduce cybersickness, despite knowing that it feels less natural and reduces spatial orientation and immersion. A secondary criteria mentioned is the constraint of time due to progressive increases in discomfort as a result of cybersickness (explained further in Section 2.1.6.4), and as a result when designing VR tasks, they should be conservative in duration.

2.5.2 Hardware

In its fairly short history, head-mounted VR was primarily limited by its hardware capabilities, reducing its usability as a result of inadequate display capabilities and the discomfort of the prototype equipment. It could be argued that only since the recent hardware developments and the commercialisation of modern head-mounted displays such as Oculus Rift and Vive, that virtual reality has reached an acceptable level of usability. It is worth noting that the past issues such as flicker, latency and tracking should still be considered due to the risk of poorly optimized software.

2.5.2.1 Legacy Hardware Issues

Flicker is the perceived inconsistency when viewing a display, such that what is being seen appears, then disappears at a high frequency. Not only is this distracting to user experience, it can cause eye fatigue and contribute to the induction of cybersickness symptoms (LaViola Jr, 2000). Flicker appears as a result of the visual display having a substantially lower refresh rate than the human eye, such that a refresh rate of 30Hz will usually remove perceived flicker from the fovea. With regards to VR especially, the eye has increased sensitivity to flicker around the periphery such that a higher refresh rate would be necessary to counteract it. Considerations about the field-of-view with respect to hardware capabilities should be made too, as to not make users susceptible to flicker and the symptoms associated with it. Modern HMDs use 90Hz and above refresh rate displays such that when combined with their slightly narrowed 110°FOV systems, flicker is no longer perceived by the vast majority of users. Some exceptions to this include phone-based HMDs, however dedicated headsets supported by graphics hardware of suitable specification should not encourage the perception of flicker. A slight variant to flicker is the issue of having a low update rate, resulting in the visual perception of freeze frames, making program content appear jerky. The update rate refers to the speed of the simulation: the rate at which new content can be rendered and pushed to the frame buffer for display. Where refresh rate is entirely hardware determined, update rate is partially dependent on the quality and optimization of the software but is still variable based on computing power available (Pausch, Crea and Conway, 1992).

Latency or lag describes the time between a user initiating and action and the action actually occurring in the virtual environment (LaViola Jr, 2000). An example of this could be performing an emergency stop in a driving simulator, where any input or processing lag could determine the success of the manoeuvre. When applied to virtual reality, a common example of lag was head movement being delayed due to issues with head tracking. If there is a high quantity of latency in a system, the visual display will be delayed in updating between actions, which is unsettling, immersion breaking and also a cause of cybersickness symptoms. While Wloka, 1995 describe many variants of lag, they largely share the same solution of high processing power (i.e. multiple cores being utilized), supported by efficiently made applications and quality systems (Zielasko et al., 2017).

Issues around calibration have also been observed due to the concerns expressed by McCauley and Sharkey, 1992, whos discussions about the ergonomics of VR systems conclude that with correct size, accurate focus and correct alignment reductions to cybersickness will be seen. Modern HMD's accommodate these factors by using adjustable straps as well as means to adjust the interpupillary distance of lenses, such that it meets the dimensions of almost any user. Some reports state that HMDs are beginning to include added comfort for bespectacled users, allowing for the use of glasses while in VR, furthering the ergonomics of the system(Sun et al., 2017).

2.5.2.2 Head tracking

A key component of virtual reality, and head-mounted displays in particular, is the ability to track the position and orientation of the users head in 3D space so that the corresponding details can be translated to virtual space. This ensures that the correct perspective of the virtual environment is displayed to the user throughout the experience. Position trackers are not perfectly accurate, and their accuracy determines how comfortable a user feels during a VR experience, as unstable information can result in jerking the users perspective about, and consequently cause symptoms such as dizziness and inability to concentrate (LaViola Jr, 2000). Tracking hardware has improved significantly along with the release of commercial headsets(LaValle et al., 2014), however there are still a couple of limitations. Firstly, the restriction on space is determined by the capabilities of the sensors, currently the Vive supports the largest area of commercial HMDs, with the recommended area approaching $11m^2$. Secondly, sensors are at risk of obstruction, a body can easily come between the headset and sensors which can cause similar unstable information to older hardware, disrupting the user experience. One potential alternative would be to use a system with electromagnetic head tracking to overcome the risk of obstruction, however there would be concerns surrounding interference from other electronic sources in the environment as well as component availability. Another option is the upcoming Oculus Quest[1], which uses cameras as components of the HMD to track the users environment then combines the information with accelerometer and gyroscope data to get an accurate determination of the users head position. Unfortunately, this technology is not publicly available but would be suitable for future iterations of the study.

2.5.2.3 Field of View

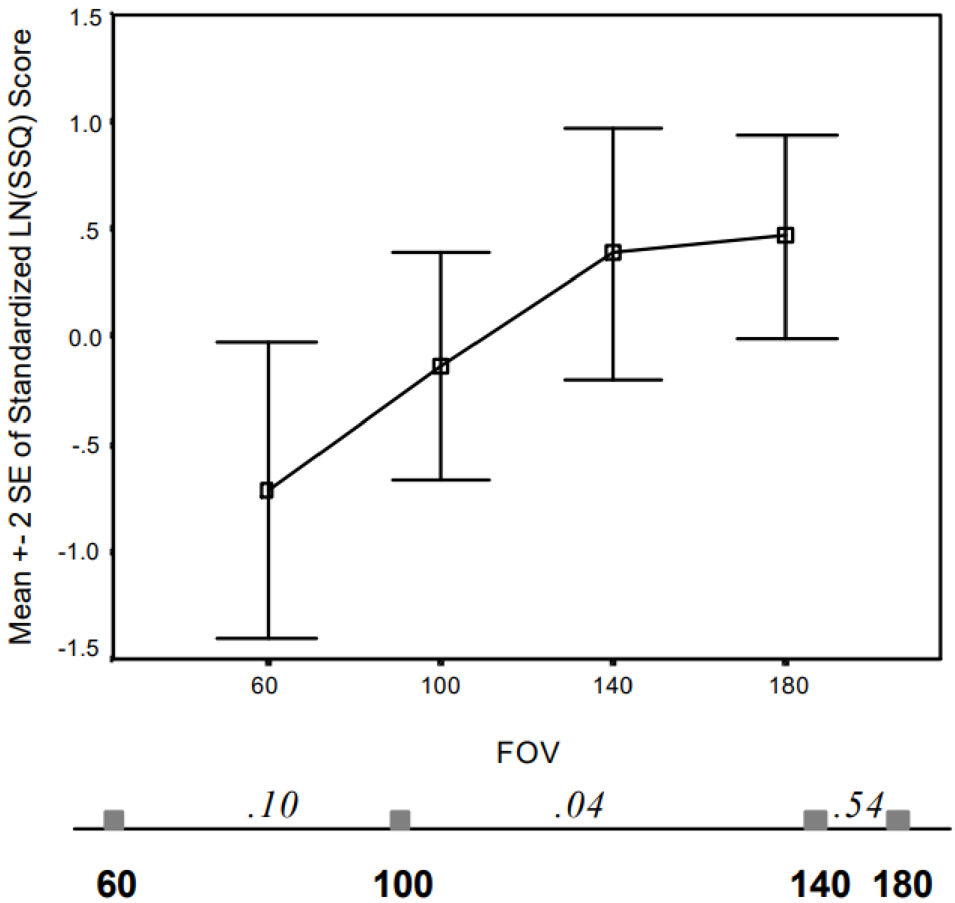


Figure 2.1: Mean and standard error of LN(SSQ) scores as a function of FOV (Lin et al., 2002).

Field of view (FOV) is the extent of the world that is seen at any given moment, measured as an arc on an axis. For example, humans have a stationary forward

[1]Oculus VR, 2018.

facing horizontal arc of 180°, and a vertical arc of about 150°. Both the Oculus and Vive VR headsets utilize a 110°horizontal arc, which is partially due to limitations lens technology, but also a development to combat cybersickness. (Lin et al., 2002) presents findings suggesting a positive correlation between sickness and increasing FOV, up to a horizontal arc of 140°, where further changes begin to have negligible impact. This can be seen in Fig 2.1, where a logarithmic transformation of the SSQ scores is performed to satisfy the assumptions based on Lin et al's normal quantile-quantile plots, the residual plots, and the Levene's test of equality of error variances. They also found that higher FOV correlates to greater presence within the virtual environment, which often correlates to positive immersion and engagement (Witmer and Singer, 1998). The 110°FOV that has recently become standard could be seen as a middle ground between presence and sickness. FOV also plays a critical part in the induction and strength of vection sensations due to a large FOV stimulating more of the retinal periphery (Kennedy, Hettinger and Lilienthal, 1990), consequently increasing the likelihood of encountering discomfort due to cybersickness (Emmerik, Vries and Bos, 2011).

2.5.3 Human Factors

In addition to the content of software and the hardware that runs it, a large number of factors are dependant on the characteristics and traits of the user. This includes inherent qualities such as gender, age and health, but also how they use virtual reality and the frequency at which they do so.

2.5.3.1 Health

Almost all studies in the field use some form of medical screening to regulate users participating in research. Due to the nature of cybersickness, it has connections with many illnesses and health conditions due to the physiological relationship with the oculomotor and vestibular systems. Common health screening includes: cold and flu symptoms, pregnancy, eye or ear infection, vertigo, claustrophobia, epilepsy and migraines as well as anything relating to balance and vision (Davis, Nesbitt and Nalivaiko, 2015)(Rebenitsch, 2015). One exception is slight vision abnormalities, which are often accepted if corrective solutions do not interfere with the virtual environment system. Outside of health effects that directly interact with sensory factors covered in cybersickness theories, considerations are often made to more generic areas such as lack of sleep, hangovers and high stress (Vinson et al., 2012).

2.5.3.2 Gender and Age

Gender with respect to cybersickness has been fairly thoroughly explored, with most studies reporting women to be be more susceptible to cybersickness. This is in line with the history of motion sickness, where women have been found more vulnerable to sickness symptoms (LaValle et al., 2014). One example of this is an investigation into seasickness by Lawther and Griffin, 1988 where findings report women more susceptible at an approximate ratio of 5:3. A more recent study looking at gender difference with regards to cybersickness when using contemporary, commercial VR headsets, found results that have a similar gender difference to the motion sickness experiment of Lawther and Griffin (Munafo, Diedrick and Stoffregen, 2017). In Munafo et al's experiment where 56% of the participants reported motion sickness, nearly 77.78% of those were female, being significantly greater than the 33.33% male response. In terms of gender differences in the incidence of motion sickness, head-mounted displays appear to be congruent with the general motion sickness literature. A point of consideration is the reported reticence of males to report sickness, to the point that it has been suggested that there is no difference in sensory response to motion stimuli between males and females, and this reticence is to blame. This point however lacks support, with other papers reporting differences in sensory response between genders such as females having a greater field-of-view, a known positive correlation with sickness outcomes(Stanney et al., 2003).

As well as natural susceptibility to cybersickness, Larson et al., 1999 recommends evaluating for gender differences in task performance when performing tests using virtual environments. Their findings initially suggested no gender difference in the virtual reality spatial rotation test, however upon further examination observe differences in the patterns of associations with spatial and verbal tasks and performance. One such observation is the advantageous spatial visualisation of males, which could play a significant role with regards to anticipating virtual environmental behaviour and in turn, controllability and cybersickness.

Age is another main predictor in the population of individual susceptibility to motion sickness but, there have been mixed results when inspecting age as a variable of motion sickness. The findings of Reason and Brand, 1975 are frequently used in the sickness communities including simulator sickness and cybersickness (Arns and Cerney, 2005). Reason and Brand found that motion sickness susceptibility is greatest in children age 2 to 12, decreasing quickly from 12 to 21, then slowly until 50. In people beyond 50, motion sickness was reported almost non-existent. Other studies largely agree, with minor differences in the age thresholds of the rate of change (Golding, 2006). The only significant variation across motion sickness papers is the effect on the elderly, where authors such as Golding find susceptibility to increase in the population over 50 years of age. Not many pieces of dedicated work exist for the relationship between age and virtual environment sickness, however those that do, contradict Reason and Brand's hypothesised relationship. Arns and Cerney found that the age of participants was a positive correlation with the severity of simulator sickness they experienced, in doing do, contrasting the beliefs that younger users were most susceptible, as well as older users being nearly immune to the symptoms of sickness.

2.5.3.3 Habituation and Prior Experience

Habituation, also know as adaptation, is one of the few techniques a user can take to reduce the occurrence of cybersickness symptoms. If a person uses a virtual reality application regularly they will slowly build up a tolerance to the activities that induce sickness. It is unsure if and how application tolerance carries over between VR applications, such that total virtual reality experience could be a predicting factor of cybersickness. Hill and Howarth, 2000 breaks up the causes of habituation into three areas:

- Behavioural adaptation - people change how they move in a virtual environment over time. For example, a reduction in head movement in VR would reduce sensory conflict and a reduction in muscular tension and strain.
- Task Practice - users may become more adept at performing a given task in VR, and as a result, become less dependant on environmental stimulus, improving stability.
- Physiological adaptation - Over the course of the VR immersion, the body acclimatizes to the obscure sensory feedback.

Hill and Howarth's studies found that daily exposure to the same VR driving simulator results in a gradual decrease in nausea. Additionally, those who were immersed twice in the same day showed less malaise, suggesting that both short and long term habituation should be appraised.

One approach has been to use an adaptation program (McCauley and Sharkey, 1992), for the virtual environment. This allows users time to adjust to the virtual environment before performing the primary task assigned. Additionally, its suggested that tasks than involve high rates of linear or angular acceleration should be gradually introduced to the virtual environment as not to conflict with the users vestibular and visual systems (LaViola Jr, 2000). Adaptation strategies appear to be the best method of cybersickness reduction, assuming that a participant is willing to take the additional time to go through the adaptation process. One concern with the use of adaptation programs is the reduction in response rate, as a normal consequence of such repetitive stimulation (Kennedy et al., 1993). A secondary concern is the natural adaptation program that the developer or administrators undergo during the creation of the system, as the repeated exposure will cause sickness underestimates. Thus, when the system is consumed by the population, unexpectedly severe outcomes may occur without suitable external testers.

When using a cave virtual reality environment (CAVE), users without previous CAVE experience indicated inferior spatial knowledge during task performance, additionally, novice users also suffered from increased levels of simulator sickness.

This denotes a possible correlation between simulator sickness and spatial knowledge (Freitag, Weyers and Kuhlen, 2016). This correlation is supported by information regarding rest frames covered in Section 2.5.1.3, where by the inability to get spatial information results in sickness.

2.5.3.4 Duration

Another somewhat unavoidable factor of cybersickness is the increased severity of sickness symptoms that accumulate over long periods of exposure, such that task duration is an important consideration. Kennedy, Stanney and Dunlap (2000) summarised the majority of writers in the field by stating that experience duration has a positive correlation with sickness, and repeated exposure has a negative correlation with sickness. Due to the concerns and issues surrounding the duration of virtual environment usage, the U.S Army Research Institute has suggested that virtual environment exposures should be restricted to 15 minutes, which can be too short for a more complex training applications (Stanney et al., 2003). Stanney el al express the necessity to be able to increase VR exposure duration while reducing the adverse side effects. One proposed solution put forward is to simplify navigational control and visual scenes, however the interrelationship between virtual system design and usage factors need to be further examined, as do less fidelity lowering answers.

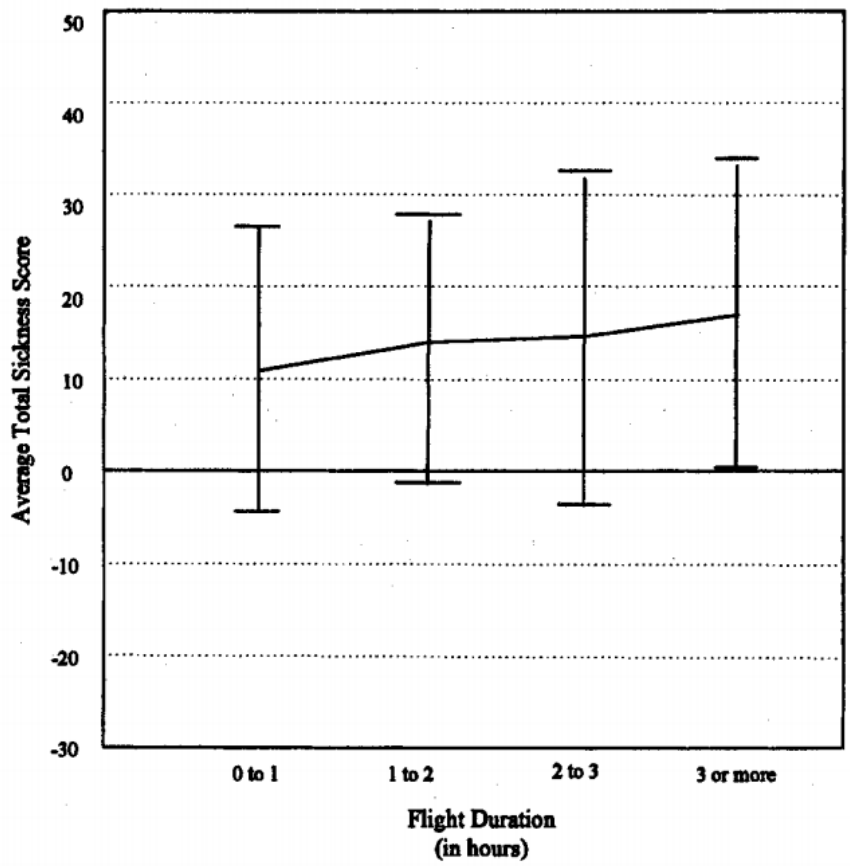
From a methodological standpoint, Kennedy, Stanney and Dunlap (2000) expresses the essential nature of temporal effects and the implications it has on experiments. Firstly, the necessity to covary or control temporal effects when assessing any technical or user effects relating to virtual environments. Secondly, to consider time as a means to manipulate sickness outcomes, and the necessity of fixed time to control for sickness and allow for quantitative meta-analysis.

2.5.3.5 Controllability

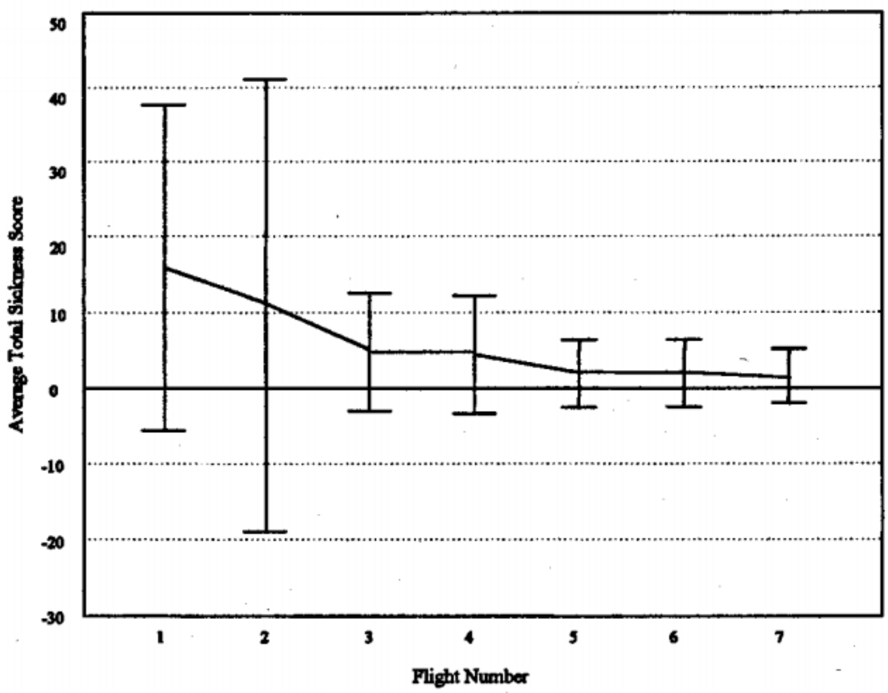
Cybersickness is also dependant on the type of task the user is performing. The degree of environmental control has substantial effect on cybersickness. A high level control results in a user being more capable of anticipating future movement within the virtual environment (Stanney and Kennedy, 1997), making them less dependant on their senses, and consequently less vulnerable to the negative effects of sensory conflict. Those with no control over the environment lack the same level of predictability, making them susceptible to sickness symptoms due to

Figure 2.2: Findings of Kennedy, Stanney and Dunlap, 2000.

(a) Duration against SSQ



(b) Repeated Exposure against SSQ



either a lack of information as per the sensory conflict theory, or an inability to anticipate adjustments to their balance and posture as per the postural stability theory (Davis, Nesbitt and Nalivaiko, 2014) (Kolasinski, 1995). This can be tied back to motion sickness, where Rolnick and Lubow (1991) assessed the difference in participant comfort between car drivers and passengers, finding that drivers had greater levels of well-being in addition to ability to continue with study tasks.

In the same sense, the difficulty of using navigational controls may play a role in the controllability of the entire virtual environment, suggesting a precaution for low complexity controls or significant adaptation time for high complexity control schemes (Stanney et al., 2003).

A variation of controllability is "enforced expectation", where virtual environment behaviours are assumed due to expectations inherited from the world. In a scenario where the expectations are not met, it can be highly disorientating to the user, as well as a contributor to sensory conflict and postural instability. One example of this is the omni-directional treadmill, where by a users expectation to be able to walk is addressed by allowing them to feel as if they covering ground rather than being limited to a confined VR play-space (Rebenitsch, 2015).

2.5.3.6 Susceptibility Checking

While a degree of predictive factors have already been analysed, there is still only finite capability in anticipating the severity of cybersickness of users. For the sake of participants, it is essential that a thorough process is adhered to, to protect exceptionally vulnerable members of the population.

For motion sickness, the motion sickness susceptibility questionnaire (MSSQ) exists, revised by Golding (1998), as means to add predictive capability to motion sickness studies. Findings by Golding show a high MSSQ score to be a good predictor of susceptibility to motion challenges, however prediction accuracy decreases for low susceptibility scores. The questionnaire is centralised around the participants history of motion sickness, however there are three key areas Golding highlights as areas that have not been accounted for, and consequently the factors in the lacking predictive power for sickness among resistant users. These areas are : initial sensitivity to motion, rate of natural adaptation, and the ability to retain such protective adaptation in the longer term. The inability to measure these innate factors narrows the degree of prediction among participants substantially, and in doing so, will create greater variance in reactions.

In most cybersickness studies that attempt to measure susceptibility, the MSSQ is used. There is not a cybersickness susceptibility questionnaire currently in major circulation, however there has been notable investigation into a potential model for predicting cybersickness severity in users. Bruck and Watters (2011) attempt to determine a factor structure of cybersickness, looking specifically at the human factors that contribute. As well as "general sickness" Bruck and Watters use the factors of arousal (or anxiety), vision and fatigue as the core facets of cybersickness, where a baseline factor could contribute to illness in a virtual environment. While it is yet to be seen, it would be interesting to observe the relationship between these factors before and after the virtual experience, as well as whether they share the predictive potential of the postural stability theory (Munafo, Diedrick and Stoffregen, 2017). Other approaches have focused heavily on the physiological information of participants to anticipate SSQ scores (Kim et al., 2005). Kim et al analyse a large amount of physiological data from their participants, including nervous data, heart period and neural oscillations alongside the MSSQ. Using stepwise regression analysis of this data, the authors found that a higher MSSQ score, an increase in heart period, increases in T3 delta power, and decreases in the T3 beta power predicted increases in the severity of cybersickness symptoms that the participant reported. While this data is hugely interesting and beneficial to understanding the underlying physiological changes tied to cybersickness, the MSSQ still held the greatest correlation with the SSQ. This suggests the pivotal physiological factor of predicting cybersickness susceptibility variance is still unknown.

Many authors recommend user screening to be carried out before use of experimental VR systems. Zielasko et al. (2017), takes this a step further, using profiling in order to provide parameters that can be used to restrict features for individuals that may be vulnerable to sickness symptoms, based off information received. One of such range is the field of view (FOV), where studies have found that a larger external field of view can correlate to a greater likelihood of encountering cybersickness (Emmerik, Vries and Bos, 2011). As a consequence, a susceptible user would be exposed to a narrower FOV, prioritizing reduced discomfort over presence. Profiling could be applied to many variable factors such as locomotion speed, environment fidelity and exposure time to make a system more accessible but without conflicting with cybersickness resistant users.

2.6 Existing External Sensory Feedback in Virtual Environments

Various forms of sensory feedback have been investigated for use with virtual reality, to support the visual and vestibular (or lack thereof) feedback with reasonable success. These forms of feedback have been used in a broad range of computer science fields for many years, spanning from tools to entertainment and have taken many different forms (Burdea, 1996). For virtual reality however, these forms of feedback are more sparse. Most commonly, force, tactile and haptic feedback have been incorporated into a range of virtual medical training and therapy systems for over two decades, with some investigations into regions such as telepresence and similar sensation based areas. There are have been some experimental investigations using more diverse feedback types as well, such as looking at thermal feedback to enhance vibrotactile systems (Benali-Khoudjal et al., 2003). While these additions often prove beneficial to their respective systems task performance or presence (Stanney et al., 1999), there is a surprising lack of external feedback applications targeting locomotion in virtual environments, and the negative side effects it generates.

When looking specifically at virtual reality, cybersickness and locomotion, external methods are quite different. In standing virtual scenarios, an omnidirectional treadmill can be used to somewhat emulate natural walking, providing appropriate reaction forces to movement and consequently satisfying concerns about incorrect sensory feedback or postural stability (Souman et al., 2011). In seated systems, hydraulic chairs capable of linear and rotational movement on multiple axis are frequently seen, which align a users body to match visual stimulus of VR, and in doing so can provide convincing vestibular feedback (Anthes et al., 2016). One of the less common methods has been seen in an investigation into haptic feedback in VR by Lécuyer et al. (2004), where by users hands are rotated to match the angle of rotation experienced in the virtual environment, and consequently users estimated their bodily rotation more accurately. The authors suggest that haptic stimulation could partially substitute for the missing information due to the absence of proprioceptive and vestibular stimuli. While this is not the only study to find benefits of haptics with regards to cybersickness, it is one of the few that address VR locomotion directly, rather than stationary environments (Rebenitsch and Owen, 2016; Moss and Muth, 2011). Importantly, this further implies that to address cybersickness it is not compulsory to address one of the conflicting systems directly, opening up the variety of possible extensions that users can infer missing information from.

2.6.1 Airflow as Suitable Feedback

Support for air based systems to accompany VR has been driven by the hindrances of wires or heavy body devices such as HMDs. Consequently, this argues that any additional carried equipment would be too much of a burden on the user, despite additional feedback being favourable for VR experiences (Suzuki and Kobayashi, 2005). Despite this, airflow or wind in virtual reality has fairly minimal research coverage, one of the only examples is in *Design and Evaluation of Wind Display for Virtual Reality*, where Moon and Kim (2004) use a wind display system called the "WindCube" with the aim of enhancing presence. Ultimately their findings did include an enhancement to presence with reasonable realism, however they could not validate that wind effects carried particular importance as sensory modality device as it only included air and appealed to the low level perceptual system. While this system was not used with locomotion, nor did it measure for cybersickness, the change in presence makes it an interesting experiment to consider due to the correlation between presence and cybersickness (See Section

2.7 for further clarification on Presence). Additionally the authors cover the "liveable" nature of the WindCube, due to the more open sensation as well as the avoidance of invasive or restricting hardware, making it highly unlikely to make cybersickness worse, should it be applied to motion based virtual environments. This aligns with existing research which has already found that somatosensory stimuli does not give rise to motion sickness (Bos, 2007), however additional research is required to determine any beneficial effects.

A lot of existing cybersickness research has overlooked somatosensory feedback as it does not directly contribute to the sensory conflict theory, however from a physiological perspective, the somatosensory nerve system is one of the three significant contributors to the central nervous system. Alongside the vestibular and visual systems, it is responsible for the bodies management of balance and posture (Fukuoka et al., 2001). A study by (Grace Gaerlan et al., 2012) investigating the balance and posture of young adults found that the predominantly the visual system was used to determine balance with other systems acting secondarily. While this might suggest that visual elements should be the focus of improvement for virtual reality, Gaerlan et al includes that the dominant system can change depending on the strength of each system in a given scenario, such that when blindfolded other systems become dominant. While virtual reality is not complete vision impairment, it restricts the visual system, such that by supplementing other sensory systems the body will be more capable of utilising them.

Due to the link between somatosensory feedback and a human being's balance and posture, and the respective connection to motion sickness, there is reason to believe in a correlation directly between somatosensory feedback and cybersickness that requires exploration.

2.7 Presence

When analysing a the effectiveness of a virtual environment, a common metric used is the "Presence" reported by users exposed to a virtual environment (Melo, Vasconcelos-Raposo and Bessa, 2018). Slater et al defined presence as the user's feeling of being more present in the virtual environment than the physical environment (Slater, Usoh and Steed, 1994)(Slater, 1999)(Melo, Vasconcelos-Raposo and Bessa, 2018). In disagreement with this, Witmer and Singer defined presence as "a psychological state of being there" by engaging with the users senses and cognition (Witmer and Singer, 1998). This remains an ongoing discussion within the community however in this work, when referring to "presence", it will be in reference to the concept as defined by Witmer and Singer.

Zielasko et al. (2017) touches on the topic of presence, as a large number of the roots of cybersickness appear to be tied to a reduction of presence, most commonly occurring in desktop settings where personal movement is restricted. The factors and applications of presence vary between forms of media, however in *Presence, Explicated* Lee (2004) separates presence in virtual environments into three dimensions, each exploring the users experience in different dimensions of the media. Spatial, or physical presence is described as the sense of being physically involved in a virtual environment or experiencing objects as though they are actual objects (Lee, 2004). Social presence is defined as experiencing social actors as if they are real, and following the same trend, self presence is explained as experiencing ones virtual self as if it is their actual self. Each aspect has notable factors for the user experience of digital games, with spatial presence often being regarded as the most significant in conventional games (Tamborini and Skalski, 2006), however based on existing research implications, personal presence is of greater importance in VR games (Schuemie et al., 2001) particularly when it comes to managing virtual reality sickness.

The relationship between presence and simulator sickness has been explored from multiple perspectives, yet existing research has returned significantly different correlations between the two. The findings of Witmer and Singer (1998) suggest a negative correlation between the results reported on the Simulator Sickness Questionnaire and degrees of presence measured using their own questionnaire. To contradict this, Slater (1999) found a positive correlation between simulator sickness and presence, attacking the work of Witner and Singer for measuring unrelated aspects when quantifying their user's presence. Others have a much broader view on the relationship, predicting that sickness may detract from presence, however the two may be physiologically unrelated. Another proposal is that the two are independent, connected by a third variable such as hardware capabilities or even genetic differences in participants Nichols, Haldane and Wilson, 2000. The ongoing discussion and polarising correlations ultimately suggest is that there is a high level of inter- and intra-individual variability between pieces of work (Zielasko et al., 2017)(Freitag, Weyers and Kuhlen, 2016)(Lin et al., 2002).

Games are not the only field which look to examine and gauge presence alongside sickness however, as virtual and augmented reality rehabilitation treatment studies have found relationships between treatment efficacy and presence (Ling et al., 2012), however have encountered issues with cybersickness which is also suspected to have correlations with presence (Kiryu and So, 2007). Ling et al found no significant correlation when looking at the relationship between the two.

In addition to its use with virtual reality and the fluctuating relationship with sickness side effects, presence has some fundamental connections with sensory feedback. As per Witmer and Singers description, presence is determined by engaging with the users senses and cognition (Witmer and Singer, 1998). Before this, in *Musings on Telepresence and Virtual Presence*, Sheridan proposes three determinants of presence (Sheridan, 1992), being:

1. extent of sensory information (the transmitted bits of information concerning a salient variable to appropriate sensors of the observer);
2. control of relation of sensors to the environment (e.g. the ability of the observer to modify his viewpoint for visual parallax or visual field, reposition his head to modify binaural hearing, or the ability to perform haptic search); and
3. the ability to modify physical environment (e.g. the extent of motor control to actually change objects in the environment or their relation to one another.)

Two of three determinants relate directly to the degree and nature of sensory feedback, thus suggesting that an increase in relevant feedback would have an increase in presence. This hypothesis aligns with the findings of Dinh et al, where subjects were exposed to additional sensory feedback alongside a VR environment.

Their experiment found that tactile, auditory and olfactory feedback all strongly indicated a higher score when measuring Presence, massively contributing to the idea that sensory feedback can enhance presence. In conclusion these findings amount to the idea that generating the same sense of motion that can potentially mitigate cybersickness, will result in the positive side effect of increased virtual presence .

2.7.1 Measuring Presence

In order to examine presence in a manner that can be measured against cybersickness, it must first be quantified. The Presence questionnaire (PQ) of (Witmer and Singer, 1998) is aimed to characterise the experience of the user in the virtual environment. To do so the items are designated to overarching factors: control, sensory, realism and distraction. Despite the questionnaire being challenged in the response from Slater (1999), who presented their own presence questionnaire (Slater, Usoh and Steed, 1994), Witmer and Singer's questionnaire remains a heavily grounded resource, used by a diverse range of research areas. The aforementioned Slater-Usoh-Steed Presence Questionnaire (SUS) however, has received criticism for only measuring one dimension of presence: "presence as transportation" (Vasconcelos-Raposo et al., 2016). Witmer and Singer later reviewed the PQ suggesting a reduced question-set, as a few were deemed unrelated to aspects presence specifically, or were so infrequent that they were non-factorWitmer, Jerome and Singer (2005). Some of these items in the revision were substituted for items that contribute to an Adaptation/Immersion subscale, aimed to address sensory and cognitive immersion, as well as spatial presence which are all particularly applicable to modern VR. Sadly, a version from Witmer and Singer including these changes is yet to be published.

Another established option for measuring presence is the Igroup Presence Questionnaire (Schubert, Friedmann and Regenbrecht, 2001), made up from a combination of existing questionnaires including that of Witmer and Singer, and Slater et al (Schuemie et al., 2001). It has undergone many revisions causing inconsistencies which are enhanced through both validated and non-validated translations (Melo, Vasconcelos-Raposo and Bessa, 2018). Besides this, it has been widely used in a range of fields from virtual narratives to phobia treatment due its broad coverage of many virtual environment aspects(Schuemie et al., 2001).

A recent evaluation of VR driving simulation against flat-screen use used the SSQ concurrently with the Presence Questionnaire (Walch et al., 2017), and while the comparison between the two was indirect, besides the multiple questionnaires contributing to survey fatigue, it highlights the compatibility of the methods as well as their applicability to modern scenarios despite being relevantly dated.

2.8 Grand Challenges

By reviewing the literature surrounding this projects topic, a number of challenges have been determined. The challenges can be summarised with the following points:

1. Currently, several cybersickness theories exist, such that designing a specialist system targeting a single issue is challenging. Specialising the system is made increasingly difficult due to somatosensory feedback with VR only being narrowly explored, in particular the use of airflow. This results in further speculation and uncertainty when assessing the topic.
2. Both hardware and software need to be suitable to run the system fluidly and consistently, such that the level of latency, frame rate, field of view and other contributing factors are all as close to ideal as possible. On the other hand performance must be considered with respect to VR fidelity in order to make a realistic and presence inducing environment.
3. The nature of measuring sickness by induction presents several human challenges, not only from an ethical perspective but from a methodological and data gathering standpoint. Duration has a positive correlation with sickness, and it is recommended to use VR for no more than 15 minutes per session, limiting experiment task variety. HMDs have a good degree of customization and calibration, however in some cases participants could be at increased risk to cybersickness. E.g. if they cannot wear glasses underneath

the display. In addition, less obvious human factors pose a difficulty to variance within participants.

2.9 Summary

This chapter has examined relative work relating to the topic of cybersickness, presence and VR Design. In doing so, this satisfies one objective of thesis, to examine existing research as means to determine a basis of potential solutions for addressing the issue of cybersickness. The insight acquired here is key to attaining the next objective of a suitably designed and implemented extension to a head-mounted virtual reality display.

Firstly, theories behind the induction of cybersickness and motion sickness have been reviewed to get a comprehensive background of the problem this thesis aims to address. Through this review it becomes apparent that cybersickness draws contributing factors from a broad range areas outside of the primary theories, with varying reports on the weight of significance each of these factors holds. Beyond this, reviewing the area of cybersickness indicates an important relationship with presence. When investigated, the review notes persistent disagreement in the community regarding the relationship between the two topics, further warranting exploration and consideration of presence in this project. Furthermore, existing sensory feedback strategies with VR are reviewed, where attempts of improving usability, task performance and sickness prevention are appraised. With these strategies in mind, physiological research is reviewed to extrapolate towards using sensory feedback to address cybersickness.

In the following chapters, the range of issues are considered and narrowed down where appropriate, allowing for the proposal of a novel approach to reducing cybersickness with the use of sensory feedback. The process used to measure the efficacy of this approach is then covered, concluding with the results then being analysed, validated and discussed.

Chapter 3

Design and Implementation: A Somatic Addition to VR

The purpose of this chapter is to discuss design choices and development methods needed to address the issues and constraints found in the previous chapter. This is carried out to partially satisfy the second objective found in §1.4 - to plan, design and implement an extension to a head-mounted VR system, addressing the findings in previous literature.

Firstly, the design is conceptualized, using knowledge gained from the literature review to discuss the foundations of a somatic VR extension for a HMD. Several ideas for a experimental system are drafted where one technique is determined to then be refined further. In the overview, the conceptualisation and a time-line of the system is discussed. After this, each stage of the systems design is explored, paying particular consideration to the issues and limitations identified in the literature review in order to create an effective comparison tool. Considerations include inducing cybersickness and how to satisfy the majority of issues available and designing a system that meets existing VR development guidelines. The actual techniques and methods used to create the artefact are discussed in the following implementation chapter.

3.1 Design Objectives

Designing for modern VR HMDs is challenging for a variety or reasons, (Rebenitsch and Owen, 2016) describes this as a consequence of having a large number of potential cybersickness factors which each have to be considered. Existing design solutions to cybersickness frequently focus on a single component, making information for more rounded solutions sparse. This has limited the ability to create guidelines for any fundamental virtual environment implementation, such that additional practical testing is often a requirement to certify the design choices selected are suitable for VR.

Particular difficulty for this project lies in assessing the factors in order to achieve a level of cybersickness measurable in users, but simultaneously bearable and usable. Additionally, minimal existing research has explored virtual reality supported by somatosensory feedback, even less so with airflow, and none whilst examining cybersickness in detail. Consequently, this area of design is highly experimental, and will have to be based primarily on existing relevant research. The goals of the design as a whole are as follows:

- Manage cybersickness by applying knowledge gained from related works and existing applications to design an application that may induce cybersickness in some users, but also mitigate severity using known strategies in order to make it usable.
- Draw from existing relevant applications and research projects to source artefact concepts which are suitable for the incorporation of additional somatosensory feedback.
- To design a system that is usable, functional and effective both with and without the additional somatic airflow feedback.

3.2 Platform Choice

To generate ideas for appropriate VR study applications, it is essential to examine what has been used in research previously. The range of VR applications is fairly broad, so the first designs for project software is primarily constrained by the target hardware. While options such as CAVEs and simulators exist, the recent increase in popularity and capability of commercial VR HMDs means that in using a HMD, this project's artefact can gain the greatest amount of reach for the general population while also being accessible financially (Rebenitsch and Owen, 2016). The two commercially leading HMDs are the Oculus Rift[1] and the HTC Vive[2]. Both have similar specifications, however as the conceptualisation process continued and the requirement of vehicular movement became clear (See Section 3.3), it became apparent users would be seated during use. Since room-scale support was no longer a necessity, the 85g lighter, Oculus Rift with integrated audio capability was finalised as our target platform for the slight benefits it offers.

3.3 Previous Studies on Measuring and Quantifying Cybersickness

During the review of the literature, commonalities and trends were observed as to the nature of applications used for VR research studies. Regular advancements in hardware and software have resulted in a wide spectrum of concepts and techniques being presented, however narrowing the applicability to the projects chosen VR system is challenging. Difficulty is further enhanced by the diversity of contributing cybersickness factors and the techniques used to assess for, and mitigate them. For the sake of this project, HMDs were the primary focus of concept trends.

[1]Oculus VR, 2018.
[2]HTC, 2018.

The first observation is the difference in study strategies between publications measuring for sickness during virtual movement, in comparison to publications measuring for sickness while stationary. Many publications that look at the effects of optical interference largely to stick to pure observation of a stationary virtual environment while the factors they are examining are applied, such as rotation, field of view changes, or image quality changes (Bonato, Bubka and Palmisano, 2009; Lo and So, 2001; Draper et al., 2001; Rebenitsch and Owen, 2016). It might be self-evident that investigations into locomotion in a virtual environment use movement based applications, however the style of these applications can be broken down further. Some authors use predetermined applications, using fixed variables and a high level of control to ensure participants receive nearly identical experiences (Davis, Nesbitt and Nalivaiko, 2015; Kolasinski, 1995; So, Lo and Ho, 2001). This allows for excellent control of key cybersickness components such as navigational speed or angular rotation, in addition to reducing the human effect on results based on personal behaviour. The disadvantage of forced motion or “passenger” experiences is the avoidance of user controlled movement, which has seen a large amount of attention for its degree of contribution to cybersickness through the hindrance of sensory adaptation (Stanney and Kennedy, 1997). Additionally, virtual presence directly stems from a the degree which a user feels in control of their surroundings, such that allowing for the control of movement can allow for greater presence (Rebenitsch, 2015; Sheridan, 1992).

An interesting strategy used by most locomotion driven studies to apply control without directly enforcing it, is the use of simple tasks to be enacted by participants. Some examples include moving a ball from one location to another, walking in a figure of eight pattern, and popping balloons (Stanney et al., 1999; Young, Adelstein and Ellis, 2007). This also acts as a distraction to participants, which can be used as a technique to obscure sickness inducing components of a virtual environment. For locomotion, a compromise between "active" and "controlled" motion control systems is an "active-passive" control system (Stanney and Hash, 1998). This design choice effectively limits the range of movements based on the scenario the user is in. The example used by Stanney and Hash is that only movement input is registered on the x and z axis until the participant is in a location suitable for vertical movement, where then only the y axis movement input is used. In more modern VE's this is somewhat in effect via the use of realistic game engine environments, for example, simulated gravity acts as a realistic prohibitor of vertical movement. Specifically for driving simulations and environments, the turning circle and other physical properties of the vehicle are could be considered forms of "active-passive" control as they restrain the user from extreme or uncontrolled movement.

Continuing the review of related literature, an infrequent type of application shared in a large number of virtual environment sickness studies, including but not limited to HMD based experiments, was driving simulation (Walch et al., 2017; Mourant and Thattacherry, 2000; Brooks et al., 2010). Driving in VR is often used as a prime example of conditions needed to induce cybersickness, through its engagement of the visual, but not vestibular sensory systems (LaViola Jr, 2000; Davis, Nesbitt and Nalivaiko, 2014). One benefit to driving when examining sensory feedback when compared to the majority of VR application contexts, is that by remaining thematically accurate and having realistic vehicular navigational velocity, there will be a greater level of expected sensory feedback (So, Lo and Ho, 2001). A greater scale of sensory potential increases the likelihood that the additional feedback will be detected due to the magnitude being unavoidable, but simultaneously contextually accurate. In an application focused on bipedal motion, feedback would be required to be realistically scaled, such that emulating delicate airflow changes during acceleration would be troublesome to keep precise and noticeable. As such, an environment traversed using vehicular locomotion was determined most suitable for this project. To make this suitable for VR however, the aesthetic of the vehicle within the VE would have to be of an exposed nature to support the user expectation of sensory feedback.

3.3.1 Software Trends

The next stage is to make decisions regarding the mechanics, content and structure of the application. The first consideration was the control scheme, as both presence and cybersickness hold relationships with control devices. Presence requires that control mechanisms use little conscious thought and feel intuitive (Witmer and

Singer, 1998; Lee, 2004). To avoid cybersickness, control mechanisms should feel directly connected to the environment, allowing users to feel competent at moving through the environment (Stanney, Kennedy and Drexler, 1997; Stanney et al., 2003; Davis, Nesbitt and Nalivaiko, 2014). For a driving simulation the simple solution is a steering wheel and pedal system, where for the majority of users, controls will be familiar or at least recognisable, with the ability to be simplified down to two control pedals and an automatic gear system. Choosing the nature of the virtual terrain is somewhat more complex due to the uncertainty regarding the severity of many contributing cybersickness factors. The main consideration is that the terrain does not encourage massively erratic rotation, acceleration or any combination of the two, particularly on multiple axes simultaneously, as to not induce severe sickness outcomes in users (Bonato, Bubka and Palmisano, 2009; Vinson et al., 2012). The theme of the visual aspects is non-consequential however a consistent degree of realism should be maintained throughout the entire usage period. Besides remaining consistent, the virtual fidelity to reality should, at a minimum, be identifiable and comparable to real world terrain, with the maximum quality of the environment not exceeding the performance demand required to meet the recommended visual performance guidelines suggested for virtual reality use (OculusOptician, 2016).

3.3.2 Feedback Trends

The final stage is identifying an approach to incorporate wind as feedback to the overall system. Inaccurate feedback would only increase the conflict of senses and enhance cybersickness via the sensory conflict theory (Davis, Nesbitt and Nalivaiko, 2014; LaViola Jr, 2000). Practicality and resources are limiting factors, such that emulating a three-dimensional wind system comparable to the WindCube would be difficult (Moon and Kim, 2004). To compromise, the aforementioned task system can be used as a method to encourage certain types of movement, in doing so, narrowing the range of directions feedback would have to be provided. Driving naturally discourages lateral movement outside of sliding or drifting, which is beneficial to the aversion of cybersickness (Trutoiu et al., 2009), as well as a reason to exclude that angle of feedback without significantly subtracting from fidelity to reality. Similarly, design techniques can be used discourage reverse movement. Removing the option to reverse would be a hindrance to player control and fidelity, as it is likely some users create scenarios where having access to reverse movement is preferable. What can be done is a restriction on prompts to move backwards, such as excluding rear windows and mirrors in combination with an environment that does not regularly require reverse movement, even when stuck. Reverse movement is discouraged in VR for the same reasons as lateral movement, as it reportedly generates more sickness than forward traversal, due to the inability to create convincing movement, and hence low quality vection (Trutoiu et al., 2009). With this, it can be ensured that the best part of the experience is spent moving forward and consequently can have a less cumbersome, more practical system for generating feedback. The benefit to only needing to provide feedback in the forward arc is that it allows for a desk mounted strategy, as it has already been determined that a forward facing desk mounted wheel is most suitable for the artefact as a control scheme. To maintain realistic feedback, the airflow needs to be dynamic, adjusting to the movement of the player in the virtual environment, varying between speeds, direction and angular velocity. This can be achieved through the use of multiple sources of airflow, with rate of flow governed and updated by the content of the application.

3.3.3 Summary

To summarise the conceptualisation process, the artefact for this project was determined to be a VR driving application, where by users wear a HMD and traverse the environment using a simplified but realistic control mechanism. A simple task should be incorporated to add control to the conditions of the study, without removing a users sense of being connected to the environment. The virtual terrain and world require many design considerations with regard to cybersickness, which is difficult to plan for, however iterative design techniques can be used to determine a suitable balance for the experiment. Accurate airflow to simulate movement should be achievable by correlating the power of the airflow sources proportional to the direction and speed of the user's movement, providing the somatosensory feedback to control for.

3.4 Supporting Design Choices

The review of related work has highlighted a lot of factors that should be designed for, even if they are not being directly examined. Most of these pertain to creating a more usable virtual experience via the prevention of cybersickness, as well as unique mechanical choices for VR and the control scheme choice to ensure task performance can be smooth. This section will cover the major decisions regarding how content is viewed when using the application, the content users can experience, and precautions to avoid major contributors to sickness outcomes.

3.4.1 Spatial Information

The first consideration to be made is to provide a user with a constant frame of reference in order to convey consistent spatial information via visual feedback. Two recommended methods have been the use of horizons and avatars (Vinson et al., 2012; Prothero, 1998). When it comes to creating a personal human avatar for VR driving, difficulty arises in aligning the avatars movements to that of the user, for example, hand movements, such that inaccurate representation could be harmful to fidelity and presence. Due to the direct control connection between the driver and car, it can be argued that the car itself is representative of an avatar, where fidelity can be maintained by matching the position of the controls within the experience to the position of the controls in reality. A horizon is far more simple to implement and keep realistic, however designing such that a player can always see it is more challenging. The horizon allows a user to subconsciously determine the vertical upright of the environment by seeing it, in the scenario a user cannot see it, a suitable and believable alternative must be used as a frame of reference. Familiar, or recognisable objects and terrain can act as these reference targets (Chang et al., 2013). For example, using traditional physics, water will always collect at the lowest point on a surface, such that users can subconsciously infer spatial orientation information from it.

3.4.2 Navigation

Perhaps the most persistent issue during design of a VR system that includes significant locomotion is that of optical flow, vection, their links to field of view (FOV) and navigational velocity. As covered in the literature review, optical flow is summarized as the viewing of ones combined movement pattern within VR content (Chang et al., 2018). The pattern of optical flow has seen many positive correlations with cybersickness (Kolasinski, 1995; McCauley and Sharkey, 1992), and mixed correlations with presence (Davis, Nesbitt and Nalivaiko, 2015; Emmerik, Vries and Bos, 2011), so generally it should be mitigated for wherever possible. The first factor to be considered is navigational speed, which is limited by application theme, as convincing vehicular movement will have considerably higher navigation speed when compared to bipedal movement. As such, other more controllable factors should undergo critical evaluation for optical flow mitigation opportunities due to the unavoidable consequences of speed on cybersickness (Bonato, Bubka and Palmisano, 2009; Vinson et al., 2012; So, Lo and Ho, 2001). The other component navigational velocity is rotation, proven to be a factor in cybersickness, particularly when applied on multiple axes (LaViola Jr, 2000; Bonato, Bubka and Palmisano, 2009; Vinson et al., 2012). To maintain fidelity, Y axis rotation is constrained by the parameters of the vehicle and interactions with the terrain, however these parameters can be influenced to reduce the likelihood of spins and jarringly sharp turns, scenarios that would likely cause sickness outcomes. The other axes of rotation also obey the physical laws of the environment, but can be modified. In racing games, a common mechanic is self-righting, to allow a player to control their vehicles rotation in order to continue playing after a crash or spin. This project plans to implement a passive, ongoing version of this mechanic, that acts as a rotation correcting tool, to prevent scenarios such as the vehicle flipping or rolling before they can happen, even in the most inexperienced or reckless user's hands. Such a system will need to continuously check for extreme rotation, gradually apply countermeasures to ensure the reaction does not appear unnatural or jarring, to maintain fidelity, high quality vection and consequently avoid aggravating cybersickness (Trutoiu et al., 2009).

3.4.3 Environmental Choices

The layout, size, terrain and texture of the virtual environment each need to be considered in order to accommodate task performance without unnecessary induction of cybersickness. Firstly, the layout should be simple enough to avoid confusion during task performance, as well as to ease the collection of spatial information by a user (Chang et al., 2013; Freitag, Weyers and Kuhlen, 2016). However, the layout should be variable enough to slow the process of adaptation as to not acclimatize a user to a universal speed, direction or rotation (Hill and Howarth, 2000; McCauley and Sharkey, 1992; Kennedy et al., 1993). After some deliberation, an approximate 'figure of eight' shaped lap was decided upon, due to the equal amount of right turns and left turns it can provide, however to improve task engagement and further avoid adaptation each long bend was changed to multiple corners of alternating directions. For the size of the driving track, to maintain the goal of a similar number of left and right turns in all players, a single lap needs to be approximately long enough to be completed once by the slowest moving participants in the procedures given time.

An important consideration for any driving application is to make the contrast between drivable regions, unsuitable driving terrain, and impassable areas obvious, to provide users with guidance. This can be done via appropriate design choices. By utilizing recognition and familiarity of participant experiences, user assumptions can be applied to how the virtual world behaves. For example, even inexperienced drivers should be able to acknowledge that driving on a road is preferable compared to dirt, which itself is better than traversing jagged rocks and so forth. This allows for a degree of guidance and control over participant actions without explicitly stating it. As for the actual surfacing of terrain in the application, the driver should be limited to entirely flat terrain as to not aggravate cybersickness. This is due to the terrain primarily having an effect on the behaviour of the car, for which the user should feel fully in control as well as to have a clear understanding on why the vehicle is behaving the way it is (Rebenitsch, 2015; Stanney and Kennedy, 1997; Kolasinski, 1995), which inexperienced users may not grasp immediately. A secondary attribute of a non-flat surface would be the effect on pitch, yaw and roll, where adjusting for repeating micro rotations that are only happening virtually would cause imbalance in a user. This imbalance would be accredited to the postural stability theory and the sickness symptoms that accompany it (Riccio and Stoffregen, 1991; LaViola Jr, 2000). Lastly, in existing games and non head-mounted multi-screen simulators, the information about terrain is traditionally conveyed to the user via rumble or haptic feedback as well as camera shake. In head-mounted VR, camera shake during head-tracking can cause severe confusion, disorientation and sickness due to the sensation of having ones head and vision manipulated externally (OculusOptician, 2016). As for haptic feedback, while most steering wheel controllers accommodate it, this study would benefit more from isolating types dynamic touch feedback, to better confirm the effect of added somatosensory feedback as airflow. Therefore, this project will not use haptic or rumble feedback, nor variable terrain surfaces as game mechanics.

Overall scene complexity is another environmental factor that needs moderating during the design process. A more complex scene may positively contribute to presence, fidelity and engagement (McMahan et al., 2012), however an overly complex scene may cause issues during locomotion due to the interaction with optical flow (Kolasinski, 1995; McCauley and Sharkey, 1992). Despite authors reporting that it may be due to the available technology at the time, such that it may no longer an issue, this project will avoid overly complex scenes until this possibility is confirmed. A supplementary potential upside of this is the effect on performance. Less complex environments will benefit performance, meaning less compromises in other aspects of performance management, making it easier to remain within acceptable capability limits and recommendations (Davis, Nesbitt and Nalivaiko, 2014; LaViola Jr, 2000).

3.5 Aesthetic Choices

To undergo the sensation of airflow during the user must feel exposed, such that a traditional car model is unsuitable, and even convertible models obscure a large amount of airflow. Therefore, to keep fidelity to reality, the choice is limited to open cockpit vehicles such as a golf cart, go-kart or dune buggy to be exposing the user, while also being controlled by a wheel and pedals. A motorbike or bicycle was considered, however concerns regarding user balance, the inability for a user to lean and the addition of physical exertion would introduce an unsupportable amount of confounding issues.

Besides the user controller vehicle, once an appropriate environment layout is confirmed via testing, suitable colours, textures and themes should make for the most believable environment possible. Maintaining a good degree of believability can enhance presence, as well as the sensation of self-motion (or vection) in users, which has direct correlations to the metric of cybersickness, and is consequently relevant to the investigation.

3.6 Designing Feedback System

The parameters for the design process is that the system is desk-based and capable of providing dynamic and variable airflow in the forward arc of the seated user using information from the virtual environment. The decision was made to ignore all forms of environmental wind i.e. airflow or air resistance not generated via locomotion. This was due to the potential confusion it could cause the user by interfering with the test condition feedback, however, artificial wind warrants future investigation for use with simulator focused virtual environments as a weakness of this solution.

The first step is determining the position and layout of the airflow sources. It is known that, ignoring the effects of wind, the sensation of airflow would be experienced in the opposite direction to which you are travelling, which during vehicular use is predominantly directly in front of the vehicle, even when turning. The only scenario in which transverse airflow might occur is during lateral movement, i.e. drifting which, as previously stated, should be avoided. The distribution of the airflow sources should therefore be weighted towards forward

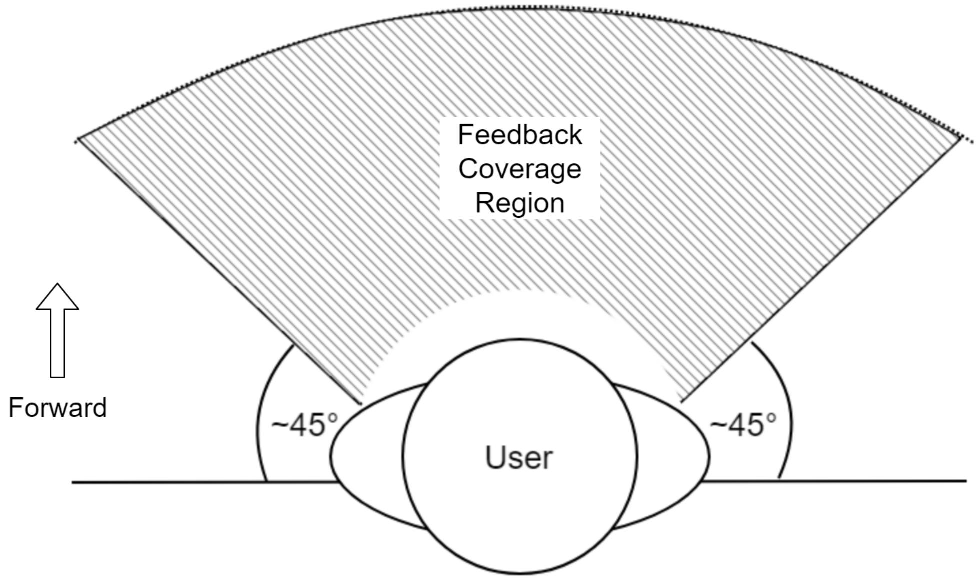


Figure 3.1: A diagram showing the region in front of the user that is being targeted by somatic feedback.

movement over lateral movement. Instead of positioning multiple sources in the same location however, forward facing air sources should be separated slightly to allow for additional directional control as well an imprecise and environmental sensation. The justification for the distribution of the forward airflow sources is to ensure that the entirety of a users torso is exposed to an equal amount of airflow, consequently encouraging users to become less conscious of the equipment in front of them, and undergo an increased sensation of presence, as per one metric of this investigations evaluation. The position of the lateral fans is determined by approximating ±45°of where users would be seated, then maintaining the same distance as the forward facing sources allowing for normalized values when determining the strength of airflow from each source. A third dimension to the array of sources was considered, however due to the aversion of vertical movement through the environment, it was quickly dropped. As for the earlier point on ensuring complete coverage, early testing revealed that single horizontal forward facing array provided enough coverage to make additional vertical sources unnoticeable.

Determining the vertical position of the array was an initial concern due to the varying heights in users, however there was the guarantee that the user's hands would be connected to the fixed position of the steering wheel controller, and consequently, the androgenic hair and skin would be active receptors of the somatic feedback. Therefore the airflow sources were vertically positioned such that the lower arc of the cone would reach the position of the steering wheel. While the upper face will be covered by the HMD, the lower face, head hair and facial hair are all suitable receptors for the feedback, and early testing showed that for all but the most extreme cases, these areas would be in range of the cone of airflow each source produces.

The final step in the design of the feedback system is to determine the power of each feedback source and to calculate it. To begin with, the forward movement vector of the vehicle can be continuously examined during the experience, where its magnitude can then be used as a means to control the power of the attached forward facing fans. With some testing, an approximate maximum speed users reach can be observed and can be paired to the maximum speed of the fans, meaning the maximum airflow will occur at the highest speeds. Following this, a ratio for forward speed against fan power can be calculated, creating proportional forward airflow for all speeds. Implementing accurate lateral airflow is slightly more complex, as it is required to determine when a user is turning, the sharpness of their turn, and whether they are drifting at all. Since the direction of the car is governed primarily by the orientation of the wheels and existing momentum, however the rotation of the user is aligned with the chassis, during turns, the difference in rotation between the chassis and the current direction of movement can be used to calculate how much lateral movement the user is experiencing. The resulting vector will have a forward and lateral component, then depending on the magnitude of each component, forward and lateral fans can be powered according to the magnitude of each component vector. An additional consideration that may seem obvious to some is that during turns, the outside edge of the vehicle is moving faster than the inside, such that the fan on the opposite end of the horizontal axis to the turn should be activated, rather than the fan in the same direction as the turn.

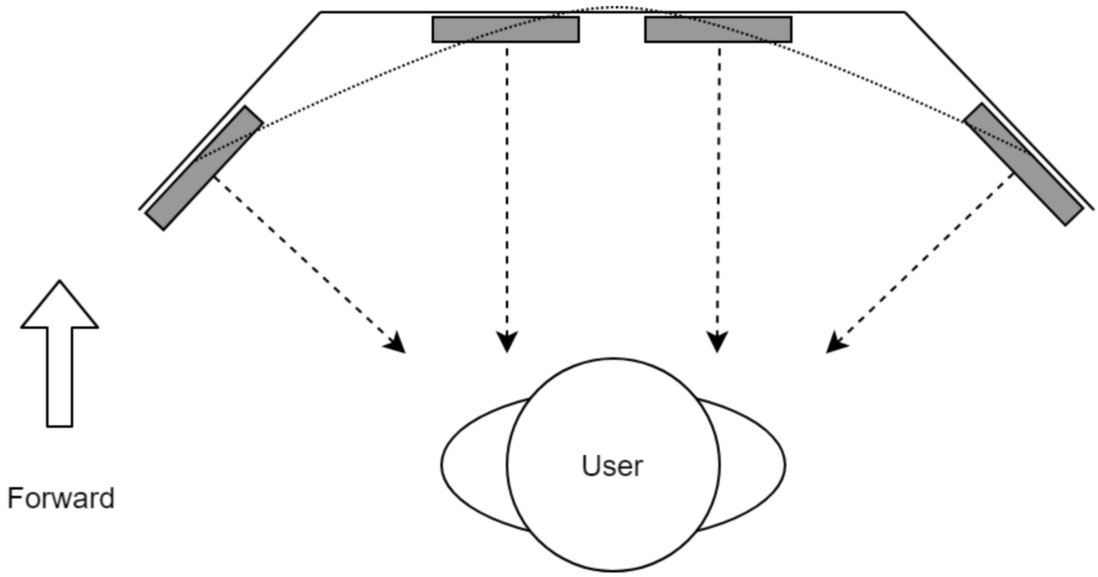


Figure 3.2: A diagram to show the planned approximate positions of the airflow sources.

3.7 Summary

To summarise, in this chapter the software application has been conceptualised and the somatosensory feedback system to accompany it. Important design choices have been discussed in preparation for the implementation of the complete system, including:

- the mechanics of the vehicle and the control scheme for accessing them;
- the environment, both mechanically and aesthetically, paying significant notice to cybersickness mitigation strategies;
- how to comprehensively convey information about the environment and vehicular motion to user; and
- how the hardware of the somatic feedback extension will change based on in-application user behaviour

The following sections will discuss how the design choices made are applied, and the processes used to apply them are enacted.

3.8 Implementation

This section will explain the processes used and decisions made in the creation of the artefact used in this project. By utilizing the design choices made in previous sections, as well as the insights from the literature review, the careful process of controlling the sickness of an application is discussed. The first stage of implementation was to create the VR driving application, and checking the functionality without any external feedback support.

3.8.1 Creating the base application

Before implementation began, a suitable development platform had to be chosen. This was narrowed down to Unity[3] and Unreal Engine 4 (UE4)[4] based on the ease of use, VR support, and documentation available. UE4 undoubtedly is the most graphically capable engine of the two, however this is not a priority for the project which consequently lead to the selection of Unity for the diverse range of assets it offers, as well as the quick and easy SDK integration. SDK and hardware integration was a particular concern for the project due to non-traditional controls and the communication method required for the somatosensory feedback sources.

Using the Unity[5] game engine and the 'CarController' demo from Unity's standard asset pack[6], with a camera rigged for use with Oculus Rift[7] a usable starting point was established. The demo scene includes functionality for adjusting a massive range of vehicle parameters, including wheel friction, engine drive, suspension and downforce. To meet the design goals of a controllable vehicle that also feels familiar and realistic, a large amount of value tweaking was done, during this initial stage, as well as throughout the implementation and testing process.

[3] Unity Technologies, 2018b.
[4] Epic Games, 2019.
[5] Unity Technologies, 2018b.
[6] Unity Technologies, 2018a.
[7] Oculus VR, 2018.

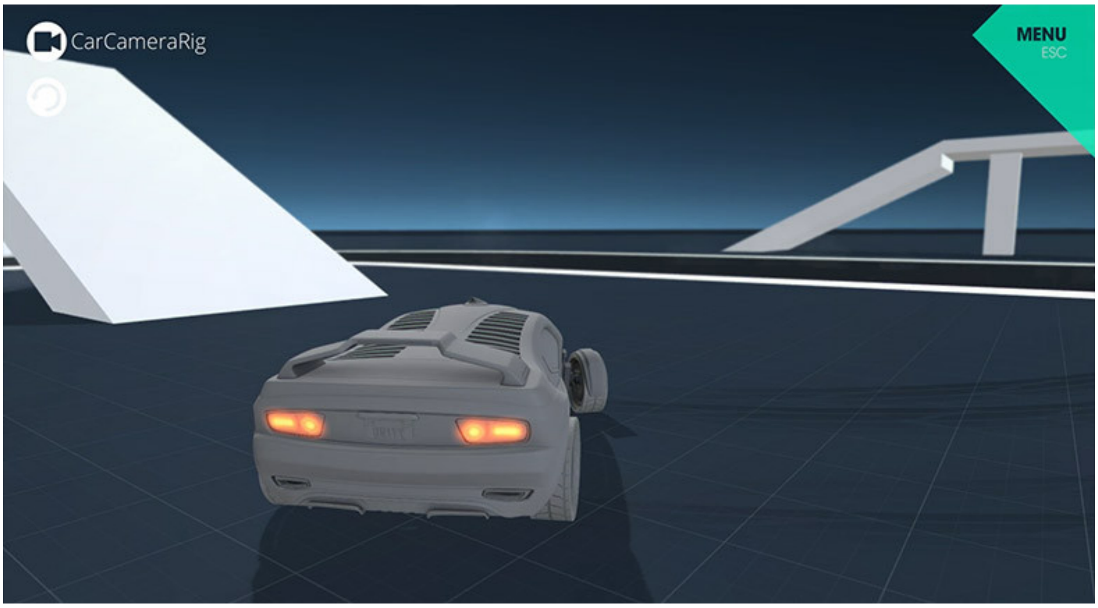


Figure 3.3: The third person perspective of the Unity Car Demo[8]. This environment was the first iteration of the prototype system.

The control system was altered to accommodate a Trust GXT 570 compact racing wheel and pedal system in order to meet the minimum objective requirements for out baseline system. This particular model of wheel was chosen for its simplicity, as we do not intend to create a simulator. By only having the most fundamental of driving controls, it promotes user interfacing and competence, intending to minimise lack of control as a potential confounding sickness factor. Alpha testing resulted in a few verbal reports of sickness outcomes when travelling on the flat track, however the vertical components caused in significant discomfort in most. This aligns with the prediction based on the literature review, however poses concerns about a suitable balance to make cybersickness measurable in participants while not reaching extremes.

The next iteration of the software addressed the aforementioned issues as well as additional advancements identified during the design process. The model of the vehicle was replaced with a dune buggy, without windscreen it would allow significant airflow during use, making it thematically accurate for the reception of wind feedback. Additionally when tested, the less cramped nature of the buggy received positive comments from testers, despite testers not reporting to be claustrophobic. Secondly the flat track was replaced with large sand dunes, using the idea of long curves being acceptable for sensory interpretation despite being on the vertical, and other axes. This change was not well received, with several testers declaring it unplayable as a result of multi-axis rotation and a lack of consistent reference information. The loss of structure from a road prompted the introduction of a simple waypoint system, where a large highly visible marker denotes a location the user should drive towards, which, when reached, causes another waypoint to appear.

Figure 3.4: First person perspective of the second iteration of the environment, the large green marker represents a waypoint within the environment.

The environmental layout that was eventually settled on fell somewhat at a midpoint between the completely flat track of the first iteration, and the largely varying amplitudes seen in the second environment. The terrain can be described as mostly flat, with some minor vertical variation, or "bumps". Additionally, the environment was designed with the rest frame concept in mind due to the issues encountered with the previous iteration. At all points, the horizon where the water meets the sky-box can be seen. Similarly, the raised mountainous terrain can be found on the inside edge of the traversal route with distinctive colours and patterns used, allowing for comprehensive spatial information and easily identified boundaries. Alpha testers mostly reported mild sickness to moderate symptoms verbally, such that the environment layout was finalized.

The final step in the creation of the base application was making it 'study ready' by refining any bugs, optimizing the performance, as well as adding some 'quality of life' changes. Sound was added to the game, to provide fundamental audio feedback, for example, engine noise when accelerating, as well as to provide a greater sense of presence by utilizing ambient noise suitable for the theme of the virtual environment. To provide visual controller feedback that would otherwise be obscured by the HMD, and to improve presence, the axis of the virtual steering wheel was aligned to match with that of physical control mechanism. This keeps users aware of the orientation of the steering wheel, without having to look at the wheels of the vehicle. Similarly, this was done with the pedals of the vehicle, as the physical versions are also obscured by the HMD and desk. Lastly, performance was appraised where it was found the system met most visual quality guidelines, but suffered from a slightly low and variable frame rate, varying between 40 and 60 frames per second (fps). A consistent rate above 60fps is recommended, and above 90fps being ideal (Oculus, 2018). To address this, occlusion culling was added and applied to the system, which prevents the rendering of objects when they are not currently seen by the camera as they are obscured (occluded) by other objects. Afterwards, the system maintained 110fps during usage, however to overcompensate, the system used was upgraded from a Nvidia GTX 970 graphics card to a GTX 1070, increasing the fps during usage to 130fps.

Figure 3.5: First person perspective of the final iteration of the environment, both the rocky hill and water regions cannot be traversed thus directing users over the slightly bumpy terrain.

3.8.2 Creating the somatic feedback extension

The first step in this process was to create a structure capable of supporting the feedback sources, that itself can be supported by a desk. To do this, extruded aluminium was used to create a scaffolding capable of supporting the forward arc of airflow sources, as seen in Figure 3.6.

Figure 3.6: The extruded aluminium scaffold used as a structure to mount airflow sources.

The next step was selecting an appropriate source of airflow to then attach to the structure. In order to meet the requirement of being controllable and a suitable size for a desk, computer case fans were deemed most suitable. This project used 1350RPM Arctic F14 High Performance Case fans, each mounted in position as seen in Figure 3.2. Any 3-wire or 4-wire case fan would be suitable, with greater output being better. The necessity of the 3+ wire fans is due to the controllability these fans provide access to, as a control signal can be sent to to change the RPM dynamically, making them ideal for this project. Each is powered by a 12V mains transformer, using adapters to connect to the power and ground pins to the transformers. In order to control the RPM of the equipment, the next step was to generate a 3.3V control signal interpretable by the on-board chip-set within the fans.

The next phase was to calculate and then apply the correct control signal corresponding to the status of the user within the virtual environment. This was done by first calculating the power for each fan to operate at, for example when travelling in a straight line, the two central fans should be operating at a high RPM, and the lateral fans should be operating enough to provide the sensation of environmental feedback but not enough to confuse the primary direction of the feedback. The rate of each fan is calculated in Unity by first retrieving the direction which the vehicle is travelling, and the forward direction from the centre point of the vehicle. The angular difference between these directions can then be used to determine appropriate feedback. When the difference tends to zero, it can be ascertained that the vehicle is travelling the same direction it is facing and that the lateral fans should be on low power. When the difference is significant it can be assumed that the vehicle is turning, such that the appropriate lateral fan should increase in power and the forward fans power should decrease accordingly, governed by the sharpness the turn.

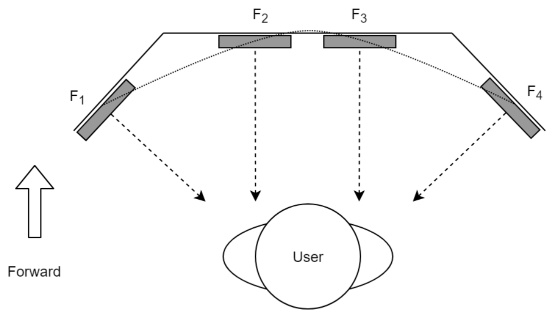


Figure 3.7: Study 1 Fan Power Distribution

To determine the power of each fan the following calculations were implemented to the application, where F_1, F_2, F_3 and F_4 represent the fans in Figure 3.7, and $\Delta angle$ is the difference between the orientation of the vehicle and the direction it is travelling:

$$
\begin{aligned}
F_1 &= k(speed) \times (0.5 - j(\Delta angle)) \\
F_2, F_3 &= k(speed) \times (1 - j(\Delta angle)) \\
F_4 &= k(speed) \times (0.5 + j(\Delta angle))
\end{aligned}
\tag{3.1}
$$

Where k is a scalar for speed and j is a multiplier for the angular effect, such that when $\Delta angle$ is at the highest representable positive angle, $(0.5 + j(\Delta angle)) = 1$, and at the most negative representable angle $(0.5 - j(\Delta angle)) = 1$. In this project the maximum representable angle is 45°in either direction, such that $-45 \leq \Delta angle \leq 45$, and consequently $j = \frac{1}{90} = 0.0\dot{1}$.

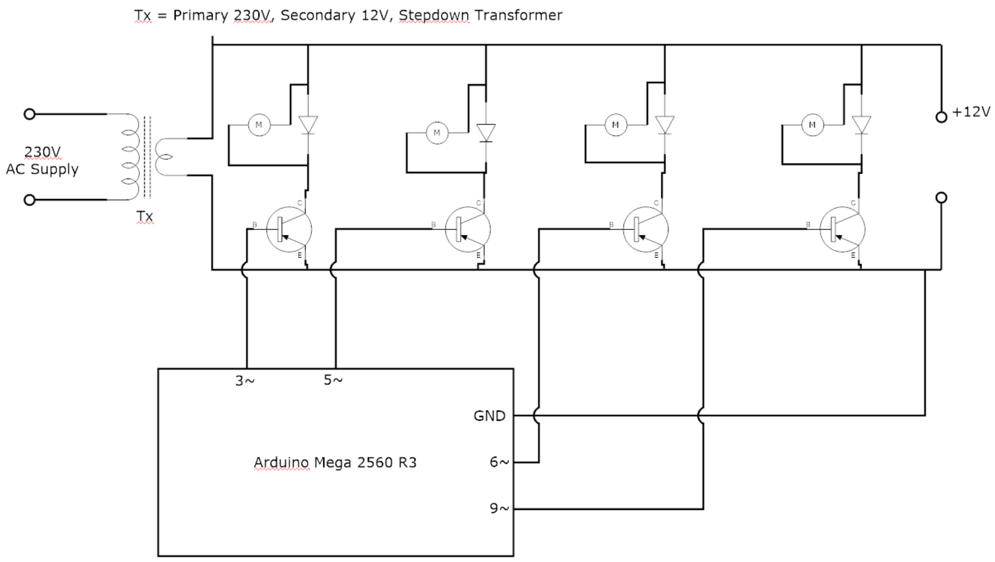


Figure 3.8: Study 1 Wiring Diagram

The control value for each fan is determined every update cycle of the simulation, and consequently is dynamic according the the users movement within the application. To allow for the transfer of data, an Ardiuno MEGA2560 R3 micro-controller was used as a firmware interface. To begin with, the controller was connected to the PC running the application via USB, allowing for its behaviour to be configured via the Arduino electronic coding platform. The micro-controller was configured to receive data from the application PC via serial connection, namely the control values for the four fans. Each fan was attached to the micro-controller via 5V wire at the pulse width modulation (PWM) ports on the device, as the case fans require a PWM input to govern the RPM. Lastly, the micro-controller was configured to process and send the input from the Unity application to the corresponding fan on every few update cycles. The final result was a system capable of passing live, accurate data from the virtual environment, to the mounted fans via the micro-controller and serial connections. The system is not however dependant on the airflow being operational, such that the base application can be operated without additional feedback just by disabling the passing of data. With the addition of the control mechanisms, the finalized system can be seen in Figure 3.9.

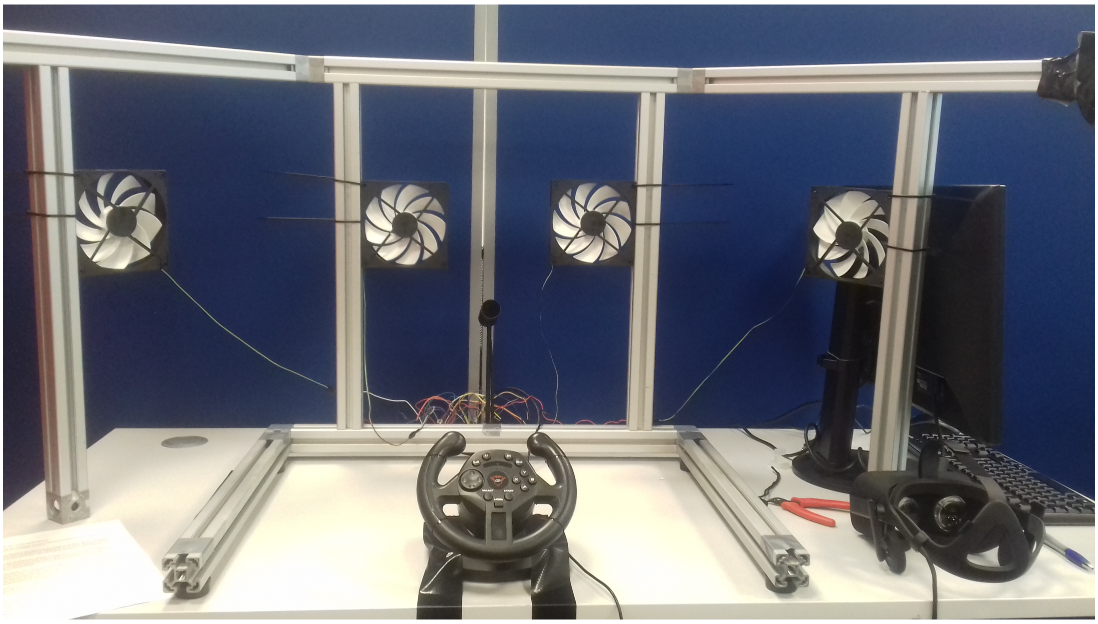


Figure 3.9: Study 1 Complete System

3.9 Summary

In this chapter, the design and implementation of an application for examining the effects of VR driving is briefly discussed, as well as the creation of an airflow system capable of providing sensory feedback using user movement information from within the virtual environment of the aforementioned application. With the system complete and ready for use, the next component of the project is devising an appropriate methodology to accurately and ethically determine the efficacy of the sensory feedback system.

Chapter 4

Establishing a Methodology

In this chapter the strategies and techniques used to assess the efficacy of the system with respect to this projects hypotheses and objectives are explored, along with the ethical approval process and steps taken to maintain an ethical procedure. The apparatus and study variables are appraised. Additionally, this chapter will cover concerns surrounding the negative consequences users may incur from undertaking the study, and the precautions and accommodations this research takes to account for them. Lastly, the methods used to record and score the aspects this experiment examines are briefly discussed with respect to the procedure and study as a whole.

4.1 Ethical Nature

Due to the minor health concerns posed to participants during the study it is important to take appropriate precautions to maintaining a healthy study environment while at the same time securing results. This section will briefly summarise the steps taken to handle the nature of the study, as well as the approach taken to achieve ethical approval.

Before the study procedure is even considered, as the previous chapter has explained, ethical design was required to be at the forefront of the creation process. The VE was designed such that the cybersickness factors, and how to regulate them were prioritised over the majority of mechanics and components. With this in mind, the primary concern when leading the study is the human factors of cybersickness, as described in Chapter 2. Firstly, to ensure no sickness susceptible users are exposed to the environment, a thorough screening process is required, examining for any non-typical level's of health as well as any conditions pertaining to the vestibular and visual senses. The complete screening process can be seen in Section 4.5. Secondly, the apparatus, as the cybersickness links between lack of control and poorly utilised hardware are easily preventable in this study scenario. Control systems and seating were configured prior to equipping HMD to ensure maximum comfort for the participant. Additionally, prior to any locomotion, participants require guidance to calibrating the HMD to ensure the best visual quality, and more importantly the prevention of cybersickness associated with clear vision. Lastly, it is essential to make sure participants have a clear understanding that there is no issue with stopping the task at any point they experience intolerable discomfort.

Regarding the task itself, the main concern is the duration of the study due to findings correlating time exposed with sickness Kennedy, Stanney and Dunlap, 2000. As such, the time a user is exposed to a VE with locomotion should be kept to the minimum required for reasonable assessment. In addition to this, participants should be reminded their performance is not be examined in any way. This is to promote sensible, relaxed movement within the virtual environment that is unlikely to prompt any uncontrolled behaviours, and consequently sickness.

The administration process for the SSQ suggests to apply it immediately after the task is completed Kennedy et al., 1993. After the task, participants should be offered refreshments to revitalise themselves at the earliest reasonable opportunity. The most suitable provisions are water to combat the sweating commonly associated with sickness, and slightly sugary foods to combat the effects of fatigue such as biscuits. Similarly, participants will be encouraged to dispel any sensations of vection by taking a few steps around the study environment. Once participants are content to continue, the rest of the data retrieval process can continue.

With regards to the ethical approval process, it is important to convey the steps taken to address each of the hardware, content, and human factors of cybersickness.

Despite this, perhaps the most important component of the process is making it explicit that the goal of the study is not to induce cybersickness in order to reduce it. Cybersickness is naturally present is VR experiences that use locomotion regardless of the mediums intent, and the goal of the project is to explore methods of handling what is already present. It cannot be assumed that reviewers are aware of VR technologies so a brief explanation may be hugely beneficial to convey that the content of projects application is harmless and its the existing byproduct of the system that is being addressed.

4.2 Experimental Strategy

One of the major limitations of this project is the uncertainty about the severity of cybersickness among users, and as such the study should avoid causing significant or prolonged discomfort where possible. Consequently, a careful approach has to be taken when deciding appropriate study methodology. Until more is known about the effects of the system the safest approach should be taken, especially since HMD oriented studies have been found to have the highest incidence of cybersickness among VR display methods (Rebenitsch and Owen, 2016). The two options this study has to consider for making a comparison by study is whether to do a direct comparison between conditions by using the same participants, or to use groups where each participant is only exposed to a single condition. The primary concern originates from the outcomes of repeated exposure to VR. Firstly, if a user experiences negative affects in the first exposure, they will hold a psychological bias going into the second exposure due the expectation of feeling discomfort. Additionally, a user may not want to undergo a second, similar condition after a poor experience in the first, such that drop out rate could become problematic. Secondly, one intrinsic by-product of VR exposure is VR adaptation, where users become increasingly tolerant to VR side effects and as such will be more resistant to cybersickness during a second condition. Similarly, task performance and familiarity improves over time, such that during a second condition a user will be more competent at traversing the environment and less susceptible to unexpected acceleration or rotation - known agitators of cybersickness. While these issues can be accommodated in the whole participant population by alternating condition order between participants, not enough is known about adaptation to say that this fully accounts for its effects. Lastly, the negative side of prolonged exposure is increased short-term cybersickness, such that back to back exposure to VR conditions may result in increased susceptibility in participants over the course of the study.

Despite all the downsides to multiple exposures, single condition groups are still less common in research than multiple exposures. This can be attributed to the large quantity of human factors that contribute to cybersickness, and consequently the variability in participant outcomes, such that a major population would have to be sampled for each condition group to be equally represented. Furthermore, each group would require identical demographics to account for the gender effect of cybersickness susceptibility. This variability includes the efficacy of reduction techniques, for example, rate of adaptation and interpretation of sensory feedback. Multiple conditions per participant somewhat combats the overall population variance, allowing for smaller groups to be more viable from an experimental perspective.

Ultimately, due to the experimental, uncertain and exploratory nature of this investigation an AB group strategy was chosen, where one group will be a control group, exposed to the base VR application, and one will be exposed to the variant with somatosensory feedback enabled. This will allow for assessment of experiment outcomes without the aforementioned concerns of short-term repeat VR exposure. This can also be used as a guideline for future experiment methodology using the system, or similar applications, to establish whether direct comparison may still be viable later in the project.

4.3 Participants

The study had 40 participants who passed the screening procedure, with 20 beginning in each group. In the control group 19 participants, 13 male, 6 female, completed the trial, with one participant being unable to complete to the study due to overwhelming sickness symptoms. This control group had an age range of 20 to 25 (mean = 20.84, median = 22). With the feedback system in place, all 20 participants finished the study, with 13 males and 7 females. During results analysis however, one participant failed to fill in their age, and since this was only noted post-anonymization, their results were removed. This group had an age range of 20 to 27 (mean = 20.74, median = 22). All participants were volunteers sourced from the University of Lincoln, and were undergraduate or postgraduate students. There was no additional incentive included with the study. This demographic was examined largely due to the age group being most resistant according to existing findings Arns and Cerney, 2005, and would not only be the most ethical approach, but also most likely to yield completed study procedures.

4.4 Task

The task assigned to participants is identical regardless of which condition group they belong. They are placed into the virtual environment, in the drivers seat of a vehicle, where they are asked to drive around the environment following large green way-point markers. Participants time driving was limited to five minutes due to concerns about prolonged exposure, where they would then be asked to stop the vehicle then remove the headset. Before the task began participants were reminded that their performance is not being assessed in a competitive sense and that should drive however they would like to.

4.5 Apparatus

The system uses the Oculus Rift consumer version 1 virtual reality headset. The device consists of a pair of OLED displays, each with a 1080x1200 resolution a 90Hz refresh rate, alongside a 110°field of view. The sensors that accompany the device support 3-axis rotation and 3-axis position tracking, which maps directly the orientation and position in the virtual environment. The device weighs 0.47kg and is worn on the head, such that the lens altered screens occupy nearly the entirety of a wearers field of vision. Participants used the Oculus Rift while seated on an armless office chair with a fixed orientation. Before the study began, as part of calibration, participants were asked to adjust the height and angle of the chair such that they were comfortable with the position of the fixed steering wheel.

The control mechanism consisted of a Trust GXT 570 Compact Racing Wheel and Pedals. The wheel was fixed to the table supporting the entire system, the participant was then asked to adjust other equipment to best suit them, with respect to the fixed position of the wheel.

The feedback system used with participants of the feedback group used 4 F17 Arctic high performance case fans as sources of airflow, each mounted on an extruded aluminium scaffold that is placed directly in front of the control mechanisms. The feedback system, the control mechanisms and Oculus Rift are all connected to a high specification PC. The PC is comprised of an Nvidia 1060 6GB graphics card, an Intel Core i7-4770 3.40GHz CPU and 16GB of internal RAM.

4.6 Procedure

This experiment was approved by the University of Lincoln Computer Science Ethics Committee. Prior to any experimentation, participants completed a consent form accompanied by an information sheet explaining the details of the study. They were also informed they could stop the experiment at any time to withdraw. Breaks were permitted, however a break mid VR exposure would result in a participants results being voided.

To reduce the risk of aggravating susceptible participants, several health conditions were considered before accepting applications. Potential participants who were not at their typical level of health were asked to not volunteer, not only to avoid equipment contamination but to also avoid cybersickness being provoked as a consequence of external symptoms. Due to the links between cybersickness and oculomotor effects, any applicants with major vision abnormalities or uncorrected visual impairments were asked to not participate. Similarly, due to cybersickness' ties with balance and vestibular effects, any participants who have suffered from motion sickness, vertigo or any other balance influencing condition in the last ten years were asked not to participate. Lastly, to comply with some VR health and safety guidelines, participants who were epileptic, pregnant or suffer from any serious medical conditions were asked to not participate. In addition to avoiding any obviously susceptible participants, this screening process sets an effective baseline entry level for cybersickness symptoms before the study begins. Consequently, it was decided that suitable precautions had been taken to normalise the participant population prior to the study such that administering the SSQ before the task was not necessary. A benefit to this is the mitigation of potentially negative expectation the users have during the study, as they will not be considering their symptoms until after the task is complete, hopefully avoiding any psychological effects derived from anticipation Hill and Howarth, 2000.

Participants also filled out a brief form ascertaining some basic information, their age, sex, and previous VR experience, allowing for the assessment of the participant demographic and for potential examination of correlations between participant information, and measured values. Each participant was assigned to a group, however were not made aware of which group they belong - there was no indication to whether the fans would be on or off prior to using the system. Prior to the reception of participants, the experiment room had its temperature set to 21°C, aiming to reduce potential bias for the feedback supported group as a consequence of temperature reduction with regards to the weather. Participants were then seated in front of the apparatus where they were given instructions about the task they were to perform as well as brief explanation of the control scheme. Once participants established an understanding of the situation, they were equipped with the Oculus HMD, where the researcher helped calibrate the device to properly fit, as well as optimize the visual quality. With the participants vision blocked by the HMD, the researcher would then enable the feedback system if the participant belongs to the additional feedback condition group. The participants would then complete the experiment task, being stopped by the researcher after five minutes. Following the completion of the exposure, participants would first immediately be asked to complete the SSQ, following this they would then be offered water and light refreshments to aid in combating any potential negative effects they were experiencing. They would then be asked to complete the Presence Questionnaire. After it was established that a participant was recovering from any negative affects, the experiment was concluded. Average exposure time was approximately 10 minutes, including calibration, brief and trial time. The entire experiment took about thirty to forty minutes depending on the nature of the participant.

Qualitative questionnaires were administered on paper, and were only identifiable by a participant identification number that was given to each participant at the start of the study, allowing for identification of their data should they wish to withdraw. All forms relating to the study are kept in a secure filing cabinet, with consent documents kept in a separate compartment from user data. When digitalized, any data was kept in a password protected folder, on password protected machines.

4.7 Quantitative Measurements

One aim of this experiment was to gather information from participants regarding any potential negative affects they experience as a consequence of using the virtual reality system. To do so there are several different quantitative methods for measuring the variety of negative effects, as well as their severity. This experiment uses the Simulator Sickness Questionnaire or SSQ (see Appendix A.2), which was originally designed for multi monitor simulators, however due to similarities in symptoms between systems and the lack of a more suitable alternative, the SSQ has seen use in a large quantity of VR studies. The 16 items of the questionnaire use 4 point likert scales to gauge each listed symptom on scale of none, slight, moderate or severe. The questionnaire is self-reported by the participant and is consequently susceptible to various psychological factors as well as personal tolerance affecting the severity between users. There has been no external reporting method that has seen as much success as the SSQ however. When scoring the questionnaire, the 16 items can be separated into two symptom categories, nausea, and oculo-motor. By summing the items of each category, and multiplying by the pre-determined weight of the symptom, the questionnaire determines a score for each scale, as well a total score for overall sickness experienced.

The SSQ is administered immediately after exposure to lower the possibility of symptom severity dissipating over time. Similarly, refreshments are not provided until after the SSQ is completed as to not override any existing symptoms before they are recorded.

To analyse the virtual reality application with regards to immersion and engagement the Presence Questionnaire was used (See Appendix A.1). While there are multiple other methods to analyse immersion and engagement, presence is most common, particularly in cybersickness oriented investigations, furthermore, the relationship between cybersickness and presence is rarely investigated directly, however existing findings are often polarised. As such, this project has an excellent opportunity to contribute to this ongoing discussion. As for how to measure presence, a few options exist. This study has chosen a revised version of the Witmer and Singer 1998 Presence Questionnaire. The questionnaire has 19 self reported items, each on a seven point likert scale. These items then correspond to scoring categories of Realism, Possibility to act, Quality of interface, Possibility to examine and self-evaluation of performance and an overall Presence score. Each of these categories can individually be compared against cybersickness to perhaps expose a more specific component of presence that interacts with sickness outcomes.

By using these two measurements it is possible to gain insight into the projects overarching research hypotheses. Furthermore, it allows for the assessment of differences between two groups, one with the incorporated feedback system enabled, one without, and consequently identify the efficacy of the system in each of the measured areas.

4.8 Risk Mitigation

While the general risks and concerns are mentioned throughout the chapter, this section will explore the most likely and most severe risks and concerns that surround the study. The exceeding concern is taking the appropriate steps to prevent excessive cybersickness and then in the scenario where someone is badly afflicted by it, taking the appropriate countermeasures to undo the effects as quickly and as effectively as possible. For the prevention of sickness, outside of the content of the application, the intrinsic human factors of participants and their interactions with the studies hardware will be the most accessible way to avert sickness.

Namely, as the calibration of hardware to participants plays a major role in the quality of interface, the calibration component of the procedure is not to be taken lightly. As part of the pre-study procedure the Oculus needs to be calibrated for each participant, through the adjustment of the straps that fasten the HMD to a user. Guidelines suggest the headset is fairly tightly fitting, to create any additional visual movement besides the head-tracking functionality. Once exposed to VR, the user can use the lens slider component of the headset to adjust the spacing of the lenses to best suit the positioning of their eyes, and consequently the clearest view of the environment, minimizing some oculomotor components of sickness by providing the best quality visual interface available. Additionally, the positioning of the chair and control systems before the study ensure that SSQ conditions such as "general discomfort" are only induced through the exposure to VR locomotion, rather than being seated awkwardly.

In the likely scenario that cybersickness is encountered, researchers should react to combat it, as to reduce discomfort in participants as effectively as possible. To begin with, due to the commonality of symptoms such as sweating, and nausea, water will be offered after the completion of the SSQ, to hydrate and cool participants. Additionally, due to the aforementioned symptoms, as well as possible fatigue, light refreshments will be offered. The intention of these provisions is to aid in a quick recovery in participants. For participants who have severe reactions to the experience, the only treatment that can be administered is additional recovery time. Non-published sources suggest chewing gum, or just chewing as a remedy, which is possibly connected to the proximity of the jaw to the vestibular system within the ear, where the stimulation of the jaws movement aids in establishing the orientation of the head. Despite this, participants will be explicitly advised to stop the study if symptoms become severe or overwhelming. Researchers will also observe the participant during the experience, and on any noticeable symptoms (i.e. sweat or pallor) will remind the participant they can stop the study. Otherwise, researchers will not interact with participants during the experience component of the study.

There are concerns about the self-reported questionnaires, particularly the SSQ that pertains to negative health effects in participants, making results vulnerable to participants disguising or lying about their symptoms in order to maintain a strong appearance. Unfortunately, apart from asking the participants to be honest, there is little that can be done to address these concerns.

4.9 Study Hypothesis

Despite this study being exploratory, there are a number of expectations and predictions based on existing research in the field. Primarily, the aim is to address this projects research hypotheses, looking for a reduction of sickness and an increase in presence for the feedback condition. This can be be broken down into more specific components of obtained measurements. For example, sickness symptoms are categorized into either oculomotor and nausea subcomponents. Since oculomotor symptoms are frequently attributed to the quality of display hardware, which will remain consistent throughout the study, reported oculomotor symptoms across both conditions are expected to be identical also. Similarly for presence, the sub-categories of "Possibility to examine" and "Possibility to act" should remain constant regardless of condition due to the unchanging mechanics within the virtual environment. Other categories of presence are more likely to show changes between conditions.

4.10 Summary

This chapter has looked at the complete process used to obtain study data for the purpose of addressing this projects research hypotheses regarding the effects of somatosensory feedback on reported cybersickness and presence. An AB group strategy was determined best due to the uncertainty surrounding the high variance of negative effects especially temporal effects like prolonged exposure and adaptation. By obtaining the severity of these effects, better appraisal can be made when considering changes to more direct comparison strategies. The steps taken for identifying suitable potential participants for the study are briefly covered, including a screening process to avoid the aggravation of symptoms in particularly susceptible users. The required equipment is outlined, as well as calibrations that take place to ensure the experience is as similar for each participant by further catering for individual characteristics that are not caught during the screening process. Lastly, the complete procedure for researchers is detailed. This includes how to administer the study from beginning to end, accounting for variable factors, the application of measurement methods, and possible risks and concerns of the study.

Chapter 5

Pilot Results

This chapter will analyse the results of the first study by examining the reported simulator sickness and presence among the population of the two condition groups. This analysis will look for differences in measurements between group A and group B, which represent users without somatic feedback, and those with additional feedback, respectively. By carrying out statistical analysis on this data it can be determined whether the main hypothesis of the project is valid, as well as the efficacy of the feedback extension on given factors.

5.1 Scoring the SSQ

The SSQ consists of 16 items listing virtual reality side effects rated from “0” (none) to “3” (severe). A revised and validated version of the questionnaire was used in this study, that narrows the examined sub-scales from three to two.

The total mean SSQ for group A is 4.00 (s.d. = 3.50, range between 0 and 11), and 3.42 (s.d. = 2.67, range between 0 and 10) for group B. The difference in post immersion responses to the SSQ for both the experimental and control group were analysed using the non-parametric Mann-Whitney U test due to the the ordinal nature of SSQ data and the non-related participant population. Participants without the additional feedback (mean = 4.00, median = 3.00) reported marginally greater simulator sickness than those with additional feedback (mean = 3.42, median = 3.00), however a Mann-Whitney U test indicates that

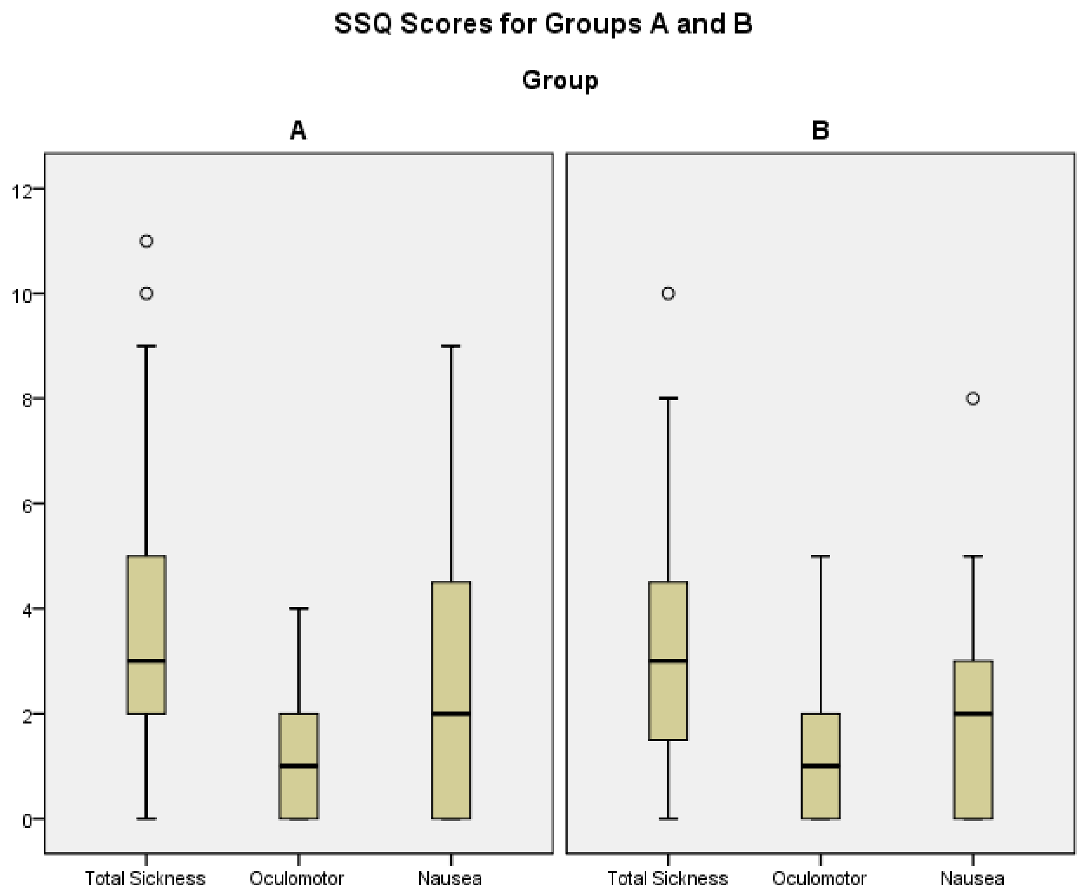


Figure 5.1: Simulator Sickness Questionnaire totals for condition groups A and B.

this difference is not statistically significant, $U(N_{Control} = 19, N_{Feedback} = 19) = 171.50, z = -0.265, p = 0.791$.

5.2 Scoring Presence

The presence questionnaire used consists of 19 items which can each be correlated to different sub-scales of presence. Each item uses a 7 point likert scale to determine a users reported sense of presence with regard to a question. A revised and validated version was used that correlates each item to a sub-scale of realism, possibility to act, quality of interface, possibility to examine and self-evaluation of performance.

The total mean presence score for group A is 108.16 (s.d. = 12.95, range between 88 and 126), and 106.74 (s.d. = 6.29, range between 97 and 118) for group B. Once

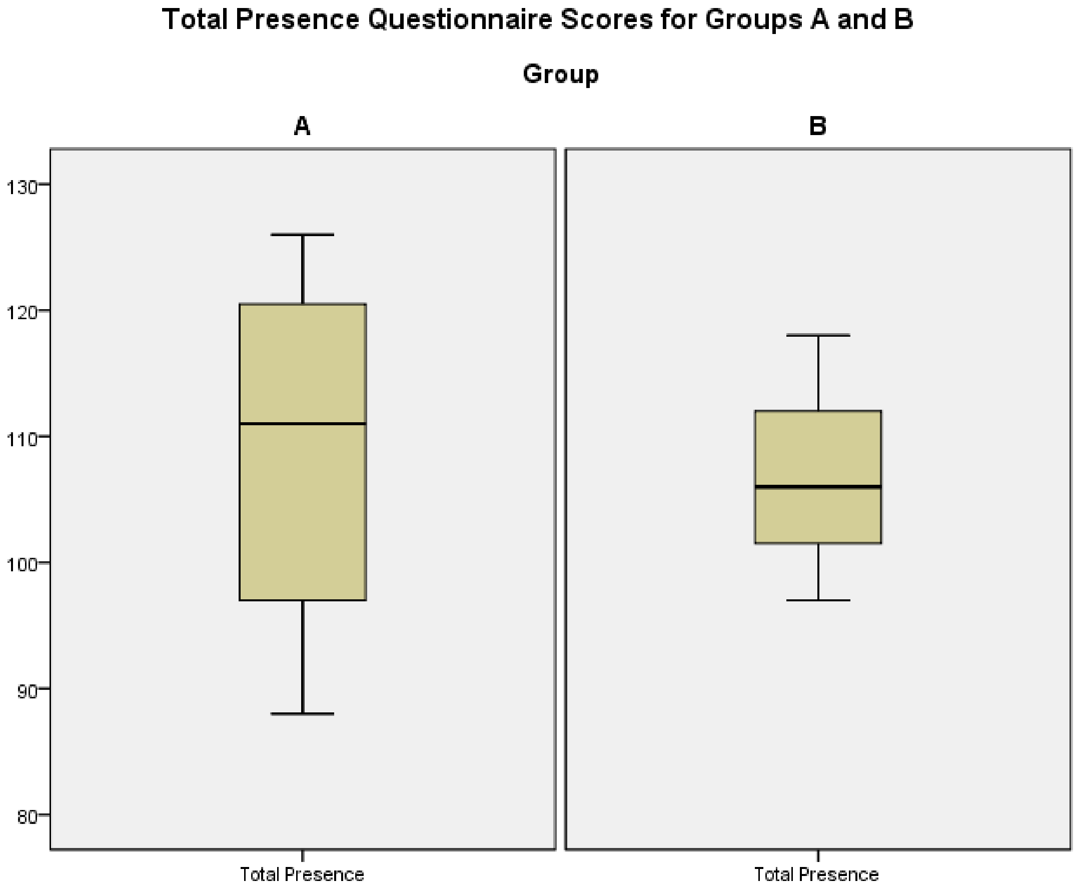


Figure 5.2: Presence Questionnaire totals for groups A and B.

again, the difference between participant responses for presence questionnaire were analysed using the non-parametric Mann-Whitney U test due to the ordinal nature of the data and the unrelated participant population. Statistically, there was virtually no recorded difference in presence, $U(N_{Control} = 19, N_{Feedback} = 19) = 173.00, z = -0.219, p = 0.826$.

5.3 Discussion

The primary aim of this study was to examine the effects of somatic feedback on reported simulator sickness, and reported sense of presence. Despite results not being significant, there is still a lot to take from the study, not only from a theoretical point of view, but also insights for this projects future studies.

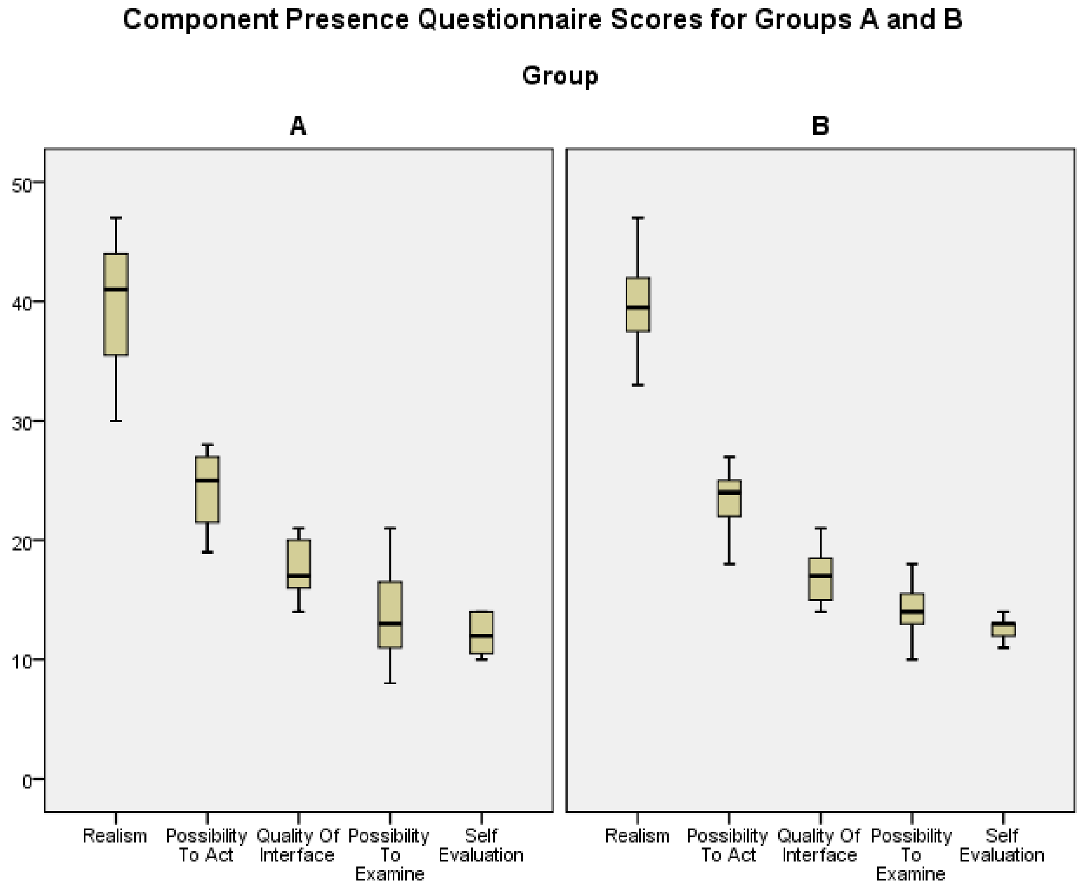


Figure 5.3: Presence Questionnaire component values for groups A and B.

Regarding the SSQ results, a slight observed reduction in reported SSQ means there's still reason to believe that a more effective solution may hold a greater and potentially more significant effect. To assess the areas of improvement, it is largely dependent on verbal feedback from participants as well as observations made by researchers. For example, several users in group B said they did not, or hardly felt the airflow of the fans, meaning they underwent comparable conditions to those of group A, a possible explanation for the marginal overall difference. Upon investigation, one possible explanation for the lack of sensation originates from the positioning of the fans, and their specifications. One example of this is where a user sits very far back with respect to the control equipment with arms outstretched, rather than keeping their torso fairly close to the control mechanism like anticipated. As seen in Figure 5.3, a user who positions themselves further back avoids the majority of lateral feedback and also experiences a diminished level of feedback from the front facing fans. The low degree of difference undergone by participants could be a contributing factor in the shallow difference in results between groups.

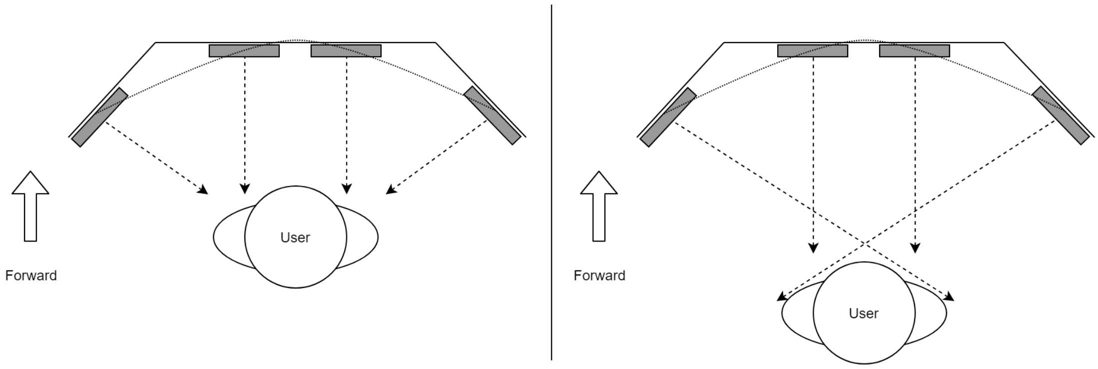


Figure 5.4: A diagram showing the difference in feedback based on the distance from the hardware extension.

During the experiment participants were observed as a means to detect and prevent a strong degree of cybersickness, however additional observations combined with verbal feedback can potentially explain the findings. Looking further at the efficacy of the fan system, observations such as static hair movement, combined with verbal reports, suggest the fans are too low powered for the speed that participants were travelling in the virtual environment, which, when considered with respect to the sensory conflict theory poses some interesting thoughts. Firstly, the inaccurate and unrealistic feedback could have a negative influence on cybersickness adding further confusion to the combination of sensory feedback sources, increasing sickness symptoms. Then following on from this, as results did not show an increase in reported sickness for group B despite the verbally reported inaccuracy, the validity and/or applicability of the sensory conflict theory comes into question.

To counteract the issue of inaccurate and low powered feedback, the solution is to increase the scale of the sensory feedback. Primarily, the power of the extensions fans should be increased to better match reality when moving at the speeds users are traversing the virtual environment. An added bonus is the reduction of distance-based diminished sensory feedback originating from participants being more comfortable further away from the control mechanisms in place. Greater power means the feedback will still be effective and detectable among these select users. To further amend the issue of participants not noticing the airflow, the surface area of the airflow source can be increased to improve the coverage.

This will accommodate an increased variety of participant builds and positions, preventing the issues the more precise CPU fans encountered.

The comments of participants and observations made regarding ineffective airflow can also be connected to the results found when examining presence. Even though presence is a secondary focus of the project, there is still an expectation to see some change between condition groups, partially due to the mixed correlations in reports from previous studies when examining the relationship between cybersickness and presence, but also due to previous findings regarding sensory feedback and presence. Hence, the justification for no difference in presence suggests the two conditions are too similar. As the relationship with cybersickness has seen both positive and negative correlations, some variation between the two conditions is expected.

As a large portion of this study was experimental, with variables and experiences that would have an uncertain effect on participants, various precautions were taken as cautionary response. One positive thing to come from the study was the overall sickness severity across both conditions (mean < 5), which, when compared to existing categorisations (See Table 5.1), was at a low level (Kennedy et al., 2003), affirming all the processes taken to control sickness to a morally and ethically assuring level. This suggests that the degree of cyberickness participants would face was overestimated somewhat, meaning that some less precarious, however more effective measurement methods may be included in the future without the risk of reaching significant levels of severity.

Table 5.1: Categorization of military simulators based on central tendency of total SSQ scores (Kennedy et al., 2003).

SSQ SCORE	**CATEGORIZATION**
0	No Symptoms
<5	Negligible symptoms
5-10	Minimal symptoms
10-15	Significant symptoms
15-20	Symptoms are a concern
>20	A problem simulator

The low mean SSQ scores, and low drop out rate across both study groups suggests that future methodology structure can be altered to improve the comparison technique without causing major concerns about the side effects participants may experience. Namely, removing the variability in each groups participant base by shifting to a comparative methodology where each participant is exposed to both conditions would eliminate significant balance issues introduced through the range of human factors that surround the field of VR usability. While multiple exposures introduce issues with repeated exposure and adaptation findings, having both conditions in a single session will mostly counteract these. This will be covered in greater depth when considering the methodology of the projects second study.

5.4 Summary

Overall, this study provided a great deal of insight into a more efficient feedback strategy and the levels of cybersickness to expect from the existing study apparatus and application. The knowledge gained from the experimental nature of the study will allow for subsequent studies to benefit from improved methodology and improved use of equipment. Conclusions can be drawn from this study however feedback and observations made during the study suggest that the main research hypotheses were not effectively addressed due to shortcomings in the implementation and methodology of this study. As such, an additional study is required with a more confident method.

The key points this study highlighted, and their utilisation are as follows:

- There was an overestimation of the severity of cybersickness participants would experience, and consequently the study employed less effective, more cautious measurement strategies to compensate and increase cybersickness prevention. These precautions have been proven excessive such that the subsequent studies can use a different, more measurement focused methodology to get a better understanding of the effects of somatic feedback and more conclusive results.

- Secondly, the levels of feedback proved underwhelming in group B, to the point where results between groups tended to be extremely similar. As such, for improved investigation, sensory feedback needs to be amplified to the point where it is unavoidable, creating sensory agreement in the visual and proprioceptive senses. While there is a low likelihood this will aggravate cybersickness, the added assurance that the system is a low risk implementation means that should results show a positive correlation with feedback, it will remain usable.
- The system overall was successful in the sense that participants engaged well with the system, there was no issues regarding the usability, or any confusion about the process as a whole. Conceptually, any future studies or implementations involving the system will require minimal change.
- Outside of the issues regarding the comparison structure of the study, the process, task and measurement strategies were largely successful. Verbal reports have made it clear however, that the project would benefit from qualitative feedback regarding the system, to identify the best and worst of each condition. The introduction of verbal reports also furthers the argument for a side by side comparison method to be applied in the future, as qualitative data can provide details regarding the difference between conditions beyond just numeric scores for cybersickness and presence.

Chapter 6

Design and Implementation: Enhancing sensory feedback

The main changes that need to be made to the system and apparatus before conducting a second study are those regarding the degree of feedback the equipment can emulate. As noted in the previous chapter, it was observed that it is necessary to improve the power and coverage of sensory feedback, making it unavoidable even for unusually positioned drivers, and guaranteed to be detectable by any user. Additionally, methodology changes have to considered, as previous findings have warned of the consequences of repeat exposures within the same session, meaning compromises or changes may have to be made within the application to mitigate cybersickness, rather than accounting for it via the study structure, as was done first time. With this in mind, the design and implementation process for this study goes as follows:

1. Replace or enhance the somatic feedback extension to meet the aforementioned requirements
2. If needed, modify the virtual environment to align with the feedback, such that there is fidelity between the real and virtual environments
3. Test for two consecutive exposures as per the planned methodology, if issues are encountered, implement in-environment mitigation strategies.

6.1 Somatic feedback changes

The solution to improving coverage and power is fairly simple, however retaining the degree of control offered by the f14 Arctic case fans requires a change to the hardware responsible for governing speed. To begin with a fan with increased size and airflow potential is required, which in turn requires a larger power supply and the space to accommodate the new hardware. A 15 inch diameter fan (See Fig 6.3), powered by a 230V mains supply was deemed suitable to replace the dual forward facing case fans. The size however makes it unsuitable for mounting on the existing aluminium scaffolding, and instead it was mounted on its own stand. It quickly became apparent that the remaining lateral facing case fans were redundant due to the outmatching specifications of the central fan overwhelming their effects. The subsequent choice was to remove them or replace them with equally capable fans. Replacing them was not practical - the newer fan was mounted on a floor stand, too large for the desk, as such the desk would obstruct the position of the lateral fans should they be replaced. A lack of lateral airflow is somewhat counteracted by the broader coverage the larger fan provides, providing airflow to the entire forward arc of the user (A seen in Fig 6.1).

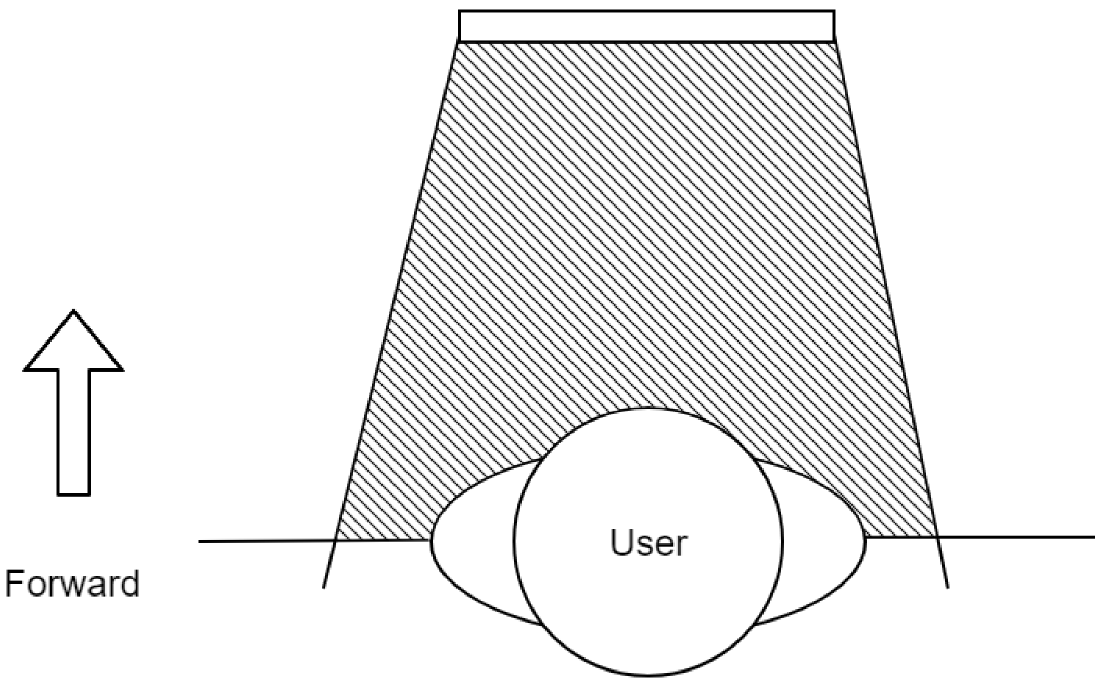


Figure 6.1: Study 2 Feedback Region: The increased diameter and power than the complete forward arc of a user is exposed the sensory feedback

Replacing the model of fan means it can no longer be controlled via PWM signal, meaning revisions to the control strategy are necessary. Initially, considerations were made to manipulate the fans built in control system, however the restricted variability quickly ruled out the option. Instead, the concept of controlling the level of power the fan uses was explored. To do this a dial operated variable power controller was implemented, allowing for control over the amount of power the fan receives and consequently its RPM and airflow. The dial itself was then attached via 5V servo to the Ardunio Mega R3 micro controller (See Fig 6.2 for the complete wiring diagram), which required a revised version of the previous control firmware. The firmware was set up to process four values received from the Unity application, however since reducing the number of operational fans, the Unity output was adjusted to only be the value for the forward facing component of the previous system. The board itself largely kept the same functionality, however passed the output signal to a servo rather than directly to the fan, the servo would then interact with the variable power dial, and consequently with the speed and power of the single fan. The output was adjusted slightly to be compatible with the servo, with the maximum value received from Unity correlating to the dial being turned to the greatest value (when the mains current is not dampened at all). Some testing revealed that switching off the fan during periods of immobility within the virtual environment was not viable, as the time taken to build the fans RPM was causing significant latency in the system when accelerating from stationary during the experience. To combat the issue, the firmware was modified so that rather than stopping the fan, a new "idle state" was established where the dial would allow an amount of power through capable of rotating the blades, without generating tangible airflow. This means that the fan is "on" constantly, however only in effect while the user is moving within the environment. This largely removed any latency during acceleration from the system.

The overall outcome of the change was a simplified iteration of the system, however it held more potential, with the ability to significantly influence a user experience and ultimately assure the uncertainty of the systems efficacy encountered in the prior study is not incurred again. One downside to the new iteration of feedback support was the lack of lateral support, and while its far from a requirement, the virtual locomotion strategy was altered to match this.

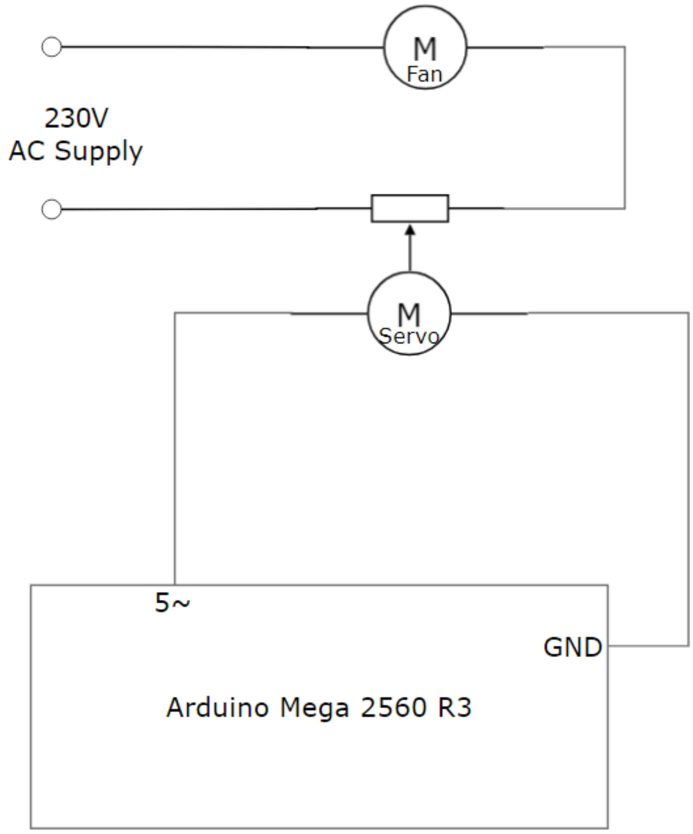


Figure 6.2: Study 2 Combined Wiring System: The signal from the Arduino microcontroller govern the orientation of the servo, which governs the power of the fan via variable resistor.

6.2 In-Environment Changes

While no issues were reported or observed with regards to the virtual environment, improvements can always be made to improve the quality of the user experience, which is already being strained by the negative side effects of VR. Additionally, the method of locomotion can be adjusted to better align with the sensory feedback, improving fidelity between virtual and physical environments.

Firstly, by considering the changes made to the feedback system, the parameters of the user controlled vehicle can be adjusted to remove any expectation of lateral movement feedback. Removing lateral movement entirely would be excessive and immersion damaging, instead, the aim is to reduce the frequency and scale of lateral movement. In this case, it is possible adjust the sideways friction component of the wheels, which contain the values for generating a two-piece

Figure 6.3: Study 2 Feedback Implementation: Visually unimpressive however gives a significant amount of feedback with noticeable variance based on virtual locomotion speed

spline curve governing what force correlates to what degree of tire slip. The stiffness value is a multiplier for the extrenum and asymptote values, such that setting it to zero disables friction from the wheels. For this variation of the study, a stiffness value 1.5 times larger than the original is used, resulting in 1.5x more lateral force being required before the tires begin to slip sideways, and consequently reducing the frequency and extremity of lateral movement in the environment (See Fig 6.4 for the complete Unity Wheel customisation available).

Besides this, the only other in-environment changes were performance centred, namely, the frequency with which data was transferred to the Arduino micro controller and attached components. Originally, data was passed every four update cycles however it can be made more infrequent to improve performance without changing the latency of the overall system. This can be done due to the time delay of the micro controller processing the command combined with the

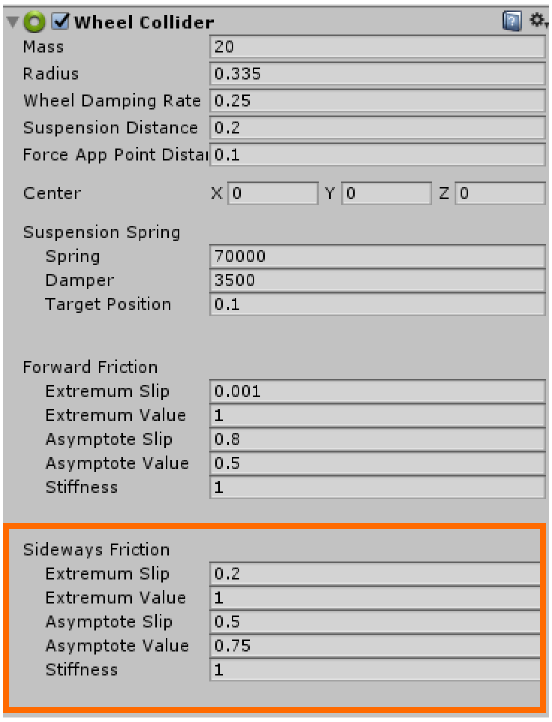


Figure 6.4: Unity's wheel collider offers a number of parameters to manage the behaviour of attached vehicles

microseconds of build up in the controlling servos motor. As such the data output frequency is decreased to once every 40 frames, which is equivalent to about 3 times per second with the system operating at 120FPS.

6.3 Summary

The primary changes made are regarding the fan configuration, where a single feedback source covering a greater area has been substituted in for the weaker, angular sources, in order to provide a more environmental sensation. In addition to the area, the difference in output is massively increased, making the feedback unavoidable during locomotion within the VE and also more potent, which is required at the greater virtual speeds. Outside of this, few changes were made to the system. Issues highlighted in the previous study were addressed and implemented along with a few quality of life changes to make the study as user friendly as the investigated topic permits. The most significant changes between this study and the former are methodological, which will be examined in the next chapter.

Chapter 7

Refining our Methodology

A major reason for reusing a large number of components from the first study is due to the issues highlighted stemming from key methodological decisions. These include the lack of difference between conditions (which has been addressed through design alterations), low population groups and the variety of human factors that can not be screened for, but hold influence on cybersickness outcomes. The side effects of methodology changes need to be considered, with regard to the participant well being during the study. Furthermore, the value of qualitative feedback was underestimated in the previous study, which this study aims to address and benefit from.

7.1 Experiment Strategy

A major limitation encountered in the previous study was the cautious experiment strategy used due to the uncertainty surrounding the severity of the side effects participants could experience as a consequence of using VR. Because of this, participants were exposed for the minimal amount of time, without repeat exposures. Groups were also selected as participants cannot undergo VR adaptation, where repeated exposure nullifies the severity of sickness, and similarly the AB group strategy avoids the increased cybersickness seen in short-term repeated or prolonged exposure. These effects hold strong implications when measuring for cybersickness across multiple conditions, as well as ongoing moral considerations. The overwhelming drawbacks of the AB group methodology encountered in the previous study largely correspond to the difficulty to draw meaningful results without a large participant population or extreme measured outcomes.

The knowledge and experience gained from the prior study suggests that a change to a direct comparison methodology will yield more conclusive results, however carries a greater risk to participants comfort, but less than anticipated at the start of the project. From this reasoning, a side-by-side comparison of both conditions was selected for this study, where participants are exposed to the system, with and without feedback, reporting on each. The prime benefit from this strategy is removing variability from the participant base, ensuring that both conditions have equally susceptible (or not) participants, with the intention of obtaining conclusive and statistically significant results. This accounts for variable human factors that can give rise to cybersickness, such as age, gender, previous VR experience, and other contributing aspects that previously caused between conditions.

It is essential to acknowledge and mitigate, where possible, the drawbacks of using a comparison methodology for a cybersickness investigation. The main problems branch from exposing a participant twice in a single session, as a participant could still be experiencing cybersickness symptoms before exposure, or be influenced by pre-existing opinions gained from their first exposure. There are two potential routes to be taken when assessing the appropriate procedure for this issue. Firstly, one option is to leave a significant amount of time (at least a day) before re-exposing a participant, allowing them to fully recover, permitting them to undergo the second exposure with the same baseline cybersickness. While this is perhaps the safest option in terms of avoiding severe levels of sickness, previous findings suggest that a delay of this duration would be enough for adaptation to occur, meaning a participant would be more resistant to cybersickness during a second VR experience. Additionally, this plan could cause logistical issues, and would likely see a significant increase in participant drop-out numbers descending from a reluctance to return to undergo unpleasant conditions again. The other option, which was ultimately selected for this study, was to expose participants to both conditions in the same session, which while morally risky, seems more prevalent in previous studies. It works on the logic that it prevents adaptation but employs a short break between conditions to avoid the effects of prolonged exposure. By separating participant exposures with a brief break that includes a short walk, any sense of vection a participant maintains from the virtual environment can be broken before second exposure. Furthermore, by alternating the condition exposure order between participants any consequence that may stem from a particular scenario can will be balanced across conditions. The process itself used is covered more in the *Procedure* section of this chapter.

To summarise, this study is going to use a direct comparison strategy, where participants experience both conditions that are being measured. While this method has slightly more risk that the previous iteration, it is more likely to have conclusive results as a result of the equal participant base and analysis methods that can consequently be applied. The increased risk is addressed in the following sections of the chapter.

7.2 Participants

The study begun with 40 participants who passed the screening procedure. Participants were assigned a beginning condition, with a 20-20 split of which condition was applied first. Of the 40 volunteering participants, 38 completed the study, 29 males and 9 females. Two participants chose not to complete the study after experiencing overwhelming sickness symptoms in their first exposure, both are male. The participant base had an age range of 19 to 28 (mean = 22.18, median = 22). All participants were volunteers sourced from the University of Lincoln, and were undergraduate or postgraduate students. There was no additional incentive included with the study. Participants in this age range were chosen once more for the cybersickness tolerance seen in the previous study and consequently the high rate of completion and ethical compliance.

7.3 Task

The task assigned to participants consists of two VR exposures, separated with data completion and a short break. For each exposure, participants wear the Oculus VR headset and are placed into the virtual environment in the drivers seat of a vehicle, where they are asked to drive around the environment following large green way-point marks. Participants drive for five minutes, twice for a total of ten minutes across both conditions. Participants are informed at the start of the study that their task performance is not being assessed in a competitive sense and that they should drive in a manner they are comfortable with.

7.4 Apparatus

The system once again uses the Oculus Rift consumer version 1 virtual reality headset with integrated headphones and the Trust GXT 570 wheel and pedals as a control mechanism, with the same specification and calibration as seen in the previous study Section 4.5 .

The feedback system uses a single desk fan with a 15" diameter head as the source of airflow, mounted on a stand at height slightly above the steering wheel control mechanism, positioned directly in front of the participants searing, approximately 1.5 metres away from them. This is then controlled with an Arduino Mega 2560 R3 micro-controller, running firmware responsible for translating information from the virtual environment to appropriate behaviour for the feedback system. The feedback system, control mechanisms are all connected to a high specification PC. The PC is comprised of an Nvidia 1060 6GB graphics card, an Intel Core i7-4770 3.40GHz CPU and 16GB of internal RAM.

7.5 Procedure

This experiment was approved by, the University of Lincoln Computer Science Ethics Committee. The consent, information and screening process remained the same as the previous study, as seen in Section 4.6.

Participants also filled out a brief form ascertaining some basic information, their age, sex, and previous VR experience, allowing for the assessment of the participant demographic and for potential examination of correlations between participant information, and measured values. Each participant was then assigned a first condition to experience, which alternates between participants such that an equal number start with each condition. Alternating starting conditions were chosen over random assignment due to the possibility of VR habituation creating a confounding variable, as participants may adapt to the virtual environment. As such, counterbalancing the task order eliminates the possibility of an uneven distribution of starting conditions artificially inflating measurements due to VR habituation. Prior to the reception of participants, the experiment room had its temperature set to 21°C, reducing potential bias for the feedback group, based on the weather. Participants were then seated in front of the equipment where they were provided with instructions about the task, as well as a brief explanation of the control scheme. Once it was clear participants understood the task, they were equipped with the Oculus HMD, the researcher would then enable the feedback system if the participant was undergoing that condition. The time taken for the feedback system to reach "resting" speed took place while the participant familiarised themselves with the environment.

Participants would then complete the experiment task, being stopped after five minutes. Participants would then immediately be asked to complete the SSQ, followed by the Presence Questionnaire. Before repeating the process with the the second condition, participants were offered water and were asked to calmly walk around the experiment room, as a means to erase existing vection before re-entering the environment, as well as to aid in the recovery process. After the second exposure, participants would once again complete the SSQ and Presence Questionnaires and then were asked to participate in a recorded short interview with questions pertaining to both experiences while also being offered light refreshments. Once the interview was concluded, and it was assured that a participant had recovered or was recovering, the experiment was concluded. Average exposure time totalled approximately fifteen minutes, including calibration, brief and trial time. The entire experiment took about forty minutes to an hour varying based on the nature of the participant.

Qualitative questionnaires were administered on paper, and were only identifiable by a participant identification number that was given to each participant at the start of the study, allowing for identification of their data should they wish to withdraw. All forms relating to the study are kept in a secure filing cabinet, with consent documents kept in a separate compartment from user data. When digitised, any data was kept in a password protected folder, on password protected machines. Interviews were recorded via dictaphone, and were transferred to a password protected folder on a PC immediately after the study was completed, then deleted from the dictaphone. Later, these recordings are transcribed for thematic analysis, where transcriptions are kept in a secure password protected folder, the audio recording is then deleted permanently.

7.6 Quantitative Measurements

As the overall aims have changed very little since the last study, the SSQ (see Appendix A.2) was once again used to assess any negative side effects participants experienced during exposures. Participants completed a copy of the questionnaire immediately after each exposure, before any symptoms can dissipate. These can then be compared against one another to look for any differences between conditions.

Similarly, by looking to re-examine the Presence of the system in both conditions, this thesis can contribute to the ongoing discussion regarding the relationship between Presence and cybersickness. As seen in the previous study, the revised edition of the Witmer and Singer Presence Questionnaire was administered after each exposure as a means to gauge engagement and immersion (see Appendix A.1).

For more details regarding the application and measurement of either the SSQ or the Presence Questionnaire see section Section 4.7.

Using these two measurements the study aims to gain numerical data relating to cybersickness as well as presence, with the goal of answering this projects research hypotheses. Using this data, comparisons between the two conditions can be made to examine for any changes that occur from the systems feedback being altered.

7.7 Qualitative Measurements

From observations made from in the first study, the value of participant opinions had initially been vastly underestimated, and with the change to comparative methodology, semi-structured interviews were included to improve the understanding of the system and potentially find justification for any findings. Semi-structured were chosen over a rigid structure to accommodate the range of uncertainties and human factors present, such that accounting for and exploring every possibility in a rigid structure is near impossible. Questions selected were fairly open, and were articulated in a fashion that would not intimidate or confuse participants with technical language surrounding the topic. The intention of these questions is to understand the low-level opinions and sensations of participants which can then be attributed to, and justified by existing research. The questions covered aspects of both cybersickness and presence but used more recognisable terminology to make questions easily understandable. In addition, generic questions regarding the study process as a whole were included to improve future understanding when measuring cybersickness via utilization of VR.

As such, the questions included are as follows:

- Did you enjoy the experience?
  - Any aspect in particular?
  - Was there any preference for either condition?
- Do you feel VR is a good platform for this type of experience?
- Did you feel comfortable when playing the game?
  - Was there any difference in comfort between sessions?
  - How could this be improved?
- Did you have any other issues when playing the game during either session?
- Would you make any changes to improve immersion or reduce discomfort?
- Any other comments or feedback about either session?
- Are you feeling better since completing the experience?

With data gathered using the interviews thematic analysis can then be carried out to ascertain recurring components relating to measured values. These components can then be linked to existing research to aid in the reasoning behind this projects findings that may have otherwise been unexplained or unaccounted for.

7.8 Risks Mitigation

The risks and concerns of this study are largely the same as the previous study (see Section 4.8). With only a single drop-out due to cybersickness in the first study it can be argued that the combination of a screening process and thorough calibration for each individual participant is an effective method to avoid the risk of creating instances of highly susceptible users. There was no noticeable changes required to either of these areas.

The primary change in the risks associated with the study comes from doubling the total exposure time of participants. The necessity of the change has been covered throughout the chapter so far, however the change does warrant some adjustments to the recovery process, to avoid severe or prolonged negative effects for participants. The first study had a short recovery process towards the end of the experience to ensure participants were feeling healthy before being debriefed, however as this study has two exposures, it was deemed best to hold a short recovery period between exposures in addition to one when concluding the study. The intermediate recovery phase is primarily to reduce the likelihood of high sickness severity outcomes following the second exposure. It does this in two ways, firstly, by consuming water and having a short break the user will begin the recovery process, likely eliminating any minor symptoms and reducing severity in any other symptoms. Secondly, participants are asked to spend a short time walking around the experiment area, this is to remove any feeling a self-motion they may still be experiencing from the exposure. Exposing a participant while they undergo vection is a fairly significant concern, as cybersickness has been linked to the quality of establishing vection, such that creating conflicting senses of self motion could have severe sickness implications as a consequence of sensory misinformation.

7.9 Study Hypothesis

The hypothesis is for this study is largely the same as the original study, due to the similarities in system and measurements. It is still expected to only see significant changes in the nausea component of sickness, as the previous study trended towards this, despite not being significant. Presence did not seem to be altered by the feedback condition during the first study, however this is arguably attributed to the poor system set-up, and still hold the original expectations. Major increases in the Realism category with a likelihood of increase in Quality of Interface and Self-Evaluation categories are still predicted. Based on existing research it is not expected to see changes in the Possibility to Act and Possibility to Examine subcategories between conditions.

7.10 Summary

This chapter largely covers the changes that had to be made as a consequence of updating the choice of experiment strategy, as the task and apparatus used remains functionally the same. The first study highlighted the requirement of a related participant base for each condition due to the massive variation between participants with regards to human factors, even with mitigation in place. This chapter discusses the pros and cons of the change to a direct comparison strategy. While the benefits of the change outweigh the issues it creates, it is important to address the concerns, especially due to the moral and ethical implications this topic has to consider. Using background research alongside the experience from the previous study, prevention and mitigation options are largely covered in order to maximize the benefits of the direct comparison strategy. The change of approach allows for more conclusive results as a consequence of each participant being exposed to both conditions, allowing for the utilization of related population appraisal methods and the elimination of variability descending from an imbalance human factors between conditions.

The next chapter looks at the results from this study, and discusses the findings, significance, and changes that can be made to the system for future studies.

Chapter 8

Study Results

This section will analyse the results of the second study by examining the reported simulator sickness and presence among the population of the two groups to gain an understanding of the efficacy of this experiment with regards to the project hypotheses. The appraisal carried out in this section will examine for any differences between conditions undergone by participants with regard to the their measured scores. By carrying out statistical analyses on this data it can be determined whether the main hypothesis of the project is valid, as well as the efficacy of the feedback extension on given factors. Justification for any findings can then be derived via thematic analysis of obtained interview data, as the numerical results themselves provide only limited depth.

8.1 Scoring the SSQ

The SSQ consists of 16 items listing virtual reality side effects rated from “0” (none) to “3” (severe). A revised and validated version of the questionnaire was used in this study, that narrows the examined sub-scales from three to two.

The total mean SSQ for condition A (without airflow) is 5.45 (s.d. = 7.008, range between 0 and 36), and 3.24 (s.d. = 3.405, range between 0 and 15) for condition B (with airflow support). The difference in post exposure responses to the SSQ for both the experimental and control conditions were analysed using the non-parametric Wilcoxon Signed Ranks Test due to the the ordinal nature of SSQ data and the related participant population. Participants reported that

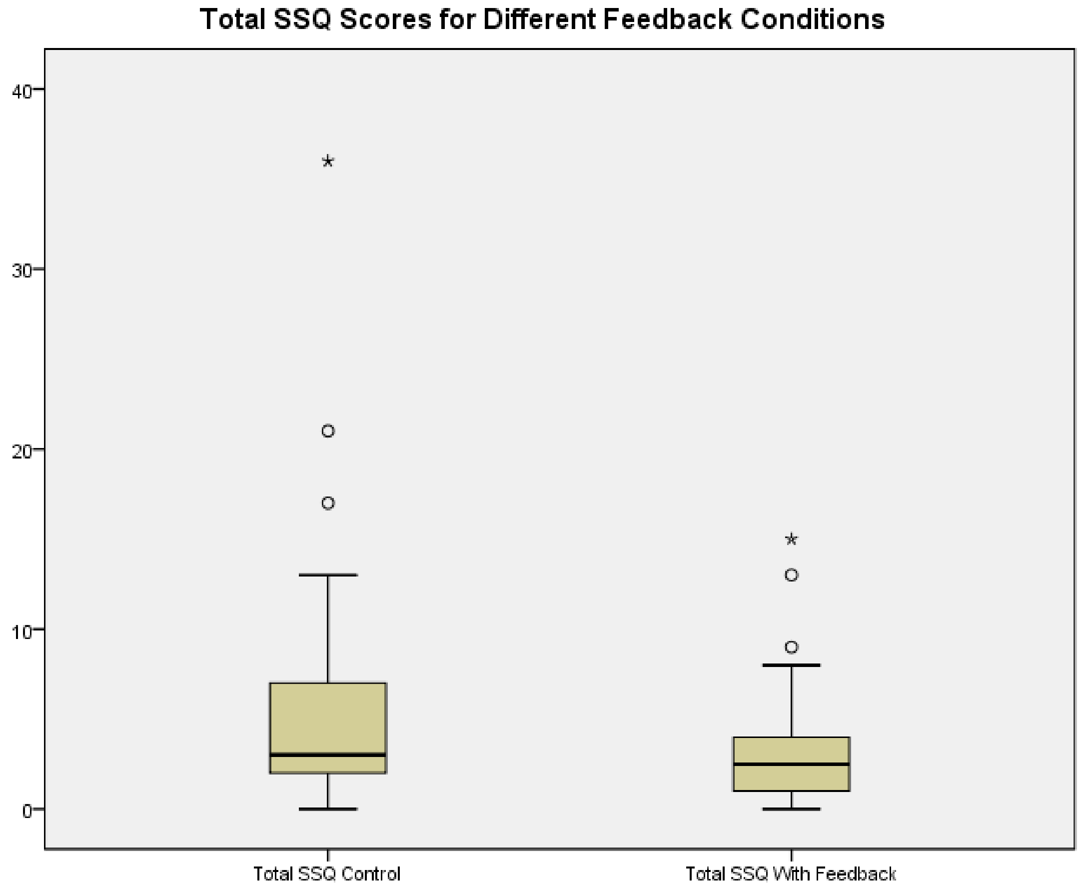


Figure 8.1: Simulator Sickness Questionnaire totals for the comparison of both feedback conditions.

the condition with airflow feedback (mean = 3.24, median = 2.50) caused less simulator sickness than the control condition (mean = 5.45, median = 3.00). A Wilcoxon Signed Rank Test indicates that this difference is statistically significant, $T = 357.50, z = -3.058, p = .002, p < .05$. The statistical averages and significance tests for each scoring sub-scale as well as each individual cybersickness symptom can be found in Table 8.1.

Table 8.1: Recorded mean and statistical test for each symptom of the SSQ as well as the nausea and oculomotor scoring sub-scales and total.

Symptom/ Category	Mean Without Feedback	Mean With Feedback	Statistical Testing
General Discomfort	.74	.45	T = 91.00, z = -2.668, p = .008, p <.05
Fatigue	.18	.13	T = 7.50, z = -1.000, p = .317
Headache	.18	.11	T = 6.00, z = -1.732, p = .083
Eye Strain	.47	.29	T = 108.00, z = -1.698, p = .090
Difficulty Focusing	.32	.24	T = 30.00, z = -1.000, p = .317
Salivation	.37	.39	T = 10.50, z = -.632, p = .527
Sweating	.71	.37	T = 62.00, z = -2.667, p = .08, p <.05
Nausea	.53	.26	T = 33.00, z = -2.157, p = .031, p <.05
Difficulty Concentrating	.18	.03	T = 6.00, z = -1.604, p = .109
Fullness of the Head	.32	.13	T = 24.50, z = -1.897, p = .058
Blurred Vision	.18	.08	T = 12.50, z = -1.414, p = .157
Dizziness With Eyes Open	.32	.13	T = 45.00, z = -1.941, p = .052
Dizziness With Eyes Closed	.29	.18	T = 15.00, z = -.957, p = .339
Vertigo	.13	.11	T = 9.00, z = -.447, p = .655
Stomach Awareness	.45	.32	T = 40.00, z = -1.387, p = .166
Burping	.08	.03	T = 4.50, z = -.816, p = .414
Total Nausea	3.61	2.24	T = 255.00, z = -2.523, p = .012, p <.05
Total Oculomotor	1.84	1.00	T = 170.00, z = -2.461, p = .014, p <.05
Total SSQ	5.45	3.34	T = 357.50, z = -3.058, p = .002, p <.05

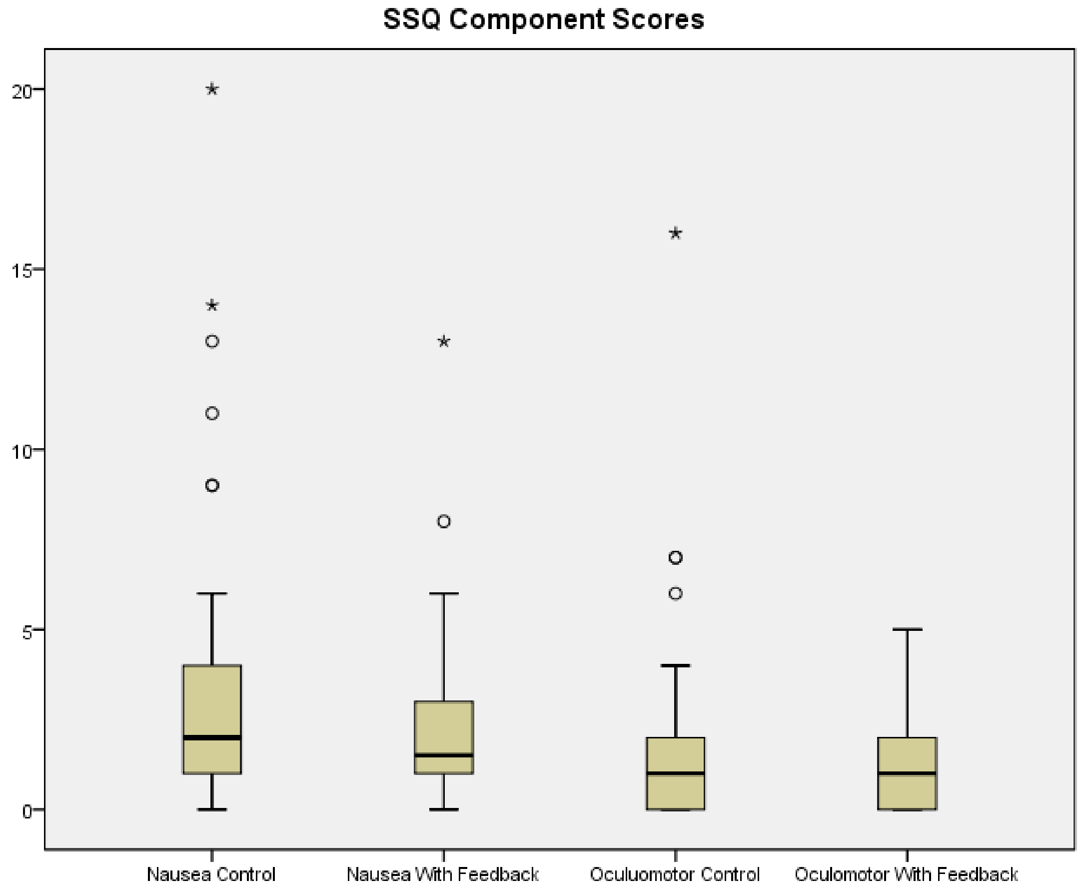


Figure 8.2: Simulator Sickness Questionnaire component totals for the comparison of both feedback conditions.

8.2 Scoring Presence

The presence questionnaire consists of 19 items which can each be correlated to different sub-scales of presence. Each item uses a 7 point likert scale to determine a users reported sense of presence with regard to a question. A revised and validated version was used that correlates each item to a sub-scale of realism, possibility to act, quality of interface, possibility to examine and self-evaluation of performance.

The total mean presence score for the control condition is 99.47 (s.d. = 13.01, range between 69 and 123), and 106.34 (s.d. = 11.49, range between 84 and 127) for the feedback supported condition. Once again, the difference between participant responses for presence questionnaire were analysed using the Wilcoxon Signed Ranks Test due to the ordinal nature of the data and the related participant population. Statistically, this test indicates that the results are statically significant $T = 658.50, z = -4.637, p = .000004, p < .05$. The statistical averages and significance tests for each presence scoring sub-scale can be seen below, and found in Table 8.2.

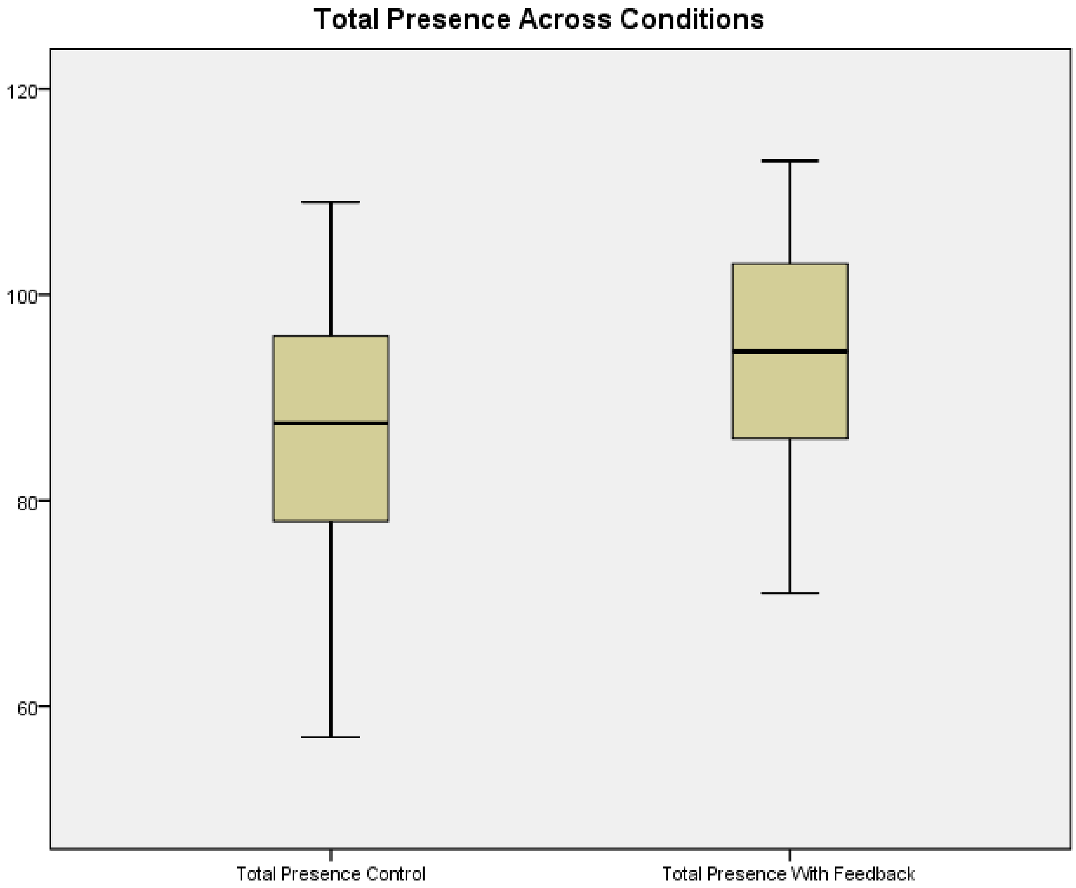


Figure 8.3: Presence Questionnaire totals for the comparison of both feedback conditions.

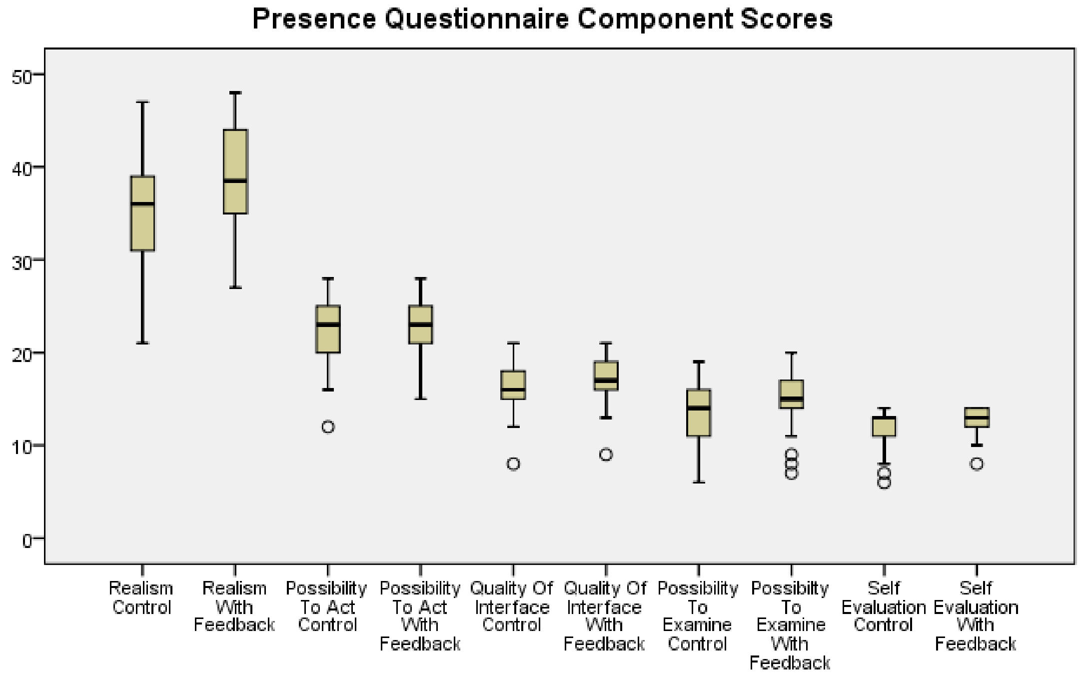


Figure 8.4: Presence Questionnaire sub-scale totals for the comparison of both feedback conditions.

Table 8.2: Recorded mean and statistical test for each sub-scale of the presence questionnaire.

Category	**Mean Without Feedback**	**Mean With Feedback**	**Statistical Testing**
Realism	35.53	38.89	T = 570.50, z = -4,199, p = .000027, p <.05
Possibility To Act	22.37	23.02	T = 284.50, z = -1.877, p = .061
Quality of Interface	16.21	17.21	T = 326.50, z = -3.353, p = .001, p <.05
Possibility To Examine	13.45	14.68	T = 374.00, z = -3.430, p = .001, p <.05
Self Evaluation	11.92	12.53	T = 225.00, z = 2.180, p = .029, p <.05

8.3 Correlation

To address existing research disputes regarding the nature of the relationship between cybersickness and presence (Witmer and Singer, 1998; Slater, 1999; Nichols, Haldane and Wilson, 2000), Spearman's rho correlation coefficient was used with the data from this study to contribute to the discussion. Due to the the uncertainty of the correlation and distribution between the two measurements, a 2-tailed significance test was used. Results show no significant correlation between the two, $r_s = -.191, p = 0.099, N = 76$.

8.4 Thematic Analysis

This section will cover which themes were identified as well as a brief definition for each, each themes relationship to quantitative data is covered in the Discussion Section 8.5.

8.4.1 Analysis Method

In order to appraise the verbal feedback of interviews, once transcribed, a Thematic Analysis was undertaken, following a deductive approach as laid out by Braun and Clarke (Braun and Clarke, 2006). Following the steps they provide, the first stage involved gaining a complete understanding of the data as a whole and beginning to construct ideas for patterns and reoccurring or decisive topics that could be developed upon. This began during the transcription process where the data has the most emotional inflection, providing a clear meaning to the statements which was conveyed in transcriptions where possible. Following this, all transcriptions were reread, cementing a number of unrefined areas that could be starting points for codes.

With a certain understanding of the complete data set, individual interview transcriptions were analysed for components of particular interest with respect to research hypotheses. Statements relevant to the research hypotheses of this project were extrapolated in a deductive manner and used assigned to codes effectively summarising the key point of the statement. Codes were generated in a theory-driven manner with respect to the projects hypotheses regarding implementation, sickness and presence. While all data was given an equal depth of analysis, particular attention was given to the many contributing factors of cybersickness identified in the Related Work chapter.

Once all the data had been coded and collated, broad themes were develop to encompass the sentiment behind the codes formulated. Related codes were then gathered into families which were enriched using particularly defining codes, and the emotional valence of these families were assessed, providing candidate themes for this analysis. These were then reviewed, eliminating poorly supported or diverse themes, and potentially collapsing themes together if they had significant common factors. The review process included examining extracts for each candidate theme and confirming their validity migrating them to a more relevant theme should the extract have several codes. Any codes that failed to fit candidate themes but were deemed significant were assigned to a "miscellaneous" theme for individual appraisal. With each codes validity assessed, a similar review was done for the candidate themes against the complete data set and research hypotheses. For the most part themes were comprehensive and unique, however, it became apparent that the candidate theme of "Sickness", despite being a primary focus for the project was too generic and was dissolved into "Motion" and "Comfort", as it effectively represents the negative element of each theme. The resultant themes following the review process can be found in the following sub-section.

8.4.2 Themes Identified

The themes identified consist of the following:

Realism - A strong theme identified from the participant base was the value of realism or immersion with respect to a positive experience. Reports elude to a positive correlation between realism and the rate and quality of immersion, as well as a positive correlation between the airflow condition and the fidelity of the virtual experience. "*VR for me is always quite difficult to immerse myself in ... Where as with the fan it actually helped because it kind of set the scene more*" (P151) "*Without the airflow you had that separation between game, and not game. Whilst with the airflow it (the separation) is a little more vague*" (P111). Another aspect of realism encountered was the idea of sensory satisfaction where by users expressed that the airflow condition provided a more complete and hence realistic sensory experience. "*I think driving games naturally lend themselves very well to kind of being immersive in the environment, especially when you have a physical steering wheel and physical pedals in addition to kind of wind coming through – like you're hitting a lot of different senses there at once*" (P412). Realism ties in with the project's examination of Presence as they share the common factor of making a user believe they are in an environment and are undergoing believable sensations appropriate to their actions. This theme supports the idea that it is difficult for a user to believe they are present in an environment if the environment itself and the sensations it provides are not believable. **Motion** - The focus of the study as a whole surrounds the effects of virtual locomotion and its outcomes. This theme looks at participants comments regarding their movement through the environment itself rather than the resulting effects. A fairly common observation voiced by the participant base was the lack of inertia during motion, being described as unnatural, with many suggesting a form of self-motion to be incorporated into the system, for example, a hydraulic chair with multiple axes of rotation. "*I feel like if when you go over the sand dunes or anything, if you were actually moving with the vehicle if it felt like you were tilted it would reduce any of the sickness because your body is doing what your brain is telling you that you're doing*" (P122). "*The next best thing would be to er, you know those moving chairs that work and tilt depending on how you move in the game*"(P252). Some participants attributed negative outcomes to their inexperience or recklessness when driving in the environment, implying a connection with any sickness they experienced. "*I spun out a few times, I went on an angle a few times in both of them which obviously made me feel a bit* *mmph. But that's my fault*" (P332). The components examined by the theme of motion have connections with all the research hypotheses of the project but have a particularly interesting contribution in justifying a link between presence and cybersickness. By looking at the linked extracts from transcripts it becomes noticeable that periods of unbelievable movement can be linked to instances of heightened discomfort. When experiencing Presence within the VE, participants express that they expect particular motion sensations such as inertia or angular motion and the lack thereof causes sickness symptoms.

Comfort - Given the nature of the topic, it is unsurprising that a number of interviewees make constructive points regarding the level of comfort, or lack thereof, that they experienced. The majority of participants experienced cybersickness, however many failed to comment on it in any depth, suggesting a lack of understanding of the cause and effects of the discomfort among inexperienced users. Of those that did comment, the most frequent statements referred to the difference in temperature between the two conditions. Primarily that the basic condition caused sweating where the airflow feedback condition did not, similarly participants commented on the difference in condensation forming on the headset lenses that obscured vision. "*The airflow really helped to prevent steaming up my glasses compared to the first time round*" (P312), "*I think with the fan was definitely better. If not mostly for cooling – err, obviously in the headset it does get quite hot so having the fan was definitely nice*" (P241). Another benefit of the airflow that was reported is less documentable via questionnaire. Several users reported being less hesitant to look around during the airflow, either because they were continuously aware of their forward vector, or because of discomfort they experienced during lateral viewing. "*without the airflow – I found myself having to look forward, like I had to constantly keep focusing on keeping my head looking forward which is basically the same as if I was looking at a screen anyway. So, I couldn't benefit from the use of a headset when the airflow wasn't on because every time I looked sideways I instantly felt sick*" (P171). While rare, some negative effects of the feedback system were reported, which were not anticipated. "*In the session with the fan my salivation increased – I think its because the fan in face was making my throat naturally drier*" (P162). Some additional comfort and sickness factors that appeared infrequently in interviews included recovery time being lower after the airflow condition and enjoyment being independent of sickness. The range cybersickness causes and effects explored in extracts of this theme provide a basis for the justification of the studies objective of learning how somatic feedback could reduce the severity and occurrence of negative symptoms.

Interfacing - Participants did not hesitate on criticizing their ability to use the system, ranging from their opinions on the audio quality and graphical capabilities to physical equipment used for the study. Some of these highlighted areas are not directly relevant to this project, however would none the less be improvements to be considered for the assembly of future applications. The frequency of control scheme issues is a concern, given the relation between cybersickness and loss of control, however complaints were more of an inconvenience rather than suggesting an aggravation of cybersickness. Some comments implied a lack of synchronisation was disorienting, as varying participant heights caused issues when aligning the virtual control scheme to the physical control scheme. "*I think there was a little bit of visual disconnect between the wheel and pedal positions. So like the wheel in the simulation was quite a bit bigger than the one here*" (P171).

Environment - Ultimately the environmental decisions were made to create baseline effect for our hypotheses to explore using different conditions, however the extracts examined by this theme suggest a brief experience alone can make the environmental effects apparent with regards to sickness as well as presence. A number of comments were directed at the virtual and physical environments, and looking at what connects them - the feedback. Firstly, a large number of comments addressed the terrain in the virtual environment, usually in relation to an aggravation of cybersickness, and while this was the intention of an uneven surface, insights about an appropriate severity can appraised. "*If I was playing a driving game I think id want it to have much smoother or flat roads*" (P352), "*The more rocks and stuff I hit where I felt like I should have been moving and I wasn't that just made me feel a bit queasy and uncomfortable*" (P452). Some interesting, more positive effects of experiencing the digital environment is the psychological interaction with the feedback system. Multiple users reported the sensation of the multi-directional airflow based on whether they are turning within the environment, which was not true in this study. "*I was surprised how well,* *like when you're turning and stuff how well it actually felt like the wind was on the left of right. It took me by surprise*" (P332), "*It was almost a pseudo effect, I knew when I was the fan wasn't hitting me on the side but it felt like it was*" (P352). This was not unanimous, with many users suggesting directional feedback as a possible enhancement.

Engagement - Engagement was generally positive among participants, however several recurring elements made it an interesting theme. In most cases, airflow was considered an enhancement to the experience, however a number of participants attributed airflow as a means of information feedback due to its dependency with virtual speed. "*With the fan it felt like I was going round faster because the fan was like - going a lot more high-powered*" (P341), "*It was just an extra added thing to allow you to perceive the events you being shown basically*" (P192). Alternatively some participants saw the airflow as more a distraction, but describe it as a distraction from the negative effects rather than hindrance of engagement. "*It might not even reduce the amount of nausea but the constant physical aspect maybe distracted from the nausea*" (P392), "*Without airflow it felt as if I was focusing more on the game itself*" (P132). A large number of suggestions were directed towards increasing the number of game elements in the experience to make it more engaging, such as the simplicity of the given task. However, as this is not the target of this project's investigation, the study focuses on implicated relationships between other themes and engagement. These included a positive influence from realism and airflow itself. "*I: From an enjoyment perspective did you have any preference between conditions? P: Definite preference for with airflow ... It felt more visceral and more real, which I suppose is the whole point of VR*" (P141). Participants also held mixed comments on discomfort and sickness detracting from the experience as a whole, for example "*I couldn't enjoy it without the airflow*" (P352), "*There was the issue of not feeling quite - your actions aren't having real consequences, like you're turning but you don't have the inertia. But overall it didn't really take me out of immersion*" (P241).

8.4.3 Outlying Codes

Lastly, there is one infrequently appearing, but interesting code that fails to be applicable to any of the determined categories. This is the recurring opinion of using VR driving as a training tool for new drivers, justified primarily by the safety and control the environment has to offer with the immersive nature of the environment. The findings of this research may progress the advancement towards this previously unconsidered contribution.

8.5 Discussion

The goal of this study was to achieve conclusive results regarding the efficacy of somatic feedback on users of VR systems. With significant results found in both SSQ and Presence, the relationship between sensory feedback and the measured areas can begin to be determined. These can be supported with insights gathered via interviews and thematic analysis to improve justification of quantitative findings.

The quantitative findings regarding sickness for the study proved to be significant when looking at the total reported score, as well as for some sub-scales of the SSQ. By assessing the effects of feedback on the symptoms that comprise cybersickness the efficacy of the system as a preventative can be appraised. General comfort was the most significantly changed symptom, however due to its ambiguous classification its hard to draw conclusions from it alone. Besides general discomfort, sweating was the symptom most affected between conditions, and can be easily justified through assumptions and interview responses. The airflow has a cooling effect on users and consequently reduces the bodies need to sweat from the confines of the headset. While it may not hold an effect on sweating as a consequence of cybersickness, it reduces the rate at which users become aware of it. In addition to comfort, several users encountered condensation forming on the HMD lenses, impairing system usability which was reduced or nullified during the feedback enhanced condition. Nausea was another symptom that saw statistically significant reductions with the addition of somatic feedback. Participants did not comment in depth about the reduction in nausea during interview besides simple observation, so an assumption can be made that the feedback is mitigating the cause of the nausea on a physiological level, as hypothesised using existing cybersickness theories.

While not found to be statistically significant, some oculomotor symptoms showed moderate but unexpected changes across conditions. Oculomotor effects such as eye strain and headaches are often attributed to the quality of the HMD used, the visual display characteristics, and the duration of exposure. Consequently, encountering significance scores less than $p = 0.1$ is surprising due to the unchanging nature of the HMD, exposure duration and any display qualities. When examined alongside the statistically significant reduction in total oculomotor scores, this suggests that the cybersickness mitigation strategy this project utilizes may contribute to counteracting hardware induced cybersickness by catering towards overarching cybersickness theories. Sadly, users struggled to contribute to the justification of this outcome during interviews as the physiological change is difficult to explain without knowledge of the field.

The only symptom with an increase in reported severity between conditions was salivation. Interviewees attributed this to the airflow drying their mouths, such that they salivated at an increased rate as a counter-reaction. Vertigo and Burping also have high statistical significance scores, however due to their low baseline frequency and severity this is less concerning to the efficacy of the solution.

While not comprehensive of all sickness symptoms, the somatic feedback system proved effective at reducing some components of the discomfort that comes with VR locomotion. As such it can be argued that, as per the project's first research hypotheses, somatosensory feedback has to potential be operationalised as a means to reduce the level of cybersickness in some VR locomotion environments.

Measuring presence also yielded statistically significant results between the study conditions, which is a positive outcome in terms of progression for the field. The reported change in total presence suggests enhancements in presence in the feedback condition, however some of the sub-scales found significant are unexpected, and should be examined with scepticism.

Firstly, of the sub-scales expected to show significance, Realism held the lowest significance value as well as the most polarising z value. As participants reported during interviews, this was expected for several reasons. These include the increased sensory combination due to another sense being immersed, an increased sense of self-motion and the dynamic feedback changes based on other environmental factors. All of which contribute to a more believable environment with greater fidelity. While it was expected, it is assuring that the changes made between this study and the prior are met presuppositions. Similarly, it was anticipated that there would be increased self-evaluation as a consequence of dynamic feedback based on speed. Users commented on this, however some users added that despite the direction of the airflow being fixed, it assisted in determining the direction they were travelling in the environment. This further led to users being more comfortable with directing their vision away from the direction they were travelling during the feedback condition. Thanks to this, it is believed that the improved understanding regarding velocity is responsible for the significance seen in the self-evaluation sub-scale. The study was not expected to show statistical significance in the Possibility to Act sub-scale, which is true for the results, however its close proximity to this projects significance threshold still warrants some investigation. Similar to the previous review of self-evaluation, ability to act may hold a connection to how comfortable users felt during exposure, as a user undergoing sickness may constrain themselves to actions that result in the least sickness, rather than what they necessarily want to do. Several comments included arguments regarding a change of driving style in the airflow condition, which can further support this judgement.

Among the PQ results, some unexpected statistically significant findings were obtained. Quality of Interface changed significantly in favour of the feedback condition, despite control schemes remaining identical between conditions, leading to believe that there is a relationship between sensory feedback and utilizing controls. This could once again be connected to the level of comfort but even post thematic analysis, lacks clear explanation. Possibility to Examine was the second sub-scale that unexpectedly returned statistically significant in favour of the feedback condition. The level of detail and interaction capabilities remained constant between conditions, making this outcome surprising, however it may be attributed to similar reasons justifying the studies findings with regards to self-evaluation. Participants mentioned feeling more inclined to view the surrounding environment during the airflow condition which partly explains this outcome. Despite this, the rate of this comment is too infrequent to explain the degree of significance alone. One possibility could be due to the increased oculomotor interference during the baseline condition, causing difficulty when examining the environment due to symptoms such as eye strain and blurred vision. This was not identified during interviews and consequently remains speculation.

Overall, the significant results from the PQ combined with user responses during interviews give probable cause to address this projects third research hypotheses. Based on the results of this study there is a significant likelihood that effectively integrated somatic feedback can enhance levels of presence in users when exposed to a VR environment.

8.5.1 Cybersickness - Presence Correlation

The performance of a significance test for the correlation between presence and sickness proved to not be significant, however the fairly low p value ($p = 0.099$) suggests that the possibility of a correlation still exists. The shallow negative correlation observed aligns closer to Witmer and Singer's results then those of Slater however based on the the context of the study, the theory that the relationship is governed by a third variable appears most likely (Nichols, Haldane and Wilson, 2000). In order to eliminate the variability of the hardware, multiple applications on the same system should be used to better determine the nature of a relationship presence and sickness.

8.6 Evaluation

Looking at the study as a whole, the project's research hypotheses have been answered fairly comprehensively, but there are still obvious areas for improvement that should be addressed based on participant feedback. Firstly, it became apparent that having limited available resources influenced multiple areas of the study. The inexpensive control system was a common area of discussion for users, inhibiting their ability to become immersed due to the awkwardness of the hardware. Similarly, increased resources would have allowed for the creation of a system with the combined directional feedback of the first study, and the increased power used in this study, resulting in a greater contrast against the baseline condition. Beyond this, a large number of users suggested incorporating a range of game elements to improve user engagement and avoid task exhaustion. These points are valid however it can be said that the implementation used for the study avoids unnecessary confounding variables. The introduction of additional game elements may diversify environmental aspects to the point of neutralising the contribution of somatic feedback by inundating the user with distractions. While unlikely to effect reported sickness, presence may not be as easily measured under these conditions. One methodological criticism received was the lack of Likert scale integration to support the qualitative feedback received from interviews. As a result of not using them, some of the qualitative data generated by interviews lacks validation breadth across the entire study. Additionally, without the quantitative data to support the arguments, it is difficult to draw meaning behind comments regarding relevant areas that aren't directly related to our research hypotheses, such as usability and engagement.

The study has been successful in addressing the research hypotheses of the project by investigating both sickness and presence in VR with the support of a somatosensory feedback system. Of these, both measurements found significant results, which supported by thematically analysed interviews, have allowed for deductions regarding the relationship between somatic feedback and VR locomotion. The somatic feedback condition proved effective at both limiting cybersickness while simultaneously enhancing user presence, as hypothesised based on existing research into each field. The meaning behind both this study and the previous study with respect to existing research is finalised in the following chapter.

Chapter 9

Conclusion

The purpose of this chapter is to provide a summary of the thesis, and a detailed discussion of the findings determined in the previous chapters. Specifically, this chapter intends to satisfy the objective found in Section 1.4 of further elaborating upon and discussing the results found throughout the project. Additionally, the discussion highlights the relevance of these findings, the limitations of this work, and also possible extensions and expansions in the future.

The discussion will begin by analysing the complete findings of both studies carried out for this project, as well as the literature reviewed in Chapter 2. Beyond this, limitations encountered are discussed to further evaluate the exploratory nature of this field, followed by an outline for future expansions and iterations in the research field.

9.1 Thesis Summary

In order of appearance, this thesis first introduces the topic of cybersickness in virtual reality and describes the issue it presents to both research and commercial outlooks. A review of the literature was then conducted to better understand the cause and effect of cybersickness, existing mitigation techniques, as well the multitude of connections virtual reality introduces, such as the concept of presence. Using this knowledge, the thoughts and process behind the design and implementation of an artefact hypothesised to reduce cybersickness and enhance presence using somatic feedback are laid out. A plan is then established to utilize the aforementioned artefact by exposing volunteers to virtual reality whilst using it. Measurements gathered from this exposure are then evaluated, where it becomes apparent that adjustments to both the artefact and how it is applied are necessary. These changes are then documented, while principally the same, key components are refurbished to create a more effective system, as well as more suitable measurement techniques. The second iteration of the study is far more successful at examining the difference between conditions, providing both quantitative and qualitative data for evaluation and discussion. Numerical results are statistically significantly in favour of the project hypotheses, with thematic analysis reaffirming some suspicions regarding the efficacy of the system. Some results are unexpected, but are evaluated and justified using information available.

9.2 Discussion

The recurring issue of sickness during VR locomotion has prompted a lot of investigation into the cause and effect, as well as possible solutions proposed by a variety of authors. Besides this, cybersickness is still prominent and a number of issues and limitations exist in the field:

- Three theories exist for the cause of cybersickness during VR locomotion, such that making a specialized solution meeting the specifications of all three is difficult.
- Current VR head-mounted displays differ significantly from the hardware used in older research, making the applicability of some existing solutions questionable.
- Current solutions are often expensive and impractical making the commercial viability minimal in an era where VR systems are seeing increased household usage.
- Software created for VR hardware has to constantly consider the potential negative effect it causes, such that designers have significantly constrained options.

- Cybersickness can be harmful if not considered for carefully, thus presenting an ethical concern. Similarly, high levels of cybersickness can hinder the methodological process of studies.
- Many current cybersickness avoidance techniques are not dynamic, preferring to prevent aggravating actions and environments.
- Few current approaches have attempted to integrate non-visual sensory feedback as a solution.
- The correlation between presence and cybersickness is a point of discussion in the research community, creating uncertainty that could potentially induce risk to users.

This thesis addresses each of these limitations. This is achieved through the design and implementation of a dynamic somatic feedback system, capable of emulating the passive airflow movement undergone during vehicular locomotion. Furthermore, this thesis showed that:

- The addition of the second iteration of the somatic feedback system significantly reduced the severity of cybersickness in users.
- The somatic feedback extension also showed an increase of presence in users, which in itself suggests benefits to user experience, but also supports the idea of a negative correlation with cybersickness.

Considering these findings, the research hypotheses presented at the beginning of this thesis have been fulfilled. Firstly, this thesis explores the creation of a traditional desk based VR driving application, that has the option of being supported by somatosensory feedback. A somatic feedback extension is devised alongside the application using a basis and concepts extrapolated from existing research. After some revision, the second iteration of the extension was administered in a user based study, where it was statistically shown that users experienced less sickness during the condition with the feedback extension in place. This highlights the potential of operational somatosensory feedback as per the projects first research hypothesis.

Next, the second study has shown that the addition of the somatic feedback extension increased recorded presence in users. This lends itself to supporting the idea of both digital and physical feedback can be used to foster presence, answering the projects second research hypothesis. As a result of these two findings the project's third research hypothesis is addressed which looks at the correlation between cybersickness and presence, however performing appropriate significance tests fail to conclusively answer the question. Despite this, insights acquired throughout the duration of the project combined with speculative existing research suggest this correlation is likely indirect, with both measurements sharing factors that change their degree of occurrence (such as somatic feedback), without being directly dependant on one another.

This work expands on existing research in related areas, with various implications across several avenues. To begin with, the artefact itself proves it can be used to the benefit of VR locomotion, with potential applications in the fields of video games, training tools and simulation. The artefact is also inexpensive, such that creating a commercially viable option is absolutely plausible. Similarly, it can easily be recreated and configured for the purpose of future applications, only requiring velocity vectors for each representable direction.

Another benefit to the somatic feedback extension besides the obvious implications for cybersickness and presence is its non-invasive nature, such that it can be integrated alongside existing exploratory and prototype VR equipment. For example, by combining the haptic feedback of an omni-directional treadmill with directional somatic feedback, the sense of touch a user would expect to experience during movement becomes comprehensive. This could reap further benefits to presence and cybersickness, as well as more game oriented elements such as user experience and immersion. This is one of many potential applications that can expand on this work in the future.

The objectives laid out at the beginning of this project have also been satisfied. This thesis has:

- Reviewed existing literature relating to virtual reality sickness, and the range of factors that have been determined to influence it. Using related works, methods of combating cybersickness are identified in a detailed review of the literature. This includes topics regarding the cause and effect of cybersickness, design strategies, hardware effects and the contribution of human physiology. This review was carried out in Chapter 2.

- Discussed and then implemented an extension capable of supporting VR head-mounted displays through the use of somatosensory feedback. This was achieved by appraising the knowledge acquired in the review of related works and applying it to a design context. As such, somatosensory feedback was determined to be both a practical and novel technique with the potential to mitigate virtual reality sickness. In Chapter 3 of this document, the processes used to conceptualize the application are covered, critically discussing the essential components of a virtual application as well as physical hardware to most efficiently address this somewhat sensitive topic. The artefact later received minor design changes and improvements based on the outcomes of the first study which can be seen in Chapter 6.
- This project consists of two user studies used to measure the efficacy of somatosensory feedback as a technique to reduce cybersickness. The first study documented in Chapters 4 and 5 did not contribute to addressing the thesis objectives at a significant level, however highlighted some of the complexities this project had overlooked when designing the system, as well as structuring the user study. The learnings of this study were put into practice for the second study, documented in Chapters 7, which provides far more confident outcomes.
- The results and discussion of the second study, covered in Chapter 8 lays out the findings of this project and analyses them. In addition to seeing the effects on cybersickness and presence as wholes, their components are analysed, and their implications are discussed using existing research along with the studies qualitative data to justify the numeric outcomes. Some results are unexpected and pose interesting questions, which are briefly documented in that chapter.

In conclusion, the proposed somatic feedback extension presented as part of this thesis meets the objectives of this research, and has explored the questions it aimed to answer.

9.3 Limitations and Future Work

This research has offered a novel approach to combating VR sickness during locomotion, but due to the scope of this project and its aims, has only investigated limited areas. As the literature review found, the range of contributing factors and theories regarding cybersickness presents many other angles that could have been taken. The digital environment, hardware and human factors each present interesting fields of research.

The primary limitation of the solution this research proposes is that this system is incapable of emulating low velocity movement, which for VR, is extremely common due to the popularity of environments that are navigated while standing. Somatosensory feedback is not exclusively airflow however, such that alternative avenues many exist for low velocity movement.

Another area that was not considered in huge depth was user familiarisation with driving. Regardless of VR experience, a user with driving experience will be more familiar with the sensation of movement, as well as the control scheme. While it can be assumed that an experienced driver is less susceptible to sickness, the value of feedback may be different to an inexperienced driver whose senses do not expect a particular nature of feedback. When further introducing VR experience, this could be an engaging research topic.

The virtual environment was subject to a number of careful design choices, however user studies highlighted the degree of influence it has on users. As such, this approach faces limitations for virtual terrains dissimilar to the one used. A future research idea may be to expose users to variable terrain environments, and examining the influence of somatosensory feedback on each.

Lastly, the project saw significantly different results between it's first and second study which is somewhat concerning, even though implementation issues were clear during the prior. Due to this, the vast majority if conclusions drawn from this project is from a single experiment's results. As such, the study needs to be repeated with different participants and look to achieve the same results.

As future work, further improvements to the somatic feedback extension presented in this thesis could include:

- Combination with existing sensory feedback approaches, such as haptic touch feedback.
- Complete directional feedback beyond just the forward arc. This could be further expanded by increasing number of axis feedback can be provided on, such that vertical locomotion is not without coverage.
- Alternative forms of somatic feedback. For example, walking around a virtual fire, with the heat radiating from an appropriate direction.
- A more game-centred study, where player immersion, usability, and player experience are measured with respect to multiple sensory feedback conditions.
- The implementation of directional airflow as wind emulation within a digital environment, measuring for immersion oriented factors.

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Appendix A

Study Questionnaires

A.1 Presence Questionnaire

No _________. Date ________.

Presence Questionnaire

Characterize your experience in the environment, by marking an "X" in the appropriate box of the 7-point scale, in accordance with the question content and descriptive labels. Please consider the entire scale when making your responses, as the intermediate levels may apply. Answer the questions independently in the order that they appear. Do not skip questions or return to a previous question to change your answer.

WITH REGARD TO THE EXPERIENCED ENVIRONMENT

1. How much were you able to control events?

NOT AT ALL SOMEWHAT COMPLETELY

2. How responsive was the environment to actions that you initiated (or performed)?

NOT RESPONSIVE MODERATELY RESPONSIVE COMPLETELY RESPONSIVE

3. How natural did your interactions with the environment seem?

EXTREMELY ARTIFICIAL BORDERLINE COMPLETELY NATURAL

4. How much did the visual aspects of the environment involve you?

NOT AT ALL SOMEWHAT COMPLETELY

5. How natural was the mechanism which controlled movement through the environment?

EXTREMELY ARTIFICIAL BORDERLINE COMPLETELY NATURAL

6. How compelling was your sense of objects moving through space?

NOT AT ALL MODERATELY COMPELLING VERY COMPELLING

7. How much did your experiences in the virtual environment seem consistent with your real world experiences?

NOT CONSISTENT MODERATELY CONSISTENT VERY CONSISTENT

8. Were you able to anticipate what would happen next in response to the actions that you performed?

NOT AT ALL			SOMEWHAT			COMPLETELY

9. How completely were you able to actively survey or search the environment using vision?

NOT AT ALL			SOMEWHAT			COMPLETELY

10. How compelling was your sense of moving around inside the virtual environment?

NOT COMPELLING			MODERATELY COMPELLING			VERY COMPELLING

11. How closely were you able to examine objects?

NOT AT ALL			PRETTY CLOSELY			VERY CLOSELY

12. How well could you examine objects from multiple viewpoints?

NOT AT ALL			SOMEWHAT			EXTENSIVELY

13. How involved were you in the virtual environment experience?

NOT INVOLVED			MILDLY INVOLVED			COMPLETELY ENGROSSED

14. How much delay did you experience between your actions and expected outcomes?

NO DELAYS			MODERATE DELAYS			LONG DELAYS

15. How quickly did you adjust to the virtual environment experience?

NOT AT ALL			SLOWLY			LESS THAN ONE MINUTE

16. How proficient in moving and interacting with the virtual environment did you feel at the end of the experience?

NOT PROFICIENT			REASONABLY PROFICIENT			VERY PROFICIENT

17. How much did the visual display quality interfere or distract you from performing assigned tasks or required activities?

NOT AT ALL — INTERFERED SOMEWHAT — PREVENTED TASK PERFORMANCE

18. How much did the control devices interfere with the performance of assigned tasks or with other activities?

NOT AT ALL — INTERFERED SOMEWHAT — INTERFERED GREATLY

19. How well could you concentrate on the assigned tasks or required activities rather than on the mechanisms used to perform those tasks or activities?

NOT AT ALL — SOMEWHAT — COMPLETELY

A.2 Simulator Sickness Questionnaire

No _________.   Date ________.

Simulator Sickness Questionnaire

Instructions : Put a cross in the column describing how much each symptom below is affecting you right now.

	None	Slight	Moderate	Severe
1. General Discomfort				
2. Fatigue				
3. Headache				
4. Eye Strain				
5. Difficulty Focusing				
6. Salivation increasing				
7. Sweating				
8. Nausea				
9. Difficulty Concentrating				
10. Fullness of the Head				
11. Blurred Vision				
12. Dizziness with eyes open				
13. Dizziness with eyes closed				
14. *Vertigo				
15. **Stomach Awareness				
16. Burping				

* Vertigo is experienced as loss of orientation with respect to vertical upright
** Stomach awareness is usually used to indicate a feeling of discomfort which is just short of nausea.