UNIVERSITY OF CAPE TOWN
DEPARTMENT OF COMPUTER SCIENCE

CS/IT Honours
Final Paper 2019

Title: Reducing Simulator Sickness for Travel in Virtual Reality

Author: Brandon Gower-Winter (GWRBRA001)

Project Abbreviation: VRMove

Supervisor(s): James Gain

Category	*Min*	*Max*	Chosen
Requirement Analysis and Design	*0*	*20*	5
Theoretical Analysis	*0*	*25*	0
Experiment Design and Execution	*0*	*20*	20
System Development and Implementation	*0*	*20*	10
Results, Findings and Conclusion	*10*	*20*	15
Aim Formulation and Background Work	*10*	*15*	10
Quality of Paper Writing and Presentation	*10*		10
Quality of Deliverables	*10*		10
Overall General Project Evaluation (*this section allowed only with motivation letter from supervisor*)	*0*	*10*	0
Total marks		**80**	

Reducing Simulator Sickness for Travel in Virtual Reality

Brandon Gower-Winter
GWRBRA001@myuct.ac.za
University of Cape Town
Cape Town, South Africa

ABSTRACT

Simulator sickness is an issue that threatens the success of virtual reality (VR). It is caused by a mismatching of the visual-vestibular senses. While the ocular component of simulator sickness has mostly been solved with the advent of new VR technology, the nausea and disorientation components have not. Haptic feedback, artificially created touch through the application of forces, that specifically seeks to remove the conflict between the visual-vestibular senses has not been well researched. We conducted a single factor repeated measures experiment ($n = 27$) to determine whether the introduction of haptic feedback in two motion-based movement interventions (tether and stepper prototypes) would induce less motion sickness when compared to an out-the-box VR controller. We measured heart rate, respiratory rate and skin capacitance over 8 minutes of travel in VR. Participants were also required to answer the Simulator Sickness Questionnaire (SSQ) [21] and the System Usability Scale Questionnaire (SUS) for each movement intervention. Our results were inconclusive. The stepper performed the worst of three movement interventions This is because it required a significant amount of physical exertion to operate. The results of the stepper were polarizing suggesting that personal fitness played a large role in the enjoyment of the stepper. The tether prototype performed similarly to the controller for all measurements. This is quite promising as the tether prototype was competing against a consumer-grade VR controller. Our results suggest that further investigation should be done on future iterations of the tether device in order to determine whether haptic feedback is in fact capable of reducing simulator sickness.

KEYWORDS

Virtual Reality, Simulator Sickness, Virtual Environments, Haptic Feedback

1 INTRODUCTION

Virtual Reality (VR) is a real or simulated environment in which a person experiences a sense of being, either through natural or mediated means [36]. VR was first introduced to the world in 1968 by Ivan Sutherland as a method for viewing simple wireframes in three-dimensional space. VR has since evolved past rendering simple geometry. With current available technologies, like the HTC Vive, allowing for large-scale virtual environments to be both fully-rendered and fully-interactable. How one traverses these environments is an interesting field of research. A phenomenon known as Simulator Sickness (SS), first documented by Havron and Butler in flight simulators [8], arises when one travels in VR. SS is a form of visually induced motion sickness [24] that occurs in approximately 30% of all people. Some of the symptoms of SS include: malaise, eye-strain, nausea and, in extreme cases, vomiting [21]. The cause of SS is also unknown with two of the of the most popular theories suggesting that SS occurs when the vestibular apparatus is stimulated unnaturally.

SS and its symptoms can be grouped into three categories: ocular, nausea and disorientation. The severity of the ocular symptoms have been reduced with recent advancements in VR technology providing HMDs with significantly higher resolutions and framerates. However, the nausea and disorientation categories dominate current SS research. Numerous methods of reducing SS, such as electrical stimulation of the vestibular apparatus [15], have been proposed and implemented with varying levels of success. One such method, that has not been well-researched, is the use of haptic feedback to reduce SS. Haptic Feedback is the use of touch to communicate with an individual. It ranges from vibrations on touch-screen devices to highly-specialized props for surgical training [37]. In the case of virtual locomotion, haptic feedback is intended to provide the vestibular apparatus, the balance organ, with signals that aid in positioning and orientating a person within a virtual environment, thus reducing the effects of SS.

Another factor affecting travel in virtual environments is the virtual environment itself. In order to simulate a human's stereoscopic vision, virtual environments need to be rendered twice, once for each eye, and as a result certain luxuries that exist for graphical applications rendered on traditional displays do not exist in VR. For example, performance is a dominant factor in the enjoyment of VR applications. While other graphical applications can afford to have performance drops for brief periods of time, a VR application that does not run at constantly high framerates(>90fps) is more likely to cause SS [1] and reduce the overall enjoyment of an application. This means that VR applications often need to reduce graphical fidelity, use optimized shaders and make use of advanced GPU techniques like instancing and static batching to meet these new requirements.

While various methods of virtual environment locomotion may yield promising results, the methods themselves must be useful. It makes little sense to propose extravagant solutions if they require an industry professional to setup every time a patient or consumer wishes to use VR. In this report we propose that in order for a movement intervention to be considered successful it needs to not only reduce the effects of SS but also be easy to setup, learn and use. This project is intended to further extend our knowledge of SS and investigate haptic feedback as a potential preventative intervention in reducing SS. The aims of this project are as follows:

(1) **Aim:** To determine whether the introduction of haptic feedback, by tether and by stepper, reduces the likelihood of someone suffering from simulator sickness when compared to an out-of-the-box VR controller.
Hypothesis: Haptic feedback will reduce the amount of simulator sickness a person feels as indicated by lower SSQ

scores, lower average skin capacitance, lower average heart rate and lower average respiratory rate. The tether will induce the least amount of simulator sickness, then the stepper, with the controller being the worst of the three movement interventions. This will be because the haptic feedback provided by both the tether and the stepper supply the vestibular apparatus with input, thus reducing the number of sensory conflicts in the brain and subsequently reducing the amount of simulator sickness one feels.

(2) **Aim:** To determine whether the haptic feedback devices(tether and stepper) are usable as movement interventions inside a virtual environment when compared to the out-of-the-box VR controller.
Hypothesis: The controller will be the most usable, then the tether, with the stepper being the least usable. This is because the controller is the most familiar of the three, the easiest to setup and requires the least number of components.

The novelty of this project lies in its exploration of haptic feedback as a preventative measure against SS. SS decreases a user's enjoyment and is a significant negative factor in flight simulator training [22] and virtual therapy [4]. The utilization of haptic feedback devices for travelling virtual worlds may not only reduce the effects of SS but provide alternative movement interventions that are more usable than current industry solutions.

This report consists of 8 sections. Section 2 is an overview of previous and related work. Sections 3 & 4 highlight the implementation of the three movement interventions and the virtual environment, respectively. Section 5 describes the experimental design and procedure. Section 6 lists our project's limitations. Section 7 is a discussion and summary of the results, and Section 8 details our conclusions and possible extensions for future work.

This project was completed by a team of three that were tasked with writing three separate reports. This report focuses on the implementation of the controller and the virtual environment while, still providing context to the project as a whole.

2 BACKGROUND & RELATED WORK

2.1 Simulator Sickness

Simulator sickness was first documented by Havron and Butler in flight simulators [8] in 1968 as a side-effect of the recent advancements in simulator technology. While the cause for SS is unknown there have been numerous theories that try to explain the phenomenon. The two most popular in current research are as follows:

2.1.1 Cue Conflict. Cue conflict, the mismatch between sensory inputs, is the most widely accepted cause of motion sickness [24]. Most commonly occurring between the visual and vestibular senses, simulator sickness arises when the input of one or more senses conflicts with the input of another. Duh et al.[12] found that lower frequency conflicts between visual-vestibular senses were more likely to cause simulator sickness than conflicts at higher frequencies. Draper et al. [11] queried image scale in virtual environments, their results suggest image scale is a provocative factor in inducing simulator sickness as it causes visual-vestibular conflicts. Prothero et al.[30] suggest an alternative to the cue conflict theory, they theorize simulator sickness does not occur from conflicting motion cues but rather the rest frames selected from those motion cues. They support this by showing that the presence of an independent visual background, which heavily influences rest frames, reduced simulator sickness.

2.1.2 Postural Instability. Postural instability has only recently gained popularity as an opposing theory to the cue conflict theory. Theorized by Riccio & Stoffregen [31]. They argue that simulator sickness arises as a consequence of attempting to balance on unfamiliar surfaces. They, among others [14], criticized cue conflict's inability to pre-determine simulator sickness. Riccio & Stoffregen note the postural instability theory does not suffer from non-determinism as postural stability tests can be performed before exposure in order to predict the likelihood of someone experiencing SS in simulators. Akiduki et al.[2] tested this theory on VR displays and found that prolonged exposure to VR significantly affected postural stability further strengthening the postural instability theory. Simulator sickness research was traditionally conducted on military personnel. Cobb et al.[9] found that the severity of the symptoms differ on the general population. They noted that their participant's experienced greater postural instability. They argue that this supports the postural instability theory as military personnel are more likely to have pre-exposure to simulators when compared to a general populous.

While the cause for SS is yet to be determined. We have a much clearer understanding of what triggers simulator sickness:

2.1.3 Eye-Strain. Eye-strain, also known as asthenopia, manifests itself by non-specific symptoms such as pain around the eyes and blurred or double vision. Eye-strain is caused by the straining of the ciliary muscle inside the iris and the overworking of the brain. The ciliary muscle allows us to focus on objects at varying distances and prolonged focus on objects that are too small or too near can cause eye-strain. In the context of simulator sickness, Mourant et al.[28] note that oculomotor symptoms, which includes eye-strain, are the most common symptoms of simulator sickness. Lampton et al.[25] note that eye strain is the most common symptom of simulator sickness displayed in participants after extended periods of time in a virtual environment.

2.1.4 Vection. Vection is the illusion of self motion. It occurs when the visual senses are entirely responsible for the sense of motion and is integral to the cue conflict theory. Hettinger et al.[17] notes that experiencing vection is polarizing. All of their participants experienced either no vection or significant amounts of vection. They also note that 80 % of the participants that experienced vection also experienced simulator sickness suggesting that there is a high correlation between sensory conflicts and simulator sickness. Interestingly, Bonato et. al.[6] found that constant vection can actually enhance the presence one feels within VR but can also induce simulator sickness depending on the individual. They also noted that variable vection (ie: apparent acceleration) significantly exacerbated simulator sickness when compared to constant vection.

SS is polysymptomatic [20] which means that no single symptom predominates. This makes diagnosing individuals with SS challenging and as a result Kennedy et al. [21] developed the simulator sickness questionnaire (SSQ) as a subjective measure for diagnosing SS. The SSQ is a simplification of the motion sickness questionnaire

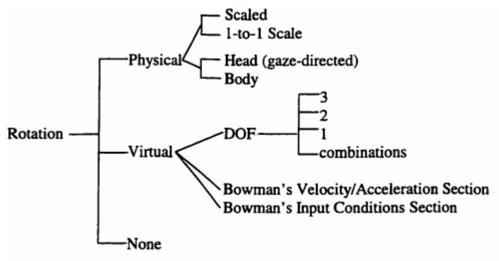

Figure 1: Arns'[3] taxonomy for rotation

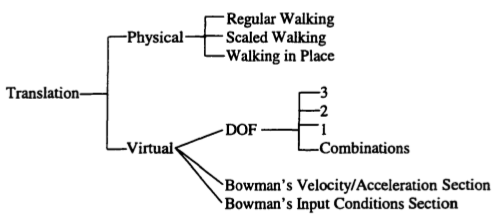

Figure 2: Arns'[3] taxonomy for translation

and eliminates the symptoms that were deemed irrelevant in the diagnosis of SS. The SSQ is widely used in SS research as a subjective measure of diagnosing SS. Some objective measures for SS include skin capacitance, respiratory rate and heart rate [23].

2.2 Locomotion in Virtual Reality

In order to design and implement movement interventions for VR, an appropriate locomotion model should be used to describe them. Numerous models for locomotion in VR have been proposed, three of which were explored for this project. Bowman's taxonomy [7] separates locomotion into three categories: direction selection, velocity selection and input conditions but is rather broad and does not take into account a user's mode of transportation. Arns [3] extended Bowman's taxonomy by adding additional modes of transportation based on the technology available. She separated rotation (Figure 1) and translation (Figure 2) and further subdivides those categories into virtual and physical components. Arns' taxonomy, while complete in 2002, does not take modern VR technology into account. Boletsis [5], attempting to create a new model for locomotion for modern-day VR, designed a typology based on 36 relevant articles. This typology (Figure 3) identifies 11 techniques for locomotion categorised into one of the following locomotion types:

2.2.1 Motion-based. Locomotion techniques that support continuous motion and employ physical movement to enable interaction fall into this category. and include techniques such as gesture-based motion, redirected walking and walking-in-place. These techniques often rely on additional hardware and software to track and simulate movement. In the case of walking-in-place, treadmills and stepping machines can be used while gesture-based motion can be tracked with additional sensors. Interestingly, redirected-walking is implemented differently to the other techniques in this category as it mismatches the users' real and virtual environments in an attempt to scale a large world into a confined space [29].

2.2.2 Room scale-based. These locomotion techniques are used when the virtual environment's size is limited by the real world. These techniques also employ physical movement to enable interaction. For example, real-walking is one of these techniques. A user moves freely about a limited space and their position is usually tracked using their HMD or additional sensors. Room scale-based techniques are often impractical with virtual environments that are larger than the physical room and as a result other locomotion techniques, such as teleportation-based locomotion techniques, are used to facilitate travel over greater distances.

2.2.3 Controller-based. These techniques involve a user utilizing a controller to artificially move around an environment. The environment is open and the motion continuous. Example techniques include, joysticks and head-direction motion.

2.2.4 Teleportation-based. Techniques under this type artificially teleport a user from one location to another. The movement is non-continuous and can appear disorientating to a user. Point-and-teleport is the most common technique in this category and has been successfully implemented by controlling when and where teleportation can take place.

2.3 Haptic Feedback

Haptic feedback provides a user with a sense of touch when interacting with a virtual environment. It has been shown that haptic feedback greatly improves presence [33] and has shown promise in medicine [37], chemistry [16] and robotics [10]. However, little research has been done to identify the effect haptic feedback has on simulator sickness. Schultheis & Rizzo [34] argue for the use of haptic feedback and highlight its usefulness in physical rehabilitation. They state that "VR provides possible rehabilitation options not available in traditional methods". Stanney [35] errs on the side of caution stating that in order for VR peripherals to be commercially successful, they need to undergo rigorous testing to not only be usable but safe and socially acceptable.

2.4 Virtual Environments in VR

Developing virtual environments for VR is akin to developing virtual environments for mobile devices. Many of the same constraints exist. The two most important concerns are as follows:

2.4.1 Environment Fidelity. Graphical fidelity has been a large focus of commercial video games over the past decade, with each subsequent game trying to one-up the other. However, VR represents is an inherently unique experience. In VR, latency greatly affects a user's presence [27] as well as the likelihood of suffering from simulator sickness [19]. This is unfortunate because in order to simulate 3D vision, virtual environments have to be rendered twice, once for each eye. Therefore, graphical fidelity is more challenging than in traditional graphical applications, resulting in more rendering effort and potentially greater latency. Fortunately research by Lok et al. [26] suggests that graphical fidelity is not a major requirement for presence and can be reduced to maintain performance.

2.4.2 Objects within a Virtual Environment. Virtual Environments are constructed from a number of objects. These objects not only

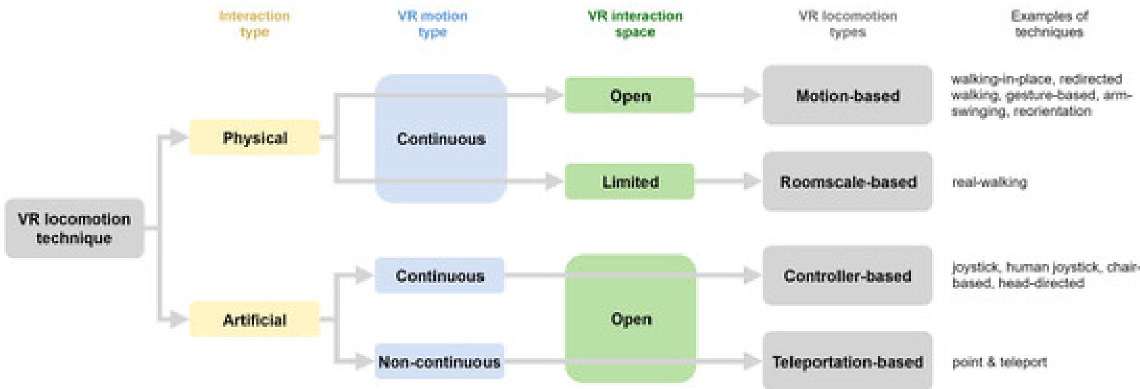

Figure 3: Boletsis' [5] model for locomotion in VR

have a visual representation but they also have properties that influence the way we perceive them. For example, a boulder is heavy and a feather is light. These properties are influenced by learned behaviour [32] and should affect the way virtual environments are designed. If virtual objects do not behave in accordance with a user's expectations or implicit understanding of how to interact with an object, it causes a cognitive dissonance known as postural instability. This is especially true for objects in motion. Hosking et. al. [18] demonstrated that our perception of objects in motion, particularly when directed toward us, is partially based on learned characteristics. The number of objects in motion should also be taken into account as this can cause sensory conflict and sensory overload. Sensory overload can cause many of the same symptoms as motion sickness. Prothero et al. [30] suggest the use of an independent visual background to help reduce the side-effects of sensory overload as it allows a person to position themselves relative to a fixed reference point.

3 MOVEMENT INTERVENTIONS

Three movement interventions were designed and implemented for this project. A controller (Section 3.1), a tether device (Section 3.2) and a stepper (Section 3.3). In terms of Boletsis' model, the tether and stepper are motion-based locomotion techniques while, the controller is a controller-based technique. Teleportation-based techniques were not investigated as we were only interested in continuous movement interventions. The implementations of the three movement interventions were left relatively open. The only requirements were that the interventions be (1) continuous and (2) implemented for walking speeds. This was because we were more interested in reducing SS for the general use case of walking. Because we were limited to motion in one direction, speed is represented as a float instead of a vector.

We elected to use the HTC Vive as our headset of choice. This decision was made for three reasons:

(1) The HTC Vive is one of the two most successful commercially available VR headsets.
(2) The HTC Vive can be paired with numerous accessories. The most important of these accessories is the Vive tracker (Figure 5), which allows for additional motion tracking and was essential in the design of both the tether and stepper prototype devices.
(3) There are numerous developer libraries available for the HTC Vive, which make installing and setting up the headset relatively trivial. This allowed us to focus specifically on the implementation of the movement interventions and the design of the virtual environment.

All movement interventions allowed for maximum travel speeds of 1.7m/s. This number was selected because the average walking speed of the average human is approximately 1.35m/s[13]. However, after pilot testing, many participants complained that the maximum walking speed was too slow. The maximum walking speed was increased to 1.7m/s to account for potential variances in participants average walking speed. The motivation behind this decision was, that should a participant feel that they are travelling too fast, they could simply slow down to a comfortable pace as all our movement interventions were continuous i.e., allowed for travel at speeds of [0,1.7]m/s.

3.1 Controller

Because we elected to use the HTC Vive as our headset of choice, it made sense to use the Vive controller (Figure 4) as the controller used in our controller-based movement intervention. The Vive controller consists of three buttons, a trackpad and a trigger. The buttons return discrete values (on/off) and could not be used to implement continuous movement. Of the two remaining input options, the trigger was used to move through the environment. This decision was made on the basis that using the trackpad to move did not feel as satisfying as the trigger. Since our movement interventions were limited to mono-directional travel, varying your walking speed felt more intuitive as you only had to press the trigger rather than track your thumb along the trackpad. It may be worthwhile to investigate the use of the trackpad to move should omni-directional movement be investigated in the future. Figure 6 showcases how the controller was used.

The trigger returns an input value of [0.0,1.0], where 0.0 is no pressure and 1.0 is maximum pressure. Using this information a formula for deriving the speed of travel is:

$$S_c = I_c \times S_{max}$$

Where S_c is the speed produced by the controller, I_c is the input value of the trigger and S_{max} is the maximum speed obtainable for the movement interventions (1.7m/s as detailed above). The value of S_c must then be multiplied by Time.deltaTime (The number of seconds since the last frame) in order to obtain the distance that needs to be travelled on the z-axis each frame. This allows for a consistent movement speed that is independent of the the performance of the application. This technique is also used in the tether and stepper prototypes.

3.2 Tether

The tether prototype is a motion-based movement intervention. It consists of a Vive tracker attached to a belt that the user wears. The tether itself is attached to the belt and then attached to a wall. The tether prototype determines speed by tracking the distance of the tracker relative to a modifiable threshold. The actual speed is determined by the following formula:

$$S_t = clamp(0, 1.7, D_t)$$

Where S_t is the speed produced by the tether and D_t is the distance of the Vive tracker from the threshold. This means that as the user walks further away from the threshold, the tether will become more tense and move the user at a greater speed through the environment. The increase in tension is intended to aid the brain in determining the speed at which it is travelling in the virtual environment, potentially reducing the effects of SS. The clamp function is simply used to limit the value produced by the tether-threshold distance calculation, with the first and second values representing the minimum and maximum, respectively. S_t is also multiplied by Time.deltaTime in order to translate the user on the z-axis in real-time. Figure 7 illustrates the tether in use.

3.3 Stepper

The stepper prototype is a motion-based movement intervention that works similarly to the tether except that it utilizes a gym stepper. The tracker is attached to a user's foot and a change in y-position is measured as opposed to the change in z-position used for the tether prototype. If you plot this change in position along the y-axis, you obtain a graph that appears sinusoidal. By calculating the gradient of the absolute sinusoidal graph one can obtain the intended velocity that needs to be applied to the user in the virtual environment as follows:

$$S_s = abs(\frac{T_{currentframe} - T_{previousframe}}{Time.deltaTime})$$

S_s is the speed produced by the stepper and T_n refers to the position of the tracker at frame n. This formula already accounts for Time.deltaTime and ensures that the speed produced by the stepper is independent of the performance of the application. We take the absolute value of the speed produced to ensure that both upward and downward steps of the stepper produce a a positive translation on the z-axis.

4 VIRTUAL ENVIRONMENT

In order to measure the effects of SS we required a virtual environment for our participants to walk through. We used Unity (Unity

Figure 4: An HTC Vive controller

Figure 5: A Vive tracker. It allows for additional motion tracking with the HTC Vive.

Technologies) to develop the virtual environment. The requirements for the environments were as follows:

(1) The environment needs to induce simulator sickness but not so much that it causes participants to leave the experiment before it has been completed.
(2) The application needs to maintain a consistently high framerate (>90fps) while still looking visually appealing.
(3) The participants should not feel bored while traversing the virtual environment.

In order to induce SS and more specifically the nausea and disorientation symptoms of SS, vection needs to occur while traversing the virtual environment. A forest path was chosen to be the locale of our virtual environment (See Figure 9). The reason for this decision is two fold. First, the sheer number of trees offer many opportunities for vection to occur thus, in theory, increasing the liklihood of SS occurring and two, the width of the forest path could be adjusted to increase or decrease the likelihood of SS occurring in our participants. A narrower path increases the likelihood of SS occurring while a wider path does the opposite.

Our second concern was the performance of the application. Both HTC and Oculus recommend VR applications run at a constant 90 frames per second (fps). This is particularly challenging because virtual environments need to be rendered twice in order to simulate stereoscopic vision. This means that render times double unless optimization techniques are used. Fortunately, Unity is one of the industry leading game engines and offers a wide-range of optimization techniques which we used in this project. The first

Figure 6: An image depicting the use of the HTC Vive controller

Figure 7: An image depicting the use of the tether prototype

Figure 8: An image depicting the user of the stepper prototype

A Summary of the Optimization Techniques utilized in this Project		
Optimization Technique	Before (fps)	After (fps)
Frustum Culling	22.4	100.1
GPU Instancing	22.4	57.3
Mobile Shaders	22.4	33.7
Static Batching	22.4	26.8

Table 1: A summary of the various optimization techniques and their associated performance gain.

technique was the use of mobile shaders. As with mobile devices mobile, VR imposes constraints on the number of elements that can be rendered at any given time. Unity's built-in mobile shaders are designed for performance. They approximate specular highlights and ignore a wide-variety of Unity's advanced lighting techniques. We made use of static batching to combine larger pieces of geometry into a single piece of geometry to improve performance. GPU instancing is capable of rendering identical pieces of geometry in a single draw call and we made use of this on smaller pieces of repeating geometry. For example, our environment contains tree models that are used over ten-thousand times. By making use of GPU instancing we were able to reduce the number of draw calls by over 85%. Despite all these methods the most significant optimization technique was frustum culling. Frustum culling involves the exclusion of objects that are not within a camera's frustum. The frustum is adjustable by manipulating the camera's near and far render planes. By reducing the far render plane we were able to achieve a consistent 90fps across the entire level. This unintentionally reduced the render distance to unacceptable levels and fog as seen in table 9 was used to prevent participants from seeing geometry pop into existence. Figure 1 summarized the various optimization techniques and the performance gain that they provided.

When testing, we noticed that walking for long periods of time with no interaction was so boring that we feared participants would not return after completing it once. We thus added interactables to the environment. Interactables needed to both keep participant's attention and be simple enough to interact with that they did not inhibit participant's walking. A global approach to obstacles was taken and they either required no interaction or could be interacted with my making use of the Vive controller's trackpad. There was also concern that certain interactables might trigger unintentional physiological responses from our participants, such as increased heart rate from fear of snakes or spiders. Our interactables, one of which can be seeen in figure 10, went through numerous iterations in order to ensure they did not affect the final results of our experiment.

5 EXPERIMENTAL DESIGN

5.1 Participants

In this project we performed a controlled single factor within-subjects experiment. We recruited 27 participants (2 Male, 25 Female) from the psychology department. They were incentivised with 4 SRPP points for completing the experiment. All participants were screened for drug abuse, alcohol abuse and epilepsy through an anonymized online questionnaire. We received ethics clearance from the UCT Science faculty and received DSA clearance for candidate recruiting. Participants were instructed to avoid alcohol, caffeine and smoking on the day of their experiment. Informed consent was obtained before the experiment and participants were informed that they could leave the experiment at anytime.

5.2 Apparatus

We made use of the HTC Vive HMD, controller and tacker as part of our virtual reality hardware package. It was connected to a desktop with an Intel i7 CPU, 8GB of Ram and a GTX 1070 as its GPU. The tether prototype required the inclusion of a tether and belt. The

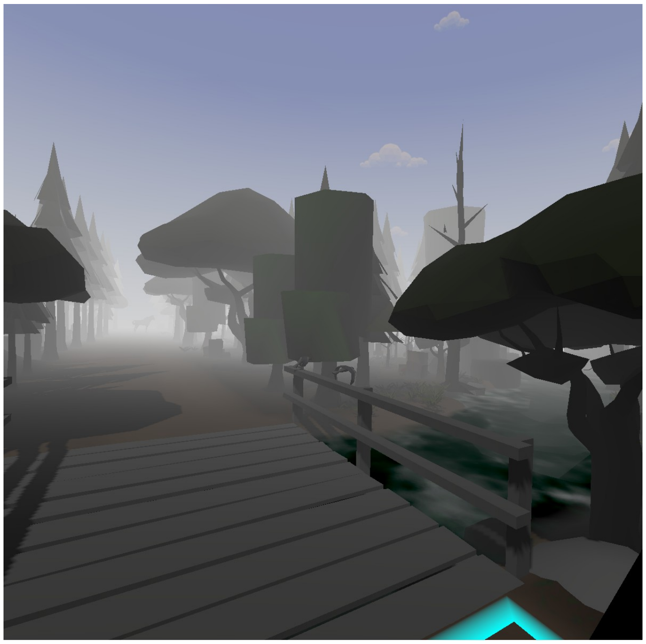

Figure 9: A screenshot of the virtual environment used for this project

Figure 10: A screenshot of one of the obstacles

stepper prototype required the inclusion of a gym stepper. For physiological measurements, we made use of a Biopac (BIOPAC Systems Inc.) for biosignal recordings. The polygraph included couplers for electrocardiogram (ECG100C), skin conductance (GSR100C) and respiratory rate (RSP100C). Data was gathered at a sampling rate of 62.5Hz.

Electrocardiogram signals were obtained by connecting three electrodes onto the participants. Respiratory rate was measured by a respiratory belt placed on a participant's diaphragm. Skin conductance was measured by preparing the participants first and second phalanges with NuPrep gel to reduce skin impedance. The skin conductance electrodes were then strapped onto the prepared phalanges with medical tape.

5.3 Measurements

5.3.1 Physiological.
All physiological measures were recorded using the Biopac.

(1) Heart rate: Measured by a three-lead system, the first and second electrodes are placed on the left and right clavicle respectively with the final electrode being placed slightly above and to the left of the umbilicus. The ECG measures the electrical current produced by heart depolarization. Results obtained by the ECG are then converted into heart rate by the supplied Biopac program. An increase in heart rate may indicate that a participant is suffering from simulator sickness or it could be related to physical exertion.
(2) Respiratory Rate: Measured by a respiratory belt. Respiratory rate measures the rate of inflation and deflation of the the diaphragm. An increased respiratory rate may be an indication of simulator sickness.
(3) Skin Capacitance: Measured by a two lead system that detects changes in the hydration state of the outer epidermis. Skin capacitance can be measured as either phasic or tonic. We are only interested in the tonic changes in skin capacitance as it will allow us to detect gradual changes in skin capacitance. An increase in skin capacitance could indicate that a participant is feeling simulator sick.

5.3.2 Subjective.

(1) Simulator Sickness Questionnaire: The SSQ, developed by Kennedy et al.[21], is a questionnaire that seeks to identify whether a participant has simulator sickness by self-diagnosis. A participant rates each of the 16 measured symptoms from none to severe. Each symptom is categorized into three categories: Nausea, Ocular and Disorientation. Specific scores for these categories can be obtained as well as the total sickness scores by multiplying each category's total scores by constants highlighted in Kennedy et al's. paper.
(2) System Usability Score: The SUS is a questionnaire that is described as being a "quick and dirty" method for measuring usability. It consists of 10 questions and is cited in over 1000 published journal articles. It is widely regarded as a questionnaire that can produce reliable results from a very small sample size. It is rather complex to score as the method for calculating a questions score is dependent on whether the question was an even numbered question or not. The final results are also slightly unintuitive as it is out of 100 but does not represent a percentage. A score of 68 is considered acceptable.

5.4 Procedure

Participants were required to spend 24 minutes in the virtual environment, split over three separate days, 8 minutes per movement intervention. This was to ensure that any simulator sickness incurred by one movement intervention did not affect the others. Upon arrival for the first time, participants were instructed to sign the consent form. They were then required to take a baseline SSQ questionnaire before being exposed to a VR acclimatization scenario for 5 minutes. This process was only completed on the first day to ensure that all participants had experienced VR at least once. On all three days participants had the ECG electrodes placed on them assisted by us in the case of male participants and by a female research assistant in the case of of female participants. Participants were then instructed to answer a pre-SSQ for their movement intervention. They were then connected to the Biopac and baseline measurements were taken to ensure all the physiological measurements were working as expected. Participants then spent 8 minutes in the virtual environment. This period of time was chosen based on a paper by Kim et al. [23] in which they recorded significant amounts of simulator sickness in a similar amount of time. Once the participants had completed their time in VR, they were immediately instructed to answer a post-SSQ for their movement intervention while connected to the Biopac. This was to minimize the recovery time before answering the SSQ. Upon completion of the post-SSQ, the participants were disconnected from the Biopac and instructed to answer the SUS questionnaire for their respective movement intervention. Once completed, the participants were handed a debrief form and were reminded of any further days they needed to complete.

6 LIMITATIONS

Simulator sickness research is an incredibly wide field of research and, due to the limited amount of time in which we could complete this project, a number of factors that would potentially affect our results were constrained. Firstly, this project only investigated the the effectiveness of introducing haptic feedback into motion-based movement interventions (tether and stepper) as a method of reducing simulator sickness. No teleportation or room-scale interventions were investigated. Only one type of VR headset, the HTC Vive, was used and, most importantly, participants could only travel in one direction and at walking speed. This is a major simplification and deviation from the need for omni-directional motion at different speeds that most VR applications require. We were also limited in recruiting participants from the psychology department and as a result our participants do not necessarily represent the average VR user. Only one virtual environment was used. This means that our results may not necessarily be significant for all types of virtual environments.

Other factors that may have limited our results include: The weather was not consistent throughout the duration of the experiment. Rain was observed on numerous days which may have affected our physiological measurements. The Biopac required a wired connection meaning that participants had to be aware of their distance from the machine, potentially affecting our physiological measures. The stepper and tether prototypes had to be designed and implemented in under three months. This left little time for iteration and as such the stepper and tether can only be considered, at most, second generation prototypes. This should be taken into consideration when interpreting the results as they were directly competing against a consumer-grade VR controller.

7 RESULTS & DISCUSSION

Once the data had been collected, our results were processed. ECG readings were converted into heart rate and all the questionnaires were scored. The following steps were taken for all data sets unless specified otherwise and all tests were conducted with an $\alpha = 0.05$. First we determined whether our data was parametric or non-parametric. This was done by conducting a Shaprio-Wilk test for normality as a well as Mauchly's test for sphericity. None of our data sets passed both the Shaprio-Wilk and Mauchly tests. This meant that all of our datasets were non-parametric. A Friendman test for significance was performed on all datasets to determine whether there were significant differences within a dataset. If a significant difference was found, a Nemenyi post-hoc test was used to determine which of our movement interventions were significantly different from the other movement interventions. The Nemenyi post-hoc test was chosen because it takes the entire dataset into consideration when comparing two movement interventions. The results obtained during the experiment are summarized below. All SSQ charts plot the change in score between pre and post questionnaires.

7.1 Physiological Measures

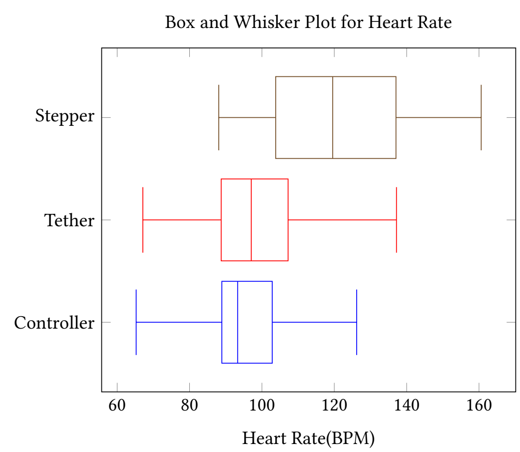

Figure 11: Box and whisker plot of average heart rate for all three movement interventions over eight minutes of exposure.

7.1.1 Heart Rate. The Friedman test $\chi^2 = 33.852, (2, 27), p < 0.05$ revealed significant differences between the three movement interventions. The Nemenyi post-hoc test revealed that the stepper was significantly different than both the controller and the tether. These results make sense because the stepper required considerably more physical work than both the tether and the controller. Unfortunately, these results to do not suggest that either the stepper or

Nemenyi Post-hoc test for Heart rate ($\alpha = 0.05$)		
	Controller	Tether
Controller	0.36	-
Tether	7.20E-08	7.30E-05

Table 2: Nemenyi Post-Hoc test results for average Heart rate.

tether reduced simulator sickness but does indicate that the stepper was significantly harder to use for an extended period of time.

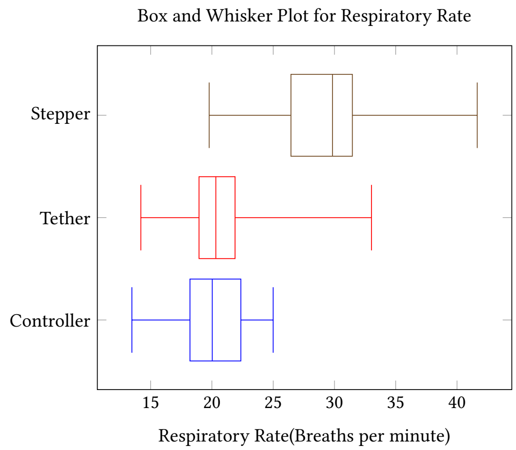

Figure 12: Box and whisker plot of average repiratory rate for all three movement interventions over eight minutes of exposure.

Nemenyi Post-hoc test for Respiratory Rate ($\alpha = 0.05$)		
	Controller	Tether
Controller	0.44	-
Tether	3.30E-08	2.10E-05

Table 3: Nemenyi post-hoc test results for average Respiratory Rate.

7.1.2 Respiratory Rate. A Friedman test $\chi^2 = 36.222, (2, 27), p < 0.05$ revealed significant differences in our respiratory rate between movement interventions. The Nemenyi post-hoc test revealed significant differences between the stepper and both the controller and the tether. The reasons for these results are most likely similar to the reasons for the HR results. The stepper required considerably more physical effort and explains the difference in mean between the stepper (29.34) and the other movement interventions(controller = 19.02 & tether = 21.29). These results do not indicate that the tether or the stepper mitigate the effects of simulator sickness.

7.1.3 Skin Capacitance. The Friedman test $\chi^2 = 24.889, (2, 27), p < 0.05$ revealed significant differences in skin capacitance. The Nemenyi post-hoc test revealed that the controller was significantly

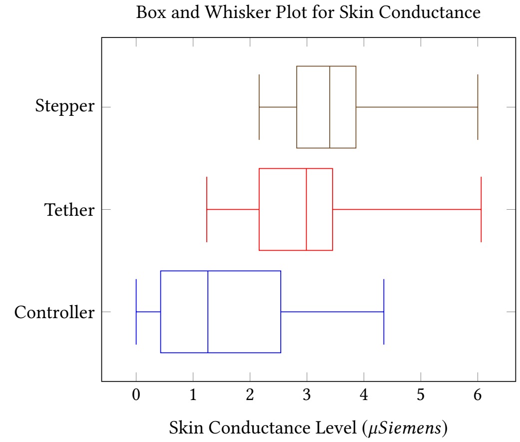

Figure 13: Box and whisker plot of average skin capacitance for all three movement interventions over eight minutes of exposure.

Nemenyi Post-hoc test for Skin Capacitance ($\alpha = 0.05$)		
	Controller	Tether
Controller	0.0031	-
Tether	2.90E-06	0.2317

Table 4: Nemenyi post-hoc test results for average Skin Capacitance.

different than the other two movement interventions. This is most likely due to the physical exertion required to use both the tether and the stepper. It should also be noted that weather has an effect on GSR readings. It rained on multiple days on which data was recorded. This may have altered the final results. The skin capacitance values suggest that the tether and stepper induced more simulator sickness than the controller.

Overall the physiological measurements suggest that the stepper performed significantly worse than the other two movement interventions. This is most likely due to the additional physical effort required by the stepper. The results also suggest that the stepper induced significantly more than both controller and the tether. This could suggest that haptic feedback may not actually decrease SS but is inconclusive because the tether seems to have performed at a similar level to that of the controller.

7.2 Subjective Measures

Nemenyi Post-hoc test for SSQ Nausea(N) Component ($\alpha = 0.05$)		
	Controller	Tether
Controller	0.0.44	-
Tether	2.90E-06	0.0007

Table 5: A summary of the Nemenyi post-hoc test results for the SSQ Nausea (N) component.

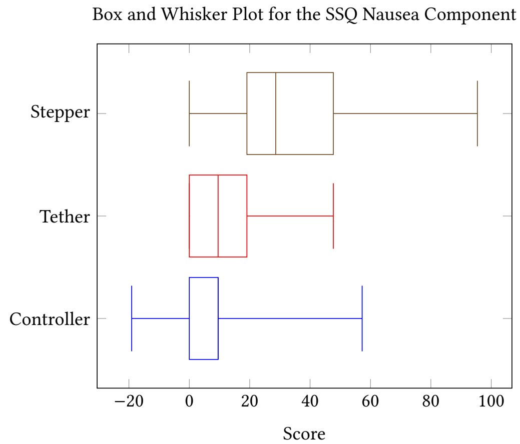

Figure 14: Box and whisker plot of the SSQ nausea (N) component for all three movement interventions after eight minutes of exposure.

Figure 15: Box and whisker plot of the SSQ ocular (O) component for all three movement interventions after eight minutes of exposure.

Nemenyi Post-hoc test for SSQ Ocular(O) Component ($\alpha = 0.05$)		
	Controller	Tether
Controller	0.74	-
Tether	0.018	0.12

Table 6: A summary of the Nemenyi post-hoc test results for the SSQ Ocular (O) component.

Figure 16: Box and whisker plot of the SSQ disorientation (D) component for all three movement interventions after eight minutes of exposure.

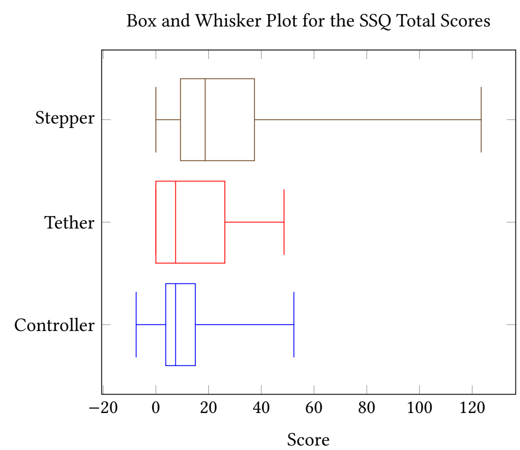

Figure 17: Box and whisker plot of the total SSQ scores for all three movement interventions after eight minutes of exposure.

Nemenyi Post-hoc test for Total SSQ Scores ($\alpha = 0.05$)		
	Controller	Tether
Controller	0.98	-
Tether	0.00013	3.10E-04

Table 7: Summary of the Nemenyi post-hoc test results for the total SSQ scores.

7.2.1 SSQ. Friedman tests revealed significant differences in the Nausea $\chi^2 = 29.558, (2, 27), p < 0.05$, Ocular $\chi^2 = 10.543, (2, 27), p < 0.05$ and Total $\chi^2 = 23.091, (2, 27), p < 0.05$ SSQ scores. Interestingly, the disorientation $\chi^2 = 3.909, (2, 27), P > 0.05$ scores did not contain any significant results. This is most likely due to the fact that participants could only move in one direction and as such orientating oneself was not a challenge. Nausea was the largest contributor to the SSQ Total and was most severe on the stepper. This may suggests that the introduction of haptic feedback may not reduce simulator sickness but is most likely due to the stepper's poor design and the participants' unfamiliarity with the device. Participants often exclaimed that they felt like they were going to fall off of the stepper and felt uncomfortable by the general lack of balance that they had while on the stepper. Contrary to the stepper, the tether did not perform significantly worse than the controller for any SS categories. This is an interesting result because the tether prototype was competing against a consumer-grade controller yet it did not perform significantly worse. This result does not eliminate haptic feedback as a possible solution for SS. Further iterations of the tether device may, in fact reduce SS. Their is an argument, while not specifically evaluated in this project, that the results of this experiment may support the postural instability theory as the tether and stepper performed worse, on average, when compared to the controller. This may be because the addition of haptic feedback does not make VR more familiar but rather exacerbates the problem as humans do not walk with the assistance of tether or stepper devices.

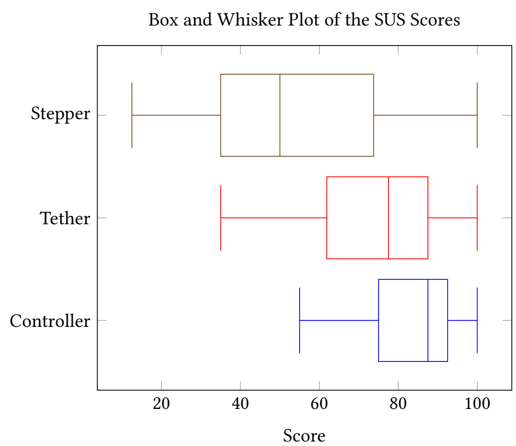

Figure 18: Box and whisker plot of the total SUS scores for all three movement interventions after eight minutes of exposure.

Nemenyi Post-hoc test for the SUS ($\alpha = 0.05$)		
	Controller	Tether
Controller	0.102	-
Tether	5.40E-05	0.064

Table 8: A summary of the Nemenyi post-hoc tests for the total SUS scores.

7.2.2 SUS. Friedman tests $\chi^2 = 20.234, (2, 27), p < 0.05$ revealed significant differences in our usability data. Nemenyi post-hoc tests revealed that the controller was significantly different to the stepper prototype. The mean score for the controller was 83.57, this was to be expected of a consumer-grade product and further highlights the disadvantages the tether and stepper prototypes had in competing with the controller. The tether had a mean score of 73.21. This is extremely promising for a prototype device. For context, any score above 68 is considered satisfactory. Future iterations of the tether may improve upon this score. An emergent behaviour was also observed during the experiments. Some participants walked on the spot while pulling on the tether perhaps indicating immersion. The stepper had a mean score of 53.75. This is considered unsatisfactory. The steppers results are to be expected because participants associated it with an increased feeling of SS. Interestingly, the usability scores for the stepper are significantly more polarizing than the other two movement interventions. It was observed, not measured, that participants would score the stepper based upon their fitness level with fitter participants giving the stepper higher usability scores and the complete opposite for participants who were less fit.

8 CONCLUSIONS & FUTURE WORK

We sought to reduce SS with the aid of haptic feedback. Twenty-seven participants tested three movement interventions (controller, tether and stepper) and their heart rate, respiratory rate, skin capacitance and simulator sickness score were obtained. Participants also scored each movement intervention with the SUS questionnaire. Our results are inconclusive. They do not suggest or reject that haptic feedback may reduce SS. The stepper prototype was a complete failure. It performed worse on all measures when compared to the controller. This can be attributed to the poor design of the stepper as well as the amount of physical work required to use it for long periods of time. The tether prototype performed about as well as the controller for all measurements. This is promising considering the tether had undergone little redesign. Future iterations of the tether may reduce the effects of SS. The controller performed the best for all measurements. This can mostly be attributed to the fact that it is a consumer-grade product and has undergone multiple redesigns to make it more usable. The controller was also the most familiar of the movement interventions which played a part in its usability.

There are numerous avenues that can be taken for future work. In our opinion, the next logical step is to further improve the tether and test the effect haptic feedback has on SS for omni-directional travel. Testing different solutions for different movement categories (teleportation, room-scale walking) and amalgamations of these categories may utilize haptic feedback more effectively than the motion-based movement interventions tested in this project. Further work can be done on analyzing the effect that the environment being traversed has on the amount of SS induced. For example, the stepper prototype might not have been significantly worse if the virtual environment was a simple endless corridor. It may be worth-while to test other kinds of devices, like a treadmill, which we feel will be slightly better than the stepper. Further work can also be done on testing this project on a more representative set of participants.

9 ACKNOWLEDGEMENTS

We would like to thank the numerous people who were involved with the VRMove project. We thank both Timothy Gwynn and Johan Bontes for their guidance on both virtual environment design and simulator sickness respectively. We would also like to thank Buhle Nongxa for assisting us as our research assistant. We would also like to thank UCT's psychology and health sciences department for loaning us the Biopac device. Lastly, we would like to thank

Assoc. Prof. James Gain for being our supervisor and guiding us throughout the project.

REFERENCES

[1] [n. d.]. Guidelines for VR Performance Optimization. https://developer.oculus.com/documentation/pcsdk/latest/concepts/dg-performance-guidelines/

[2] Hironori Akiduki, Suetaka Nishiike, Hiroshi Watanabe, Katsunori Matsuoka, Takeshi Kubo, and Noriaki Takeda. 2003. Visual-vestibular conflict induced by virtual reality in humans. *Neuroscience letters* 340, 3 (2003), 197–200.

[3] Laura Lynn Arns. 2002. A new taxonomy for locomotion in virtual environments. (2002).

[4] J Gayle Beck, Sarah A Palyo, Eliot H Winer, Brad E Schwagler, and Eu Jin Ang. 2007. Virtual reality exposure therapy for PTSD symptoms after a road accident: An uncontrolled case series. *Behavior therapy* 38, 1 (2007), 39–48.

[5] Costas Boletsis. 2017. The New Era of Virtual Reality Locomotion: A Systematic Literature Review of Techniques and a Proposed Typology. *Multimodal Technologies and Interaction* 1, 4 (2017), 24.

[6] Frederick Bonato, Andrea Bubka, Stephen Palmisano, Danielle Phillip, and Giselle Moreno. 2008. Vection change exacerbates simulator sickness in virtual environments. *Presence: Teleoperators and Virtual Environments* 17, 3 (2008), 283–292.

[7] Doug A Bowman, David Koller, and Larry F Hodges. 1998. A methodology for the evaluation of travel techniques for immersive virtual environments. *Virtual reality* 3, 2 (1998), 120–131.

[8] John G Casali and Lawrence H Frank. 1986. Perceptual distortion and its consequences in vehicular simulation: Basic theory and incidence of simulator sickness. *Transportation Research Record* 1059 (1986), 57–65.

[9] Sue VG Cobb, Sarah Nichols, Amanda Ramsey, and John R Wilson. 1999. Virtual reality-induced symptoms and effects (VRISE). *Presence: Teleoperators & Virtual Environments* 8, 2 (1999), 169–186.

[10] Nicola Diolaiti and Claudio Melchiorri. 2002. Teleoperation of a mobile robot through haptic feedback. In *IEEE International Workshop HAVE Haptic Virtual Environments and Their*. IEEE, 67–72.

[11] Mark H Draper, Erik S Viirre, Thomas A Furness, and Valerie J Gawron. 2001. Effects of image scale and system time delay on simulator sickness within head-coupled virtual environments. *Human factors* 43, 1 (2001), 129–146.

[12] Henry Been-Lirn Duh, Donald E Parker, and Thomas A Furness. 2004. An independent visual background reduced simulator sickness in a driving simulator. *Presence: Teleoperators & Virtual Environments* 13, 5 (2004), 578–588.

[13] Kay Fitzpatrick, Marcus A Brewer, and Shawn Turner. 2006. Another look at pedestrian walking speed. *Transportation research record* 1982, 1 (2006), 21–29.

[14] Lawrence H Frank, John G Casali, and Walter W Wierwille. 1988. Effects of visual display and motion system delays on operator performance and uneasiness in a driving simulator. *Human Factors* 30, 2 (1988), 201–217.

[15] Thomas L Grey and Gregory J Gruzdowich. 2001. Electro-acupuncture method using an electrical stimulator. US Patent 6,272,383.

[16] Erica Harvey and Chaim Gingold. 2000. Haptic representation of the atom. In *2000 IEEE Conference on Information Visualization. An International Conference on Computer Visualization and Graphics*. IEEE, 232–235.

[17] Lawrence J Hettinger, Kevin S Berbaum, Robert S Kennedy, William P Dunlap, and Margaret D Nolan. 1990. Vection and simulator sickness. *Military Psychology* 2, 3 (1990), 171–181.

[18] Simon G Hosking and Boris Crassini. 2010. The effects of familiar size and object trajectories on time-to-contact judgements. *Experimental brain research* 203, 3 (2010), 541–552.

[19] David Kanter. 2015. Graphics processing requirements for enabling immersive vr. *AMD White Paper* (2015).

[20] Robert S Kennedy and Jennifer E Fowlkes. 1992. Simulator sickness is polygenic and polysymptomatic: Implications for research. *The International Journal of Aviation Psychology* 2, 1 (1992), 23–38.

[21] Robert S Kennedy, Norman E Lane, Kevin S Berbaum, and Michael G Lilienthal. 1993. Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. *The international journal of aviation psychology* 3, 3 (1993), 203–220.

[22] Robert S Kennedy, Michael G Lilienthal, Kevin S Berbaum, DR Baltzley, and ME McCauley. 1989. Simulator sickness in US Navy flight simulators. *Aviation, space, and environmental medicine* 60, 1 (1989), 10–16.

[23] Young Youn Kim, Hyun Ju Kim, Eun Nam Kim, Hee Dong Ko, and Hyun Taek Kim. 2005. Characteristic changes in the physiological components of cybersickness. *Psychophysiology* 42, 5 (2005), 616–625.

[24] Eugenia M Kolasinski. 1995. *Simulator Sickness in Virtual Environments.* Technical Report. Army research Inst for the behavioral and social sciences Alexandria VA.

[25] Donald Ralph Lampton, Mar Esther Rodriguez, and James Eastham Cotton. 2000. Simulator sickness symptoms during team training in immersive virtual environments. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, Vol. 44. SAGE Publications Sage CA: Los Angeles, CA, 530–533.

[26] Benjamin Lok, Samir Naik, Mary Whitton, and Frederick Phillips Brooks. 2003. Effects of handling real objects and avatar fidelity on cognitive task performance in virtual environments. In *IEEE Virtual Reality, 2003. Proceedings.* IEEE, 125–132.

[27] Michael Meehan, Sharif Razzaque, Mary C Whitton, and Frederick P Brooks. 2003. Effect of latency on presence in stressful virtual environments. In *IEEE Virtual Reality, 2003. Proceedings.* IEEE, 141–148.

[28] Ronald R Mourant and Thara R Thattacherry. 2000. Simulator sickness in a virtual environments driving simulator. In *Proceedings of the human factors and ergonomics society annual meeting*, Vol. 44. SAGE Publications Sage CA: Los Angeles, CA, 534–537.

[29] Thomas Nescher, Ying-Yin Huang, and Andreas Kunz. 2014. Planning redirection techniques for optimal free walking experience using model predictive control. In *2014 IEEE Symposium on 3D User Interfaces (3DUI).* IEEE, 111–118.

[30] Jerrold D Prothero, Mark H Draper, DE Parker, MJ Wells, et al. 1999. The use of an independent visual background to reduce simulator side-effects. *Aviation, space, and environmental medicine* 70, 3 Pt 1 (1999), 277–283.

[31] Gary E Riccio and Thomas A Stoffregen. 1991. An ecological theory of motion sickness and postural instability. *Ecological psychology* 3, 3 (1991), 195–240.

[32] Holly A Ruff. 1984. Infants' manipulative exploration of objects: Effects of age and object characteristics. *Developmental Psychology* 20, 1 (1984), 9.

[33] Eva-Lotta Sallnäs, Kirsten Rassmus-Gröhn, and Calle Sjöström. 2000. Supporting presence in collaborative environments by haptic force feedback. *ACM Transactions on Computer-Human Interaction (TOCHI)* 7, 4 (2000), 461–476.

[34] Maria T Schultheis and Albert A Rizzo. 2001. The application of virtual reality technology in rehabilitation. *Rehabilitation psychology* 46, 3 (2001), 296.

[35] Kay Stanney. 1995. Realizing the full potential of virtual reality: human factors issues that could stand in the way. In *Proceedings Virtual Reality Annual International Symposium'95.* IEEE, 28–34.

[36] Jonathan Steuer. 1992. Defining virtual reality: Dimensions determining telepresence. *Journal of communication* 42, 4 (1992), 73–93.

[37] P Ström, Leif Hedman, L Särnå, A Kjellin, T Wredmark, and L Felländer-Tsai. 2006. Early exposure to haptic feedback enhances performance in surgical simulator training: a prospective randomized crossover study in surgical residents. *Surgical endoscopy and other interventional techniques* 20, 9 (2006), 1383–1388.