



UNIVERSITY OF CAPE TOWN

DEPARTMENT OF COMPUTER SCIENCE



# CS/IT Honours Final Paper 2019

Title: The Effect of Haptic Feedback on Simulator Sickness in VR

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Project Abbreviation: VRMOVE

Supervisor(s): James Gain

Category	Min	Max	Chosen
Requirement Analysis and Design	0	20	5
Theoretical Analysis	0	25	20
Experiment Design and Execution	0	20	0
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
<u>Overall General Project Evaluation</u> ( <i>this section allowed only with motivation letter from supervisor</i> )	0	10	
<b>Total marks</b>		<b>80</b>	

# Haptic Feedback Tether as an Aid to Simulator Sickness

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## ABSTRACT

This paper explores haptic feedback as a potential intervention to reduce simulator sickness experienced at walking speed. Haptic feedback is in the form of a tether-like device. The proposed tether device is attached around the users waist on one end and attached to the wall on the other end. The device moves the user forward in VR with a speed proportional to the force applied to the tether (and by extension, the force applied to the user). This device is evaluated in comparison to using a controller for movement as well as in comparison to using stepper device for movement. 27 participants were recruited to navigate through a virtual environment for 8 minutes on three different days. Each day the participant used a different movement method. The same environment was used on all three occasions. While in the virtual environment, participants were required to move through the environment and interact with environment elements. A simulator sickness questionnaire was completed before and after each movement method. Three physiological measures were also taken before and during navigation in the environment. Finally, a System Usability Scale questionnaire was completed by each participant for each movement method. When compared to the controller, there was found to be no reduction in simulator sickness when the tether was used by participants. When the stepper was used there was in actual fact an increase in simulator sickness symptoms. No difference in usability scores was found between the tether and controller. The stepper, however, was found to have lower usability scores than the controller and tether. The results of our study suggest that haptic feedback is not an effective intervention for simulator sickness.

## KEYWORDS

Virtual Reality, Simulator Sickness, Cybersickness, Motion Sickness, Haptic Feedback, Virtual Environments

## 1 INTRODUCTION

In 1987 a company in the USA named VPL sold the first pair of VR goggles. These goggles, dubbed the Eyephone 1, were sold at an eye-watering \$9400 a piece, and were a great commercial success. In the late 80s and early 90s VR was all the rave and featured at major theme parks such as Universal Studios as well as in arcades. However, the commercial success of VR was short-lived due to reports of consumers getting nauseous, dizzy, experiencing headaches and, in extreme cases, vomiting. The hype could only carry VR so far until Simulator Sickness began to take its toll on the industry. Simulator Sickness is an umbrella term encompassing all negative symptoms experienced during or as a result of VR. VR has seen a resurgence in popular culture recently with the likes of Oculus (now owned by Facebook), HTC and Google touting new VR Head Mounted Displays (HMDs) that provide better performance, a more

immersive experience and at a lower price point. Simulator Sickness, however, remains an issue. Modern games are now designed in such a way that simulator sickness is avoided, but this is more of a band-aid than a remedy to the problem. In this paper we discuss the use of haptic feedback, and specifically a tether device as an adjunct mechanism for the purpose of movement through VR without the adverse symptoms often accompanying such movement. This tether device is evaluated against the HTC Vive controller and a stepper machine as movement methods.

The main component to simulator sickness we are interested in tackling isvection, which is best described as the experience of a sense of self-motion. Vection is a quick trigger for simulator sickness and is the main physiological cause behind motion sickness. Other triggers related to the simulator or hardware being used, such as low frame rates or judder exist too, however, these triggers are not related to movement in VR but rather to the equipment being used. Therefore symptoms experienced due to these triggers can be remedied by software optimizations or hardware improvements.

Simulator sickness, aside from making the virtual experience unpleasant, can leave lasting effects of light-headedness and confusion even after exposure to the virtual environment [Kellogg and Gillingham 1986]. This is both a usability and safety concern, in that people will not be interested in engaging with VR and also, depending on the severity of the symptoms, might leave people temporarily incapacitated. Therefore, it is necessary to investigate a feasible and usable solution to this problem, lest history repeat itself.

Haptic feedback has been seen to be an effective means of interaction with objects in VR with positive results found in research on haptic props to enhance the VR experience. In light of this, we aim to explore haptic feedback as an effective means of travel in VR, as opposed to using the conventional controller for movement. Ultimately, the research questions to be answered are the following:

- (1) Does the use of a tether device for movement at walking speed reduce simulator sickness when compared to the standard controller?
- (2) Does a tether device achieve higher usability scores when compared to the standard controller?

## 2 BACKGROUND AND RELATED WORK

In order to provide a holistic view of our research we present the required background information pertaining to the research questions to be answered, as well as the current research results related to the research questions. Specifically, this information is to provide an understanding of simulator sickness and also to give an overview of what research surrounding movement interventions for reduced simulator sickness symptoms already exists.

## 2.1 Simulator Sickness Causes, Symptoms and Theories

Simulator sickness is classified as a syndrome and hence is simply a label for a group of symptoms which consistently occur together, or a condition characterized by a set of associated symptoms.

Common symptoms of simulator sickness are the following:

- General discomfort
- Stomach awareness
- Difficulty concentrating
- Headache
- Eyestrain
- Sweating
- Nausea
- Dizziness

This list is not exhaustive but should provide a good indication of what can be expected when Simulator Sickness is experienced. Some common causes are discussed below.

*Latency.* Latency is the delay between the user input and the observed output. In most VR systems, latency is the largest source of error [Holloway 1997].

*Calibration.* Calibration is the correct mapping between real world user input and input to the system. If calibration is not accurate, it may be a major cause of simulator sickness. In the worst case, bad calibration may result in unstable, shaky scenes and scene motion when the user moves their head [Holloway 1995].

*Field-of-view (FOV).* A wider FOV will result in more sickness due to higher sensitivity tovection which in turn is due to more stimuli to peripheral vision [Lin et al. 2002].

*Refresh rate.* The higher the display refresh rate, the lower the latency, judder and flicker. [Jerald 2015]

*Flicker.* Higher luminance results in more flicker. In the best case flicker is a distraction and results in eyestrain. In the worst case it can cause seizures. [Jerald 2015]

*Conflict between vergence and accommodation.* Conventionally, accommodation remains constant but vergence does not. Therefore when visuals are placed close to the eye it may induce eyestrain. Therefore it is advised to either avoid it or only do for short periods of time to reduce strain on the eyes. [Donders and Moore 1864]

*Binocular Images.* Either monocular or binocular imaging may be used. Monocular uses the same one image for each eye while binocular imagine uses two slightly different images to provide the illusion of depth. Incoherent binocular images can lead to double images and eye strain. [Donders and Moore 1864]

We are most interested in causes ofvection as other causes can easily be managed.

Looking at the theories behind simulator sickness, there are multiple candidates with merit however the two most prominent theories are the sensory conflict theory and the postural instability theory.

The sensory conflict theory proposed first by [Reason and Brand 1975] says that simulator sickness occurs when there is discord

between input from bodily senses that expect to receive coordinated input. For example, stimulation of the vestibular system is usually accompanied by visual information corresponding to such stimulation. This discord may occur in VR when visual and auditory signals for motion are provided by the simulation. The brain expects corresponding vestibular and proprioceptive (relating to body position and movement) stimuli originating from the movement of the body which, unless the body genuinely is moving, will not be observed. When input from these senses do not correspond as expected then symptoms similar to those experienced during motion sickness may occur.

The postural instability theory by [Riccio and Stoffregen 1991] suggests that stable posture is a primary goal in animals and therefore, by extension, in humans. This postural stability is dependent on the environment and humans adapt their physical positioning to ensure this stability. When no such adaptation is possible for long periods of time the body begins to show symptoms of motion sickness. [LaViola 2000] states that the body is constantly moving and maintaining bone position to ensure stable posture. When the wrong muscle control is applied due to perceiving visual motion inconsistent with the physicality of the body, postural instability occurs. This is substantiated by the experiments done by [Stoffregen and Smart 1998] in which participants were exposed to different visual patterns via a head mounted display and postural sways were observed to precede motion sickness in participants.

According to [Bertolini and Straumann 2016], sensory conflict is the most widely accepted theory behind simulator sickness.

A study done by [Kennedy et al. 1987] states that repeated exposure tovection leads to reduced simulator sickness symptoms over time, as the brain learns to accommodate the mismatch. The study was carried out 10 participants who repeatedly experienced a visual/vestibular conflict over trials and days. These participants were shown to have reduced symptoms of dizziness and ataxia.

It is estimated that 95% of people are able to adapt to the mismatch after repeated exposure tovection [Tyler and Bard 1949]. The remaining people, regardless of the amount of exposure, do not adapt or experience reduced symptoms.

## 2.2 Haptic Feedback

Current literature around haptic feedback for movement in VR is sparse, however two interesting works of research surrounding haptic feedback for manipulation of objects in VR are discussed. Firstly, a device providing Dynamic Passive Haptic Feedback (DPHF), which is a combination of Active Haptic Feedback and Passive Haptic Feedback is introduced by [Zenner and Krüger 2017]. The device, named Shifty, is a rod-shaped DPHF proxy object used to interact with items in the virtual environment. Described best by [Zenner and Krüger 2017] themselves: "It is an ungrounded generic physical proxy that uses actuators to slowly shift an internal weight, changing its passive haptic properties in order to enhance the perception of objects during VR interaction." Positive results were observed from the experiments in which twelve participants were asked to interact with objects in a virtual environment. Participants reported higher levels of realism and enjoyment although higher levels of exertion and fatigue were also reported.

The second paper we discuss is by [Fujinawa et al. 2017] where they investigated illusory shape perception in VR with the help of weighted haptic props. Similar to the first paper, the weight applied gives the illusion of differently sized and shaped objects. The difference between the first and second paper is that the prop is a similar shape to the object they would be interacting with in VR, albeit in a smaller scale. It was found that while users were able to perceive illusory shapes, the actual shape of the prop made no difference to the perception of the participant.

What these papers tell us is that haptic feedback can be used effectively to enhance the VR experience as far as interaction with objects is concerned. We now posit haptic feedback as a potential means of providing relief to simulator sickness. It aims to do so by providing additional, reinforcing sensory cues or signals such as the feeling of force being applied. There is current literature that does look at alternative movement methods such as the World-In-Miniature approach by [Stoakley et al. 1970] and the Jumper method by [Bolte et al. 2011] but no method similar to the proposed tether device has been researched.

### 2.3 Simulator Sickness Measurements

The Simulator Sickness Questionnaire(SSQ) by [Kennedy et al. 1988] has been used regularly throughout literature. To ensure that results from our work may be compared to current work in the field we shall follow suit. Two ways of conducting the SSQ and analyzing SSQ scores have been seen in literature. [Kennedy et al. 1988], the original author simply took one SSQ measurement after completion of the experiment. The same approach was followed by [Kim et al. 2005]. This approach has been criticized by [Bruck and Watters 2009] as it does not take a baseline reading before the experiment. They argue that a baseline reading against which to evaluate the reported symptoms is required in order to associate reported symptoms with simulated motion in the experiment. If a baseline reading is not taken, it cannot be said with surely that the symptoms reported were not already present before the experiment had begun. [Kennedy et al. 1988] does however state that all participants are assumed to be in good health and if upon asking participants, any are not, they are not included in the experiment. It can therefore be inferred that the expected score of a baseline SSQ will be zero for all participants as they are in good health and will report no symptoms before exposure. We are inclined to side with [Bruck and Watters 2009] and do not believe Kennedy's approach is reliable. However to ensure that our work is comparable we will follow both approaches and report both SSQ data compared to a baseline as well as post experiment SSQ data without comparison to a baseline reading. The SSQ can be seen in figure 17 in the appendices.

We will also make use of physiological measurements in light of work done by [Harm 2002; Kim et al. 2005] which support the claim that the use of certain physiological measures provide an objective, unbiased measurement of sickness over a VR experience.

Physiological data that changes as sickness occurs include the following:

- Heart rate
- Blink rate
- Electroencephalography (electrical activity of the brain)
- Skin capacitance

### 2.4 Usability Measurements

The System Usability Scale (SUS)[Brooke and others 1996] will be used to evaluate the usability of the tether and it will be compared to the stepper and to the standard controller. The SUS is widely used when testing new systems and has short, easy to answer questions. This is important due to how many times participants complete questionnaires throughout the course of the experiment. The possibility that participants get tired of answering questions should be minimized so as to ensure reliable answers.

## 3 TETHER DESIGN AND IMPLEMENTATION

The final design for the tether device required three iterations of development, each iteration simplifying upon design choices from the previous iteration. The first design sketch involved the use of a cable of some sort and an arduino microcontroller to report on tension applied to the cable. This tension would proportionally move the participant forward in the virtual environment. The material of the cable and the way that tension would be reported was left undecided.

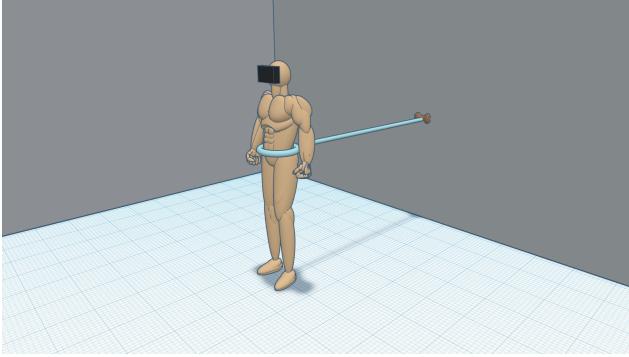


**Figure 1: The draft design of the second iteration of the tether**

The second iteration of the tether design used a cable without any elasticity connected to weights over a pulley. This would provide tension as the participant moves forward. The cable attached to the participant pulls on the weights and the weights move up. The HTC Vive Tracker would then be attached to the weights and tension would be inferred based on the upward and downward movement of the tracker. This design is shown in Figure 1. Using inferred tension meant that the HTC Vive Tracker could be used instead of an arduino microcontroller as the Vive Tracker already had a refined, robust and easy to use API. The arduino-based approach would require an API to be developed and tested. The problem with this approach is that the amount of force required to lift the weights remains constant regardless of how far the weights are raised, while the tether approach aims to provide a force proportional to the speed the user of the device moves at. To clarify, the force required to hold a weight at 1 meter above the ground is the same as the force required to hold a weight at 2 meters above the ground. We require that the further the participant is from the base of the tether, the more force they are required to exert.

The third and final iteration of the tether device removed the weights and utilized a cable that would have a degree of elasticity but exert a force proportional to how much it has been stretched. The cable would exert a maximum tensile force when stretched to its longest length. This maximum force is a specification of the cable selected and in the case of the experiments this specification was 42 KG. 42 KG was chosen as anything less than 42 KG seemed

to stretch too easily and would invite participants to walk forward more than they should be able to. A prototype sketch is shown in Figure 2. A participant using the tether can be seen in Figure 3 and 4.



**Figure 2: Draft final tether design. The user, with the cable attached around their waist, steps forward. By pulling on the tether, they move forward in the virtual environment**



**Figure 3: Tether device with participant at rest**

## 4 METHODS AND EXPERIMENT DESIGN

Here we discuss how we designed the experiment and how data was collected.

### 4.1 Virtual Environment

In order to induce a measurable amount of simulator sickness the environment had to be specifically designed for this purpose. The environment was made to allow movement only in a single direction without the ability for rotation. A forest path was chosen for two reasons: firstly, a forest path with trees on either side would clearly



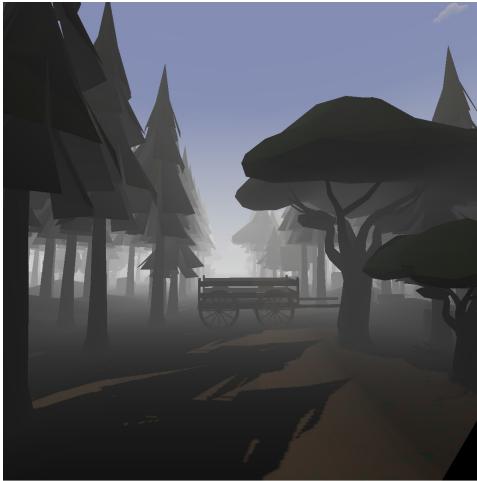
**Figure 4: Tether device with participant in motion**

and intuitively indicate that it was not possible for the participant to turn or move off of the path, and secondly, having trees on either side adds the element ofvection. The environment was designed to be as long as required to keep the participant moving through it for approximately 8 minutes. This duration was chosen after reviewing work done in [2005] where 9.5 minutes were used. Some participants vomited during those experiments and as we were working with students who had classes after the experiments we wanted to limit the effect size. We therefore decided to reduce the time in the experiment to roughly 8 minutes. We believed this to be sufficient as [Kim et al. 2005] reported physiological changes measured within the first four minutes on average. Interactive elements were added to the environment to keep the participant relatively engaged so as to avoid physiological responses due to boredom. The final environment can be seen in Figure 5 and 6



**Figure 5: Screenshot from the VE**

Unity was used to create the VE with the help of the SteamVR plugin for VR related components. Two iterations of the environment were developed. The first was a high-fidelity prototype that allowed us to begin work on implementing the movement methods as quickly as possible.



**Figure 6: Screenshot from the VE**

In the final iteration of the environment, fog was used as a means of reducing the amount of objects rendered at any one time. This was done to maintain maximum frame rates at all times as dropped frames is a common cause of eye strain, amongst other simulator sickness symptoms, and therefore needed to remain a nonfactor.

## 4.2 Equipment

The equipment used was a desktop PC, an HTC Vive and a BIOPAC MP150. The PC was equipped with a GTX1070 graphics card, an Intel® Core™ i7-6700K Processor, 8 Gigabytes of RAM and a 512 Gigabyte SSD. The BIOPAC was used with the following modules for electrocardiograph, respiratory sinus arrhythmia and galvanic skin response, ECG100C, RSP100C, GSR100C, respectively.

## 4.3 Measures

Both subjective and objective measures were used. Both the SSQ, for measuring simulator sickness, and the SUS, to measure usability of the system, are subjective measures while the physiological data collected served as an objective measure for simulator sickness. We made use of the BIOPAC MP150 to measure physiological changes. The BIOPAC MP150 provides readings of the following physiological data:

- Electrocardiography
- Respiratory rate
- Galvanic Skin Response

The electrocardiogram data was converted into heart rate in beats per minute (BPM) and the respiratory rate was converted to breaths per minute. These conversions were facilitated by the Acqknowledge Software. The Galvanic Skin Response data is in the standard format of microsiemens and therefore no conversion was necessary.

## 4.4 Participants

The twenty-eight participants recruited were undergraduates from the Psychology Department of the University of Cape Town. The data of twenty-seven participants is included in the research, as one of the female participants were excluded due to abnormally high baseline SSQ scores. This clearly indicated that the participant was not in good health and as stated by [Kennedy et al. 1988] this contravenes the SSQ assumptions on participants. Twenty-five of these participants were female and two of them were male.

## 4.5 Experimental Procedure

The experimental procedure was broken up into three phases. Phase one is the initialisation phase - the electrodes are attached to the participant and they are verbally informed of what will be required of them. To ensure that all participants had a minimum level of experience with VR, all participants were required to play a VR game for 5 minutes before the experiment started on the day of arrival. This allowed any physiological changes due to the excitement and novelty of VR to wear off. The second phase was the experiment phase where the participant was required to navigate through the virtual environment using one of the three movement methods. Phase three was the debriefing phase where participants completed the last questionnaires and were directed towards the necessary health services if needed.

A pipelined approach was followed whereby two rooms were used. The first room was used for phase one and the second room was used for phases two and three. While a participant was completing phases two and three, another participant would arrive and begin phase one.

Due to the placement of electrodes on intimate areas, a female research assistant was employed to help female participants place the electrodes on their bodies. Due to the risks associated with VR experiments, all researchers obtained a certification in Level 1 First Aid. Ethics clearance was obtained for this research experiment and all participants took part voluntarily and signed a form of informed consent. Participants were thoroughly briefed before the experiment, as well as debriefed after the experiment. Participants were made aware that they could halt the experiment and quit at any time. The debriefing process ensured that participants knew how to get help for any symptoms they may feel after leaving.

A blow-by-blow description of the experiment process is given below:

- (1) Phase One
  - (a) Participant enters room one
  - (b) Overall procedure is explained, written informed consent is obtained and any questions that the participant may have are answered
  - (c) The electrodes are placed on the participant
  - (d) If it is the participants first day, they are placed in a VR carnival game for 5 minutes.
  - (e) The participant completes a baseline SSQ
- (2) Phase two
  - (a) Participant enters room two
  - (b) Electrodes are connected to ECG wires, respiratory belt is put on and GSR electrodes are connected to fingers

- (c) A one minute baseline reading of the physiological data is taken
  - (d) The movement method is introduced to the participant and navigation is explained
  - (e) The HMD is put on the participant and the controller is given to them
  - (f) The participant navigates through the environment until completion or for 8 minutes, whichever is shorter
  - (g) The HMD and controller are removed. The physiological measurement apparatus is disconnected from the participant. The participant is disconnected from the tether, or climbs off the stepper, depending on the movement method
- (3) Phase three
- (a) The participant completes a post movement method SSQ
  - (b) The participant completes a SUS for the movement method they used
  - (c) The participant is debriefed both verbally and provided a written copy of debriefing and leaves the experiment

Each participant undertook this process on each of the three days that they attended the experiments.

## 5 RESULTS AND DISCUSSION

In order to develop meaningful insights from the data we collected we first needed to process the data. Broadly speaking there are three different data sets per participant, per movement method.

The following is an example data set for a given participant and a given movement method:

- (1) System Usability Scale
- (2) Simulator Sickness Questionnaire
  - (a) Pre-method questionnaire
  - (b) Post-method questionnaire
- (3) Physiological data
  - (a) Heart rate
  - (b) Respiratory rate
  - (c) Galvanic Skin Response (Skin conductance)

The way this data will be processed and interpreted will be discussed in the following sections. Where statistical analysis was performed,  $\alpha=0.05$  was used.

### 5.1 SSQ Results

Each participant completed an SSQ questionnaire for each movement method before and after the experiment.

The symptoms asked about in the questions are clustered into three groups, namely Nausea (N), Oculomotor (O) and Disorientation (D). When scoring, the Total (T) score is the sum of the N, O and D point scores. This means that if for example 'Difficulty Concentrating' falls into both the N and O clusters, its numeric point score will be counted twice towards the total score.

To calculate the score for a completed SSQ the following procedure is followed:

- (1) Convert each answer to a numeric point score
- (2) Sum up the scores for each cluster.
- (3) Multiply the components by their corresponding weights

This will then provide scores for each of N, O and D clusters, as well as a score for T where T is the total SSQ score. Further detail regarding point scores and weights used can be found in the works of [Kennedy et al. 1988].

For each participant and each movement method, the pre movement method SSQ and post movement SSQ scores were calculated. The pre SSQ score was then subtracted from the post SSQ score so that a delta could be measured. The mean and standard deviation of these deltas were then calculated. Therefore, each movement method had a mean SSQ score increase and a standard deviation of SSQ score increase. To ensure that our results are comparable with literature only using one SSQ score (without a baseline) we also include data using only the post movement SSQ. Figure 7 and 8 show box and whisker plots of both methods of SSQ analysis.

A Shapiro-Wilk test of normality was then performed on all data sets. None of the data was seen to be normal and it could therefore not be assumed to be parametric. Therefore, a Friedman's repeated measures ANOVA for non-parametric data was performed to test if there was a significant difference between groups of symptom measurements across the three movement methods. The Friedman test reported evidence of significant differences between all data sets. The results can be seen in Table 4 and 5.

Looking at the results from the Friedman tests, significant differences for symptom clusters were found to be evident across all movement methods except for the Disorientation cluster. A Nemenyi post-hoc test was then performed on the data sets to establish which data sets differ from which other data sets. The results are shown in Table 6 and 7.

The Nemenyi test tells us that for the nausea symptom cluster there are significant differences between the stepper and the controller, and between the stepper and the tether, but not between the tether and the controller. This is the case regardless of whether SSQ scores were compared to baseline values. For the oculomotor cluster the Nemenyi test tells us that, where SSQ scores were compared to their baseline and the delta's taken, there was only a significant difference between the stepper and the controller. Where SSQ scores were not compared to baseline values, no differences between data sets were reported. This is despite the fact that the Friedman test reported a difference between data sets and is likely due to the small sample size and low statistical power of the Friedman test. For the disorientation symptom cluster the Friedman test reported no significant difference in data sets across movement methods so no post-hoc test was necessary. Finally, for the Total (T) score, significant differences were reported between the stepper and the controller, and between the stepper and the tether, but not between the tether and the controller. As with the nausea cluster this is the case regardless of whether SSQ scores were compared to baseline values or not.

### 5.2 Physiological Results

With the use of the BIOPAC three physiological measures were collected over a period of 8 minutes for each participant and each movement method. This resulted in 3 data files per participant, each containing 3 measurements. In order to process this data, the first and last 30 seconds were removed. This is due to observations of inconsistencies at the beginning and end of the experiment.

Nausea	Oculomotor	Disorientation
General Discomfort	General Discomfort	Difficulty Focusing
Increased Salivation	Fatigue	Nausea
Sweating	Difficulty Focusing	Fullness of Head
Nausea	Difficulty Concentrating	Blurred Vision
Difficulty Concentrating	Eyestrain	Dizzy (Eyes open)
Stomach Awareness	Blurred Vision	Dizzy (Eyes closed)
Burping	Headache	Vertigo

Table 1: Table of Symptom Clusters

Dataset	N		O		D		T	
	Mean	Std. Dev						
Controller	6.36	14.25	7.58	12.08	13.92	16.38	9.97	18.03
Tether	11.66	13.83	10.67	13.67	15.47	21.61	13.99	29.75
Stepper	31.8	21.17	17.41	18.43	30.42	41.23	29.23	14.23

Table 2: SSQ Delta Data

Dataset	N		O		D		T	
	Mean	Std. Dev						
Controller	12.01	13.39	13.19	14.5	13.92	16.83	16.21	14.52
Tether	13.78	14.57	13.19	13.72	15.47	23.27	16.48	15.25
Stepper	34.27	22.65	21.34	19.27	26.81	41.82	33.11	27.36

Table 3: SSQ Post Experiment Data

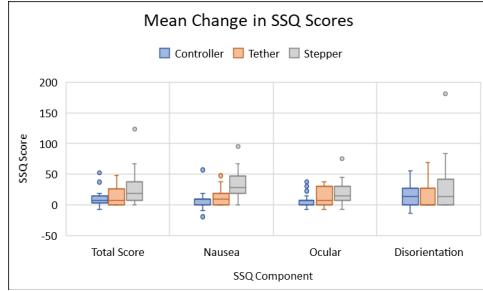


Figure 7: Box and whisker plot of SSQ Mean Deltas for each movement method

	X <sup>2</sup>	p-value
N	29.56	<b>0.000003816</b>
O	10.54	<b>0.005135</b>
D	3.91	0.1416
T	23.09	<b>0.00000968</b>

Table 4: Friedman test Chi-Squared and p-value statistics for SSQ Delta

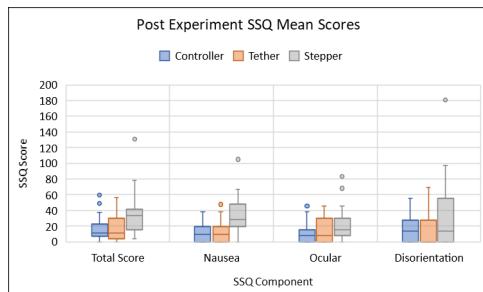


Figure 8: Box and whisker plot of Post Experiment SSQ Data for each movement method

	X <sup>2</sup>	p-value
N	30.80	<b>0.00000020</b>
O	6.93	<b>0.03</b>
D	5.91	0.05
T	23.09	<b>0.000019</b>

Table 5: Friedman test Chi-Squared and p-value statistics for Post Experiment SSQ

	N	O	T
Tether-Controller	0.4385	0.735	0.97729
Controller-Stepper	<b>0.0000029</b>	<b>0.018</b>	<b>0.00013</b>
Stepper-Tether	<b>0.0007</b>	0.119	<b>0.00031</b>

Table 6: Nemenyi Test Results for SSQ Delta

	N	O	T
Tether-Controller	0.73456	0.938	0.4385
Controller-Stepper	<b>0.0000057</b>	0.18	<b>0.0062</b>
Stepper-Tether	<b>0.00018</b>	0.088	<b>0.000054</b>

Table 7: Nemenyi Test Results for Post Experiment SSQ

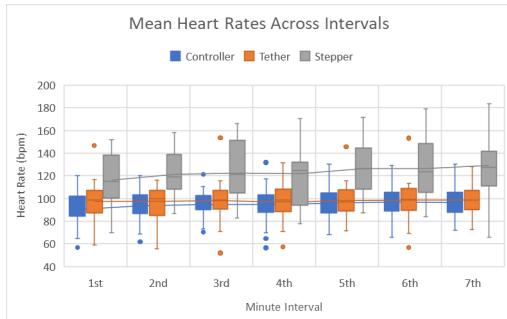


Figure 9: Box and whisker plot of average heart rate data over minute long intervals

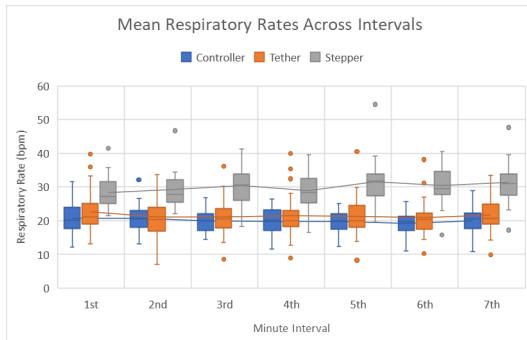


Figure 10: Box and whisker plot of average breathing rate data over minute long intervals

For example, some people would get confused at the beginning and start late, and at the end some would not stop when given the instruction to stop. By removing the first and last 30 seconds we lower the risk of these inconsistencies affecting the data gathered. After this process, the ECG data was converted to beats per minute, and the respiratory rate converted to breaths per minute. This was done using the Acqknowledge software.

Following the example of [Kim et al. 2005], the physiological data was grouped into minute long sections and the mean heart rate, respiratory rate and galvanic skin response was calculated for each minute.

Table 8 shows the mean and standard deviation statistics for Heart Rate (HR), Breathing Rate (RSP) and Galvanic Skin Response readings. Figure 9, 10, 11, 12, 13 and 14 show box and whisker plots of both interval and total physiological data.

A Shapiro-Wilk test of normality was then performed on all data sets. Heart Rate readings across all movement methods were seen to be normal. Mauchly's sphericity test was then performed on the

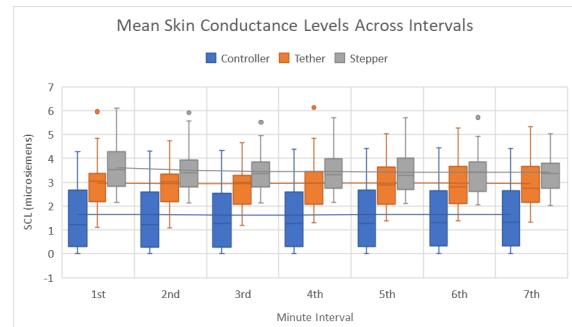


Figure 11: Box and whisker plot of average skin conductance data over minute long intervals

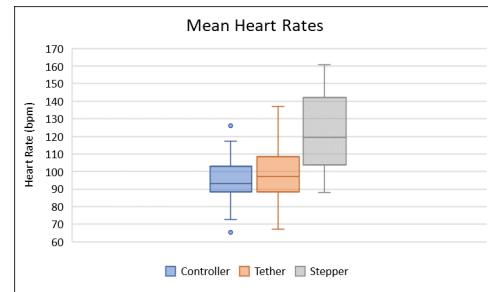


Figure 12: Box and whisker plot of average heart rate data over all intervals

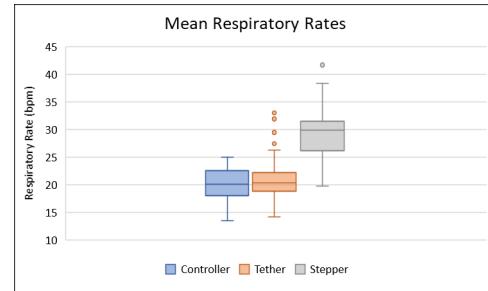


Figure 13: Box and whisker plot of average breathing rate data over all intervals

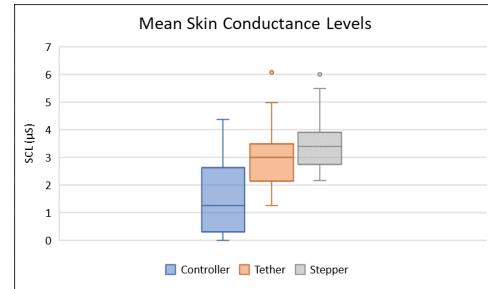


Figure 14: Box and whisker plot of average skin conductance data over all intervals

Dataset	HR		BR		GSR	
	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev
Controller	94.04	14.02	19.92	3.02	1.65	1.31
Tether	97.23	15.03	21.29	4.73	2.96	1.04
Stepper	121.02	21.55	29.34	9.01	3.49	0.95

Table 8: Physiological Data Statistics

	Mean	Std. Dev.
Controller	83.33	12.36
Tether	73.14	19.51
Stepper	54.44	23.92

Table 11: SUS Mean and Standard Deviation for each Movement Method

	X <sup>2</sup>	p-value
HR	33.852	<b>0.000000045</b>
BR	36.222	<b>0.000000014</b>
GSR	24.889	<b>0.000003940</b>

Table 9: Friedman test Chi-Squared and p-value statistics for each physiological measure

	HR p-value	BR p-value	GSR p-value
Tether-Controller	0.36	0.44	<b>0.0031</b>
Controller-Stepper	<b>0.000000072</b>	<b>0.0000000033</b>	<b>0.0000029</b>
Stepper-Tether	<b>0.000073</b>	<b>0.000021</b>	0.2317

Table 10: Nemenyi Test Results for Physiological Measures Across Movement Methods

data, however, the data was found not to have sphericity ( $W=0.30$ ,  $p=0.000009$ ) and could therefore not be assumed to be parametric. Breathing rate data for the controller and stepper was normal but the data for the tether was seen to be not normal. Galvanic Skin Response data for the tether and stepper were normal but the data for the controller was seen to be not normal. None of the data being compared could thus be assumed to be parametric. Therefore, a Friedman's repeated measures ANOVA for non-parametric data was performed to test if there was a significant difference between physiological measurements across the three movement methods. The Friedman test reported evidence of significant differences between the all data sets. The results can be seen in Table 9.

A Nemenyi post-hoc test was then performed to identify between which data sets there was a significant difference. The results for each set of physiological data is shown in Table 10. Significant values have been emboldened.

From the Nemenyi results it can be seen that for both Heart Rate and Breathing Rate there was a significant difference between the controller and stepper, and between the stepper and tether, but not between the controller and tether. For Galvanic Skin Response there was a significant difference between the controller and stepper, and between the controller and tether, but not between the stepper and tether.

### 5.3 SUS Results

Each participant completed an SUS questionnaire for each movement method after they have used it. Standard scoring was used as per [Brooke and others 1996]. SUS scores have a range of 0 to 100.

The mean and standard deviation for the SUS scores across movement methods are shown in table 11 above. A Shapiro-Wilk test of

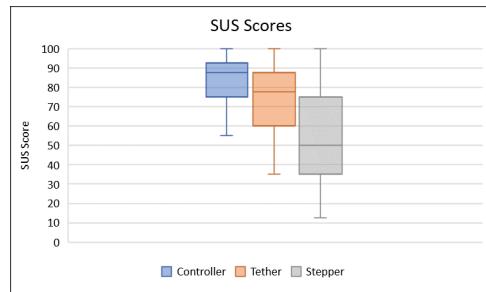


Figure 15: Box and whisker plot of SUS scores for each movement method

Movement Methods Compared	p-value
Tether-Controller	0.082
Controller-Stepper	<b>0.0000230</b>
Stepper-Tether	0.051

Table 12: Nemenyi Test Results for SUS Data sets

normality was then performed on the data. The data for the controller and stepper was normal but the data for the tether was seen to be not normal. The data sets being compared could therefore not be assumed to be parametric. Therefore, a Friedman's repeated measures ANOVA for non-parametric data was performed to test if there was a significant difference across the three movement methods. The Friedman test reported evidence of significant differences between the datasets ( $p=0.00009$ ,  $X^2=18.56$ ). A Nemenyi post-hoc test was then performed to identify between which data sets there was a significant difference.

As seen by the results in Table 12 there is only a significant difference in SUS results between the controller and the stepper.

### 5.4 Discussion

Looking at the statistical tests run on the data, we can see that there are no significant differences between the controller and tether, both for SSQ and SUS scores. This is confirmed by the physiological data where a similar trend can be seen. The Nemenyi test reports significant differences between the controller and the stepper, and the tether and the stepper but not between the tether and controller. The usability scores tell the same story, with no significant difference in usability scores between the controller and tether. This makes sense due to the nature of movement. Both the controller and tether require the user to remain stationary while they experience movement in the virtual environment. Only the way movement is triggered differs. When compared to the stepper, both the tether

and controller are significantly different and report lower post SSQ scores and lower SSQ score increases. Some interesting observations were made during the experiments. Some participants decided to walk in place while using the tether. This may explain why some SSQ scores for the tether have such large standard deviations. Also, while it was not tested for, the results of this study seem to point towards the postural instability theory as the underlying theory behind simulator sickness. According to the sensory conflict theory there should have been a significant difference between the tether and the controller because more of the participants' senses are being engaged and therefore more (or less, in the case that the brain was able to reconcile a pulling force with experiencing motion) sensory conflict should have occurred. With the stepper, the simulated walking motion was theorised to provide less conflict, however, since the stepper had a component of oscillation it is hard to say whether this may have interfered. Both the tether and the stepper add an additional component of maintaining balance in the real world while moving in the virtual world. This was most complicated in the stepper due to the participant moving up and down and also oscillating without being able to see the world around them to orient themselves. The stepper also had the worst overall performance. This would be consistent with predictions of the postural instability theory and although it has not been tested for, the data observed from the experiment is more supportive of the postural instability theory than the sensory conflict theory.

## 6 LIMITATIONS AND FUTURE WORK

Some limitations to the study include aspects of the virtual environment, our recruitment of participants and the equipment used. It was very challenging to create a single virtual environment that did not encourage the participants to stop (as this would preventvection) while also maintaining viewer interest. Unfortunately, based on verbal feedback, some participants did indeed get bored. When recruiting participants the psychology department was used as they had a research recruiting system in place. Perhaps due to the ratio of genders in the department, we had a skewed ratio of two males to twenty-five females. Due to the wired nature of the BIOPAC, the participants' range of motion was limited and this may have affected their physiological readings and changed the way they used each of the movement methods. The tether also may have been too strong for some participants and the stepper had an oscillation component. Lastly, seeing as participants knew the aim of study and that simulator sickness was a risk, it may have biased their reporting on symptoms. Future work should perhaps focus more on methods to shorten the amount of time taken to adapt tovection occurring, or potentially improve on the stepper and tether design and retest the hypothesis.

## 7 CONCLUSIONS

In conclusion, the tether provided no significant improvement over the standard controller based movement. That is not to say that the tether is worse, but perhaps a tether like device would be more suitable as a prop for a use-cases where movement with force-feedback is expected, such as exercise simulations for example. The rudimentary nature of the movement interventions and physiological data measurements may have prevented the full potential of haptic

feedback as an intervention to be realized. However it is still clear that haptic feedback did not effectively aid simulator sickness in VR. Future work should not rely on haptic feedback alone to aid in reducing simulator sickness symptoms but perhaps haptic feedback could be used indirectly with a different approach.

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## A APPENDICES

### Questionnaires

	Strongly disagree				Strongly agree
1. I think that I would like to use this ballot frequently.	<input type="checkbox"/>				
2. I found the ballot unnecessarily complex.	<input type="checkbox"/>				
3. I thought the ballot was easy to use.	<input type="checkbox"/>				
4. I think that I would need the support of a poll official to be able to use this system.	<input type="checkbox"/>				
5. I found the various parts of this ballot were well integrated.	<input type="checkbox"/>				
6. I thought there was too much inconsistency in this ballot.	<input type="checkbox"/>				
7. I would imagine that most people would learn to use this ballot very quickly.	<input type="checkbox"/>				
8. I found the ballot very awkward to use.	<input type="checkbox"/>				
9. I felt very confident using the ballot.	<input type="checkbox"/>				
10. I needed to learn a lot of things before I could get going with this ballot.	<input type="checkbox"/>				

Figure 16: The System Usability Scale Questionnaire given to participants (as a Google Form)

No_____	Date_____			
<b>SIMULATOR SICKNESS QUESTIONNAIRE</b> Kennedy, Lane, Berbaum, & Lilienthal (1993)***				
Instructions : Circle how much each symptom below is affecting you right now.				
1. General discomfort	None	Slight	Moderate	Severe
2. Fatigue	None	Slight	Moderate	Severe
3. Headache	None	Slight	Moderate	Severe
4. Eye strain	None	Slight	Moderate	Severe
5. Difficulty focusing	None	Slight	Moderate	Severe
6. Salivation increasing	None	Slight	Moderate	Severe
7. Sweating	None	Slight	Moderate	Severe
8. Nausea	None	Slight	Moderate	Severe
9. Difficulty concentrating	None	Slight	Moderate	Severe
10. « Fullness of the Head »	None	Slight	Moderate	Severe
11. Blurred vision	None	Slight	Moderate	Severe
12. Dizziness with eyes open	None	Slight	Moderate	Severe
13. Dizziness with eyes closed	None	Slight	Moderate	Severe
14. *Vertigo	None	Slight	Moderate	Severe
15. **Stomach awareness	None	Slight	Moderate	Severe
16. Burping	None	Slight	Moderate	Severe

\* 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.

Last version : March 2013

\*\*\*Original version : Kennedy, R.S., Lane, N.E., Berbaum, K.S., & Lilienthal, M.G. (1993). Simulator Sickness Questionnaire: An enhanced method for quantifying simulator sickness. *International Journal of Aviation Psychology*, 3(3), 203-220.

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Figure 17: The Simulator Sickness Questionnaire given to participants (as a Google Form)