The relationship between heart rate and self-reported sickness in commercially available virtual reality environments

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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ABSTRACT

Virtual reality (VR), while beneficial in research, training, and entertainment has the tendency of causing cybersickness (CS). The symptoms range from mild to severe depending on the individual. There exists a gap in the academic literature regarding the combination of physiological and subjective measures of CS. It is currently unknown whether there is a relationship between these different measures and whether they can be used to predict CS before symptom development. A total of 18 young healthy adults were collected. Participants explored a CS inducing VR game ADR1FT (AD) for up to a maximum of 30 minutes twice. In one condition they were asked to rate their sickness levels based on the Fast Motion Sickness (FMS) scale every 2 minutes, and the next condition they were only asked to rate their sickness only at the beginning and end, while their heart rate (HR) was recorded. It was seen that both FMS and HR increased with prolonged exposure to VR. A paired t-test did not find the final FMS scores following the two conditions to be statistically different, suggesting that continuously asking for perceived ratings of sickness did not bias the participants to report a higher final FMS score. Additionally, heterogenous individual responses in FMS and HR revealed those that could be considered as “responders” and “non-responders,” suggesting that response to CS could be bimodal: slow and fast responders. We suggest that these results can be explained by sensory conflict theory, where in discrepancy between visual and vestibular inputs for self-motion, effect both subjective and physiological response.

ACKNOWLEDGEMENTS

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1. INTRODUCTION

1.1 Overview

The nervous system can be divided into three sections – the central nervous system (CNS), the peripheral nervous system (PNS), and the autonomic nervous system (ANS). The CNS consists of the brain and spinal cord. The brain plays a central role in the control of most bodily functions, including awareness, movements, sensations, thoughts, speech, and memory. Some reflex movements can occur via spinal cord pathways without the participation of brain structures; however, it has been shown that the cortex plays a role in reflexive behaviours such as balance control (Jacobs, Horak, & Health, 2007). The PNS consists of the nerves and ganglia separate from the brain and spinal cord. The nerves in the PNS connect the CNS to sensory organs, as well as other organs in the body, to transmit information to the brain and spinal cord from the rest of the body (afferent information), and transmit information to the body from the brain and spinal cord (efferent information). The ANS controls physiological and stress responses and maintains internal homeostasis without any conscious recognition by the organism. One of the main sources of input into the nervous system (generally defined) is sensory information. The PNS has evolved several sensory end organs to detect multiple types of energies, which represent the interaction between external environment and organism. Multisensory integration is the process by which a combination of stimuli from different senses produce a neural response that differs significantly from that evoked by the individual component stimuli (Calvert, Spence, & Stein, 2004). While there has been

previous work that has established the relationship between the PNS, ANS, and CNS (Barr, 1974; Mai & Paxinos, 2012; Nieuwenhuys, Voogd, & Huijzen, 2008), the purpose of this thesis is to establish whether individual differences in multisensory integration, which is traditionally considered as functions of the PNS/CNS, can explain individual differences in sickness arising from conflicting multisensory stimuli that are typical in virtual and other human-made environments (Davis, Nesbitt, & Nalivaiko, 2014).

The CNS is challenged with having to process information from the external environment through multiple sensory systems that may or may not agree. When sensory information is congruent, multisensory integration is a means through which the CNS can determine sensory information is coming from a common source. Cue conflict occurs when there is a discrepancy between incoming stimuli from sensory organs – this information can lead to errors in perception, motor control, and sickness (Reason & Brandt, 1975). Cue conflict theory is widely accepted as the primary theory behind motion sickness, where discrepancies between movement of the self and movement of environment are not in agreement. A common example of motion sickness is when you are in a ship cabin; in that environment everything in the cabin (including you) will move with the ship, thus visual information will appear static. However, since the vestibular system works relative to gravity, it will detect movement, thereby causing a mismatch of incoming sensory information. Cue conflict is most likely to occur in man-made environments, such as the prior ship example – a specific type of sickness arising from cue conflict in virtual environments is known as

cybersickness. It is thought that the root of cybersickness involves cue conflict between the visual and vestibular senses.

Virtual reality (VR), though revolutionary and beneficial in work and entertainment, has the tendency of leaving the user feeling unwell – the feeling of cybersickness (McCauley & Sharkey, 1993). Cybersickness is a type of motion sickness that has emerged recently, specifically triggered by exposure to VR. It has been stated that representation of motion in a virtual environment creates ambiguities in visual, vestibular, and proprioceptive cues because these systems provide visual cues consistent with self-motion, whereas corresponding vestibular cues are absent (McCauley & Sharkey, 1993). Thus, this mismatch of sensory information can lead to the development of cue conflict.

A study done by Aoki and colleagues (2000), explored the cardiovascular responses to vection in ten subjects. Vection is the illusion of self motion due to visual stimulation, despite no real body movement. It was observed that blood pressure (BP) in the radial artery rose consistently in six subjects (Aoki, Thilo, Burchill, & Gresty, 2000). Additionally, a similar increase in BP to a real tilt (similar to the visually induced tilt) was observed (Aoki et al., 2000). With respect to sickness, approximately around the same time as Aoki and colleagues, Holmes and Griffin showed that heart rate (HR) can increase significantly with increasing subjective ratings of sickness (Holmes & Griffin, 2001). Holmes and Griffin investigated changes in HR and heart rate variability (HRV), of forty subjects, prior to and during the development of nausea. HR, HRV, and sickness ratings were recorded pre-exposure and concurrent with a sickening stimulus.

Like most studies done during that time, this study used optokinetic stimulation as a nauseating stimulus – optokinetic stimulation involves visual targets (typically vertical stripes) moving left to right at a constant speed. It was observed that HR increased significantly with increasing subjective ratings of sickness, as seen on Figure 1 (Holmes & Griffin, 2001). It has been suggested that the increase in HR can be attributed to an increase in sympathetic stimulation of the heart, which would suggest that a simple measure of HR may be a useful indicator of the degree of motion sickness (Holmes & Griffin, 2001).

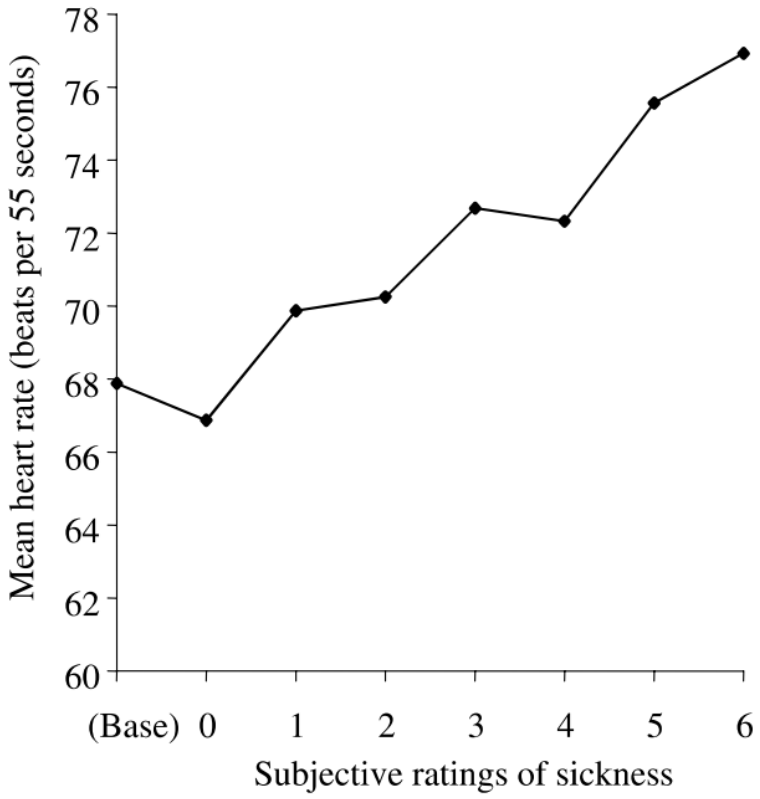

Figure 1: Mean heart rate at the baseline (Base) and at each rating of motion sickness (Holmes & Griffin, 2001).

As seen on Figure 1, Holmes and Griffin used a 6-point Likert scale measure subjective ratings of sickness. While this method was adapted from

previously published work (Golding & Kerguelen, 1992), it has not been validated and it does not fully capture responses to sickness. Subjective methods are commonly used to assess the sickness users feel after being exposed to a virtual environment: 1) Motion Sickness Susceptibility Questionnaire (MSSQ); Appendix A, 2) Simulator Sickness Questionnaire (SSQ); Appendix B, and 3) Fast Motion Sickness Scale (FMS). The MSSQ is a reliable and valid self report questionnaire that allows for the quantification of individual differences in motion sickness, based on previous experiences with different modes of transportation (Golding, 1998). The SSQ is a reliable and valid self report measurement tool that is specific to motion simulators, which enables the researchers to quantify the participants' cybersickness levels after exposure to VR – even though the SSQ was created for motion simulators, it is the most commonly used questionnaire for quantifying cybersickness in all types of sickness. (Kennedy, Lane, Berbaum, & Lilienthal, 1993). The SSQ consists of 16 symptoms, which are divided into three distinct symptom groups: oculomotor (SSQ_O), disorientation (SSQ_D), and nausea (SSQ_N) – a given virtual environment may affect one or more of these symptom groups. Participants completing the SSQ rate each one of the items on a Likert scale (none, slight, moderate, severe). One limitation of the SSQ is that it is administered before and/or after test session and does not capture change in sickness over time. The FMS allows for comparisons of motion sickness severity at different time points throughout the experiment. It consists of a 20-point verbal rating system, where zero signifies the absence of sickness and 20 signifies extreme sickness, recorded at a given frequency (e.g., 1Hz (Keshavarz, Hecht, &

Mainz, 2011)). While subjective ratings such as MSSQ, SSQ, and FMS have been used to a large extent in the literature, very few have investigated combining the subjective ratings of motion sickness with physiological recordings in order to predict one's sickness. Additionally, it is still unclear whether frequently asking participants to rate their sickness will affect the sickness severity outcome.

The objective of this thesis is to determine the relationship between HR and the FMS, and other measures of sickness (MSSQ and SSQ). Another objective is to assess whether there is a significant difference between final subjective scores measured at the end of the test session when participants are asked to frequently report their subjective sickness compared to when they are not asked. Examining a relationship between cybersickness and recorded psychophysiological measures would not only help us better understand CNS function and reduce cybersickness, it would also be a huge step in predicting cybersickness.

In this thesis I will provide a general literature review of how the CNS processes and integrates incoming information. Then, I will provide a summary of possible mechanisms responsible for development of cybersickness, as well as its typical measurement techniques. Next, I will provide a general summary of a few physiological measurement techniques commonly used in combination with subjective rating scores. Finally, I will investigate the psychophysiological relationship between subjective ratings and physiological techniques to better understand cybersickness.

1.2 Central Nervous System

The CNS has the extraordinary capability of combining different sensory inputs from the external world. By combining information across the senses about a common source, the CNS can improve the localization and discrimination of objects, which in turn leads to a more accurate representation of the external world (Calvert et al., 2004). This ability is known as multisensory integration - a process that in turn affects the perceptions, decisions, and actions of an individual (Calvert et al., 2004). Before integrating the incoming sensory information, the different sensory organs must first detect the appropriate signals. The two major sensory systems emphasized in this thesis are the vestibular and visual systems.

Vestibular system

The vestibular system is a sensory system which detects self-motion and tilt of the head relative to gravity and initiates movements to maintain balance and orientation. Anatomically the vestibular system is composed of 5 organs: semicircular canals (anterior, horizontal, and posterior) and otolith organs (utricle and saccule). The semicircular canals allow for the transduction of angular acceleration and the otolith organs allow for the transduction of translational acceleration, thus permitting the CNS to sense head motion in all six degrees of freedom (Khan & Chang, 2013). The utricle and saccule are in the vestibule and each contains a sensory neuroepithelium known as the macula, which is embedded with mechanoreceptive hair cells. The macula of the utricle senses motion in the horizontal plane, while the macula of the saccule senses motion in

the vertical plane. The semicircular ducts are contained in the bony semicircular canals, and each duct is sensitive to movement in its specific plane. The semicircular ducts open into the utricle, and at the end of each duct there is a dilation called the ampulla which contains the crista ampullaris. The crista ampullaris is coated by a gelatinous substance known as the cupula, which is embedded with mechanoreceptive hair cells (Scherer & Clarke, 2001).

When head position is altered due to rotational acceleration, the cupula is displaced, causing the hair cells to consequentially bend in the opposite direction of the rotation. This results in opening of ion channels and depolarization of the hair cell, resulting in an increased firing of its associated afferent fibers. Alternatively, when rotational velocity of the head becomes constant, the membrane potential of the cell is normalized by the cupula returning to its upright position. During a head rotation to the right, the rate of firing from the right labyrinth increases, whereas the rate of firing from the left labyrinth decreases. This push-pull principle provides increased sensitivity and permits accurate bi-directional measurement (Scherer & Clarke, 2001). For example, when a person turns their head to the right, the stimulus to the right vestibular organ leads to an increase of the afferent firing rate on the nerve fibres leading to the vestibular nuclei; at the same time, the firing rate on the nerve fibres from the left vestibular organ decreases.

Once the mechanical energy is converted into a neural impulse, the vestibular nerve projects the information to the vestibular nuclei, composed of four second order vestibular nuclei: the inferior, medial, lateral, and superior

vestibular nuclei. These nuclei can be found in the floor of the fourth ventricle in the medulla and pons (Brodal, 1974). The main descending tracts from the vestibular nuclei are the lateral vestibulospinal tract and medial vestibulospinal tract. The lateral vestibular tract starts in the lateral vestibular nucleus and descends the length of the spinal cord ipsilaterally (which allows for an upright stance and walking). The medial vestibular tract starts in the medial vestibular nucleus and extends bilaterally through mid-thoracic levels of the spinal cord (which affects head movements and aids head and eye movement integration) (Khan & Chang, 2013).

In addition to descending pathways, there exist parallel ascending tracts as well. Afferent vestibular information enters the cerebellum through the inferior cerebellar peduncle and innervates the flocculonodular node, which coordinate postural adjustments to maintain balance control (Watson, Kirkcaldie, & Paxinos, 2010). Another receiving point for incoming vestibular information is the basal ganglia, which is known to be involved in multisensory integration (Stiles & Smith, 2015). It has been observed that projection fibres from the medial vestibular nucleus to the thalamus (parafascicular nucleus), synapse with neurons projecting into the dorsolateral putamen of the basal ganglia (Lai, Tsumori, Shiroyama, Yokota, & Nakano, 2000). In macaque studies, the main receiving area of the vestibular information is found between the ventral part of the primary somatosensory cortex and the insula. The equivalent area in human brains is in the post-central gyrus of the parietal lobe, referred to as the parietal-insular vestibular cortex (PIVC). The input to this area is not limited to vestibular

information as it also receives visual information and information from receptors in the neck (Watson et al., 2010).

The primary functions of the vestibular system include spatial orientation, maintenance of balance, and stabilization of vision through vestibular-ocular reflexes. An additional vestibular function related to motion sickness has been proposed which states that the vestibular system plays a role in the emesis (process of vomiting) of ingested neurotoxins. Its occurrence in response to motion would be an accidental by-product of this system through evolution. Thus, the purpose of motion sickness is hypothesized to be the same as for any emetic response, which is to protect the organism from the toxic effects of potentially harmful substances that it may have ingested (Treisman, 1977). The recognition that the vestibular system influences the autonomic nervous system emerged from studying vertigo and its symptoms, which suggest involvement of both cranial and visceral mechanisms in balance disorders. As a result, interactions between vestibular and autonomic systems have been viewed as a unidirectional influence of vestibular or visual information on autonomic regulation (Balaban, 1999).

Visual system

The visual system is the part of the CNS which gives organisms the ability to process visual detail by detecting and interpreting information from visible light to build a representation of the surrounding environment. Every object in the environment is made of material substances, and it is because of the way the light is reflected from different surfaces that visual perception is possible. The

light reflected from the surfaces in the environment forms a densely structured optic array at a point of observation (Gibson, 1956), and becomes focused before reaching the photoreceptors in the retina as light passes through the cornea and lens of the eye (Kandel, Schwartz, & Jessell, 2000). The neural signals are initially processed by the retina. There are two types of photoreceptors within the retina: rods and cones. Rods (outnumbering cones 20 to 1) capture more light because they contain more photosensitive visual pigments compared to cones; therefore, rods are sensitive enough to be evoked even by a single photon. In contrast, cones have a better spatial resolution, are concentrated in the fovea, and consist of three types (each sensitive to a different part of light spectrum) (Kandel et al., 2000).

The output of the retina is conveyed by the ganglion cells – these cells take the sensory information and transmit them as action potentials. Action potentials are then carried by the optic nerve to the lateral geniculate nucleus (LGN) of the thalamus and the superior colliculus (SC) for further visual processing. LGN, a bilateral structure, contains six layers. Each layer receives signal only from a single eye; the ipsilateral eye (occurring on the same side of the body) sends signals to layers 2, 3 and 5 and the contralateral eye (occurring on the opposite side of the body) sends signals to 1, 4 and 6 layers. As such, each eye sends half of the signals to the left hemisphere LGN and the other half to the right hemisphere LGN (Kandel et al., 2000). LGN is the main connecting ipsilateral point between the optic tract and primary visual cortex (V1).

V1 is the earliest cortical visual area which is in and around the calcarine fissure in the occipital lobes of mammals. It is highly specialized for processing information about static and moving objects and pattern recognition. V1 transmits information to two primary pathways, called the ventral stream and the dorsal stream (Mishkin, Ungerleider, & Macko, 1983). The ventral stream of projections leads to the inferotemporal cortex, and the dorsal stream terminates in the posterior parietal region. It is important to note that the proposed functions of these streams were largely determined from behavioural lesion studies. Previous research has shown that monkeys with lesions of the inferotemporal cortex were impaired in visual pattern discrimination and recognition. Alternatively, monkeys with posterior parietal lesions behaved in the opposite pattern (Ungerleider, Mishkin, Goodale, & Mansfield, 1982).

The visual and the vestibular systems are heavily integrated allowing the CNS to receive additional sensory information to form a more meaningful representation of the environment. The vestibulo-ocular reflex (VOR) functions to stabilize images on the retina relative to space by producing eye movements that counter head movements (Purves, Augustine, & Fitzpatrick, 2001). For example, a right rotation of the head excites neurons in the right vestibular nucleus and results in reflexive eye movements to the left. This is due to excitatory projections from the medial vestibular nucleus crossing to the contralateral abducens nucleus, eventually leading to two outputs. One output is a motor pathway that causes the lateral rectus of the left eye to contract, and the other output is a projection that crosses the midline and ascends via the medial longitudinal

fasciculus to the right oculomotor nucleus, where it causes the medial rectus of the right eye to contract (Bagnall, du Lac, & Mauk, 2013). This integration allows for conjugate eye movements, thereby enabling bilateral fixation on a single object during head movements.

In addition to coordinating movement of the eyes relative to the head, visual and vestibular pathways converge as early as the vestibular nucleus and are found elsewhere from the projections of the vestibular nuclei. Thus, from the very first synapses, vestibular signals may already be influenced by visual output. There are many potential sites suitable for integration of vestibular and visual information: medial superior temporal area (MSTd), ventral intraparietal area, posterior parietal cortex, and superior temporal polysensory area (DeAngelis & Angelaki, 2012). It is believed that MSTd is a good candidate for integrating visual and vestibular signals as it has large receptive fields and the selectivity for complex optic flow patterns (Duffy & Wurtz, 1991). Additionally, MSTd contains neurons sensitive to physical translation in darkness (Bremmer, Kubischik, Lappe, & Hoffmann, 1999), suggesting the presence of vestibular signals used for heading perception; thereby being a potentially good location for integration with optic flow signals.

Optic flow

Optic flow can be defined as the motion of all the surface elements from the visual world. Humans are constantly surrounded by moving people and objects and as individuals move through the world, the objects and surfaces within the visual environment flow around them (Lee & Kalmus, 1980). A

visualization of optic flow can be seen in Figure 2. The human visual system can determine the current direction of travel from the focus of expansion of visual input. As objects move past the visual field in the opposite direction of the individual's movement, the brain can deduce that the body must be moving in the opposite direction of the movement of the visual field. For example, as an individual turns their head to the right, their visual field moves to the left relative to their head. The brain will use this information from optic flow to deduce the true direction of the head. Motion is an integral part of our visual experience and a fundamental property of the world. It is the abundance of information that aids and supports a wide variety of visual tasks, including 3D shape acquisition, recognition of objects, perceptual organization, and the understanding of an environment (Fleet & Weiss, 2005). In a virtual environment where the acceleration of the optic flow can be adjusted, a higher acceleration of visual cues may lead to increased cue conflict between the visual and vestibular systems. This is due to incongruent sensory information presented to the CNS from the two modalities; the visual system is presented cues that portray movement, while the vestibular system does not perceive movement to be occurring.

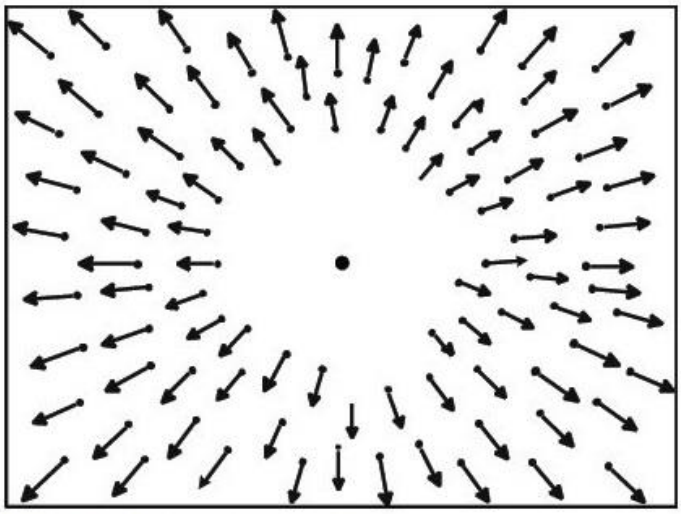

Figure 2: This image illustrates optic flow – a visualization of the objects and surfaces within the visual environment flow around a point.

1.3 Cybersickness

Sensory conflict typically occurs as a result of immersion in human-made environments (planes, trains, boats, automobiles, etc.). More specifically, it occurs in virtual environments where the sensory visual information is incongruent with vestibular and proprioceptive information. With advancement of VR technology, a new type of motion sickness has come to light specifically caused by exposure to VR. VR is an artificial, yet realistic, environment that is created with a computer and presented to the user by stimulating senses such as vision, hearing, and touch in such a way that the user is immersed in the new virtual environment. Though revolutionary and beneficial, VR has the tendency of leaving the user feeling unwell – the feeling of cybersickness (McCauley & Sharkey, 1993). The interesting aspect of cybersickness is its ability to affect individuals differently; a virtual experience presented to two subjects may affect them in completely different ways, and consequently individuals experience

cybersickness differently. However, it has been shown that as the exposure to the virtual environment is prolonged, there is an increase in severity of symptoms associated with cybersickness (Keshavarz et al., 2011). The symptoms of cybersickness range from severe stomach discomfort, nausea and vomiting to less severe symptoms such as cold sweating, fatigue, drowsiness, and increased salivation (Oman, Lichtenberg, Money, & Mccoy, 1986). Not only are these symptoms concerning to the individual, but they can lead to impairments in balance control and gait, as well as an increase in postural sway. Laboissière and colleagues (2015) have suggested that the sensory re-weighting mechanism has the ability to explain the differences in individual variances in motion sickness sensitivity (Laboissière, Letievant, Ionescu, & Barraud, 2015). The sensory re-weighting mechanism states that to maintain an upright stance, during a change in sensory conditions, the sensory inputs are continuously re-weighted through short-term neuroplasticity (Horak & Macpherson, 1996). Short-term neuroplasticity refers to changes in neural excitability where synaptic efficacy changes over time in a way that reflects the history of presynaptic activity (Stevens & Wang, 1995). The short-term neuroplasticity is primarily led through long-term potentiation (LTP), first discovered in 1973 (Bliss & Gardner-Medwin, 1973). The two phases of short-term neuroplasticity are early and late phase. The early phase consists of an increase in synaptic strength through an increase in the release of neurotransmitters and an increase in neurotransmitter receptors, and the late phase consists of an increase in dendritic connections. It is a commonly held understanding that incoming sensory inputs are dynamically re-

weighted to maintain upright stance as the environment and received information change. Sensory re-weighting is required to maintain stability when an individual's environment is changed.

Postural stability

The general definition of balance, or postural stability, is the ability to maintain the body's center of mass over its base of support (Pollock, Durward, Rowe, & Paul, 2000). Conversely, postural instability has been described as the inability to maintain the body in a stable position. Postural instability, one of major contributors to falls, can be caused by exposure to virtual environments. The postural instability theory states that the loss of postural control can be a leading cause of motion sickness, and the amount of postural instability determines the degree of motion sickness (Nishiike et al., 2013). Stoffregen and Smart (1998), found that an increase in horizontal movement around the center of gravity (postural sway) preceded motion sickness, even before the awareness of the symptoms, which further validates the postural instability theory. One valid way of measuring the displacement of Center of Pressure (COP) is the path length – the cumulative distance travelled in the horizontal plane by the subject's COP whilst in a quiet stance (Donath, Roth, Zahner, & Faude, 2012).

A properly functioning balance system allows for automatically adjusting posture to maintain stability in various conditions and activities such as recognizing orientation of movement with respect to gravity, providing clear and stable vision while moving, as well as identifying direction and speed of movement. Though often forgotten about and taken for granted in daily life, the

balance system plays an important role in everyone's life. Balance control is commonly defined as the means in which the CNS integrates sensory information from other systems to maintain, achieve and restore the state of balance during various postures. Balance control is a complex skill based on the interaction of dynamic sensorimotor processes including sensory input from vision, proprioception, and the vestibular system. Balance control's main functions can be divided into postural orientation and postural equilibrium. Postural orientation is the active control of body alignment with respect to gravity, internal references, and visual environment; whereas postural equilibrium is stabilizing the body's centre of mass during disturbances in stability, using the coordination of sensorimotor strategies (Horak, 2006). It is important to note that in addition to the contribution of sensory information, there may also be psychological factors that impair our sense of balance. That said, it is a well established fact that vision plays a significant role in balance control (Manchester, Woollacott, Zederbauer-Hylton, & Marin, 1989).

Autonomic measures of sickness

While the vestibular system is often seen as only being responsible for balance responses, vestibular nucleus connections with brain stem nuclei have been found to mediate autonomic function (Balaban & Beryozkin, 1994). By inserting a neuroanatomical tracer into the vestibular nuclei of rabbits, Balaban and Beryozkin were able to observe the contribution of the caudal aspect of the medial vestibular nucleus and the inferior vestibular nucleus to the nucleus tractus solitarius and the dorsal motor nucleus of the vagus nerve. As the vagus

nerve contributes to the ratio of sympathetic and parasympathetic activity, these vestibulo-solitary pathways could be potential substrates for vestibular effects on the control of respiratory, cardiovascular and gastrointestinal functions (Balaban & Beryozkin, 1994).

Studying the development and progression of motion sickness, or cybersickness, requires a combination of physiological measurements reflecting autonomic responses and subjective statements. Both are equally important as autonomic responses tend to be highly individual and subjective, and certain measured values may actually reflect states other than sickness (Dahlman, Sjörs, Lindström, Ledin, & Falkmer, 2009). In studies looking into motion stimuli and cybersickness, the most common measurements are electrocardiogram (ECG) and measuring the heart rate (HR), electrodermal activity or galvanic skin response (GSR), respiration rate, skin temperature, and blood volume pulse (Cowings, Naifeh, & Toscano, 1990).

Dahlman and colleagues (2009) investigated the effects of sickness on these previously mentioned autonomic responses. They found that compared to baseline values, skin conductance increased at the start, was close to baseline level by mid-test, but then increased again prior to stop (as seen in Figure 3). The same study observed a decrease in blood volume pulse, compared to the baseline, at the start of the test followed by an increase in blood volume pulse mid-test and at the termination point. A study done by Mekjavic and colleagues showed that sickness attenuates vasoconstrictor response to skin thereby enhancing heat loss and lowering of body temperature (Mekjavic, Tipton,

Gennser, & Eiken, 2004). Various studies have shown an effect on HR during exposure to sickening stimuli, resulting in increased HR (Cowings et al., 1990; Dahlman et al., 2009).

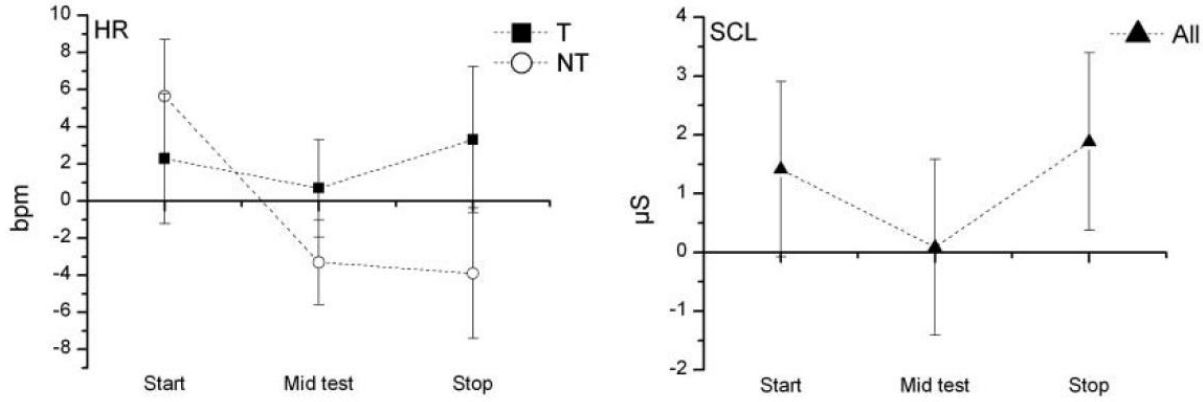

Figure 3: Changes in autonomic responses measured as HR and skin conductance level (SCL) measured as differences from baseline. Baseline level is indicated by the horizontal line. T = (n = 16) terminated the experiment early due to sickness; NT = (n = 22) endured the entire 25 minutes of exposure (Dahlman et al., 2009).

A more recent study by LaCount and colleagues (2011), aimed to understand the relationship between ANS outflow and increasing nausea perception. Their 17 motion sickness prone subjects (measured through the MSSQ) were presented with a sickening visual stimulus of black/white stripes translating left-to-right at a constant speed (62.5°/s) projected on a concave screen positioned 10 cm in front of their eyes. Left-to-right horizontal translating stripes have been shown to induce a linear vection sensation wherein subjects experience a false sensation of translating to the left (Koch, 1999). Each trial was split into 4 time-zones – Time “I” was 5 minutes of physiological recordings before the sickening stimulus. Time “II” was used as a reflection of initial

response. Time “III” was used as a reflection of the most nauseating response, and finally time “IV” was used as a reflection of participants’ recovery. In total, the participants were exposed to sickening stimulus for 20 minutes with 5 minutes before and after also being recorded (LaCount et al., 2011).

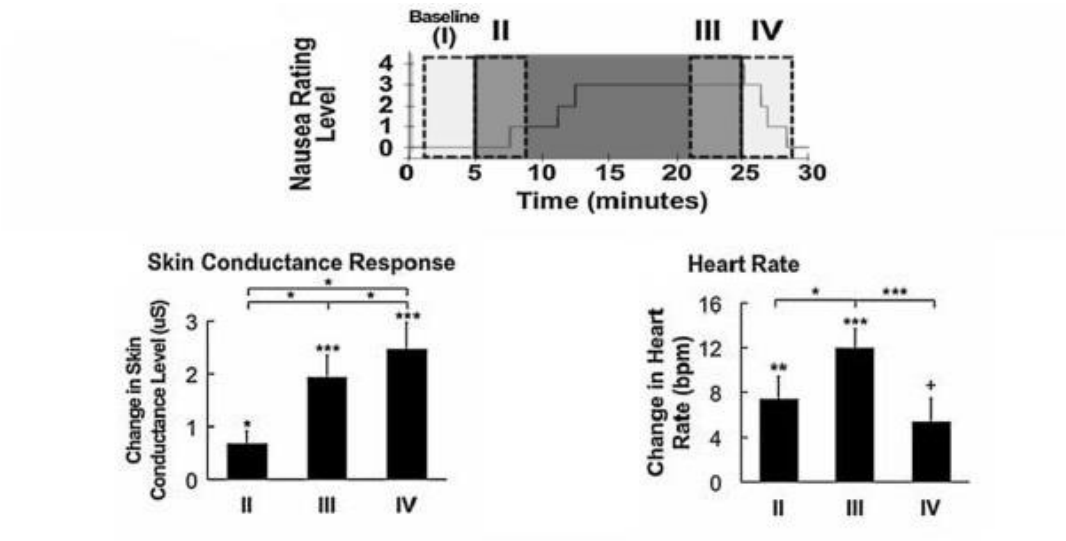

Figure 4: Changes in autonomic responses measured as HR and skin conductance level measured as differences from baseline. Figures adapted from (LaCount et al., 2011).

Observing Figure 4 shows that HR increased from baseline for the increasing time-zones but decreased once the visual stimulus ended. LaCount et al., found that nausea correlated with increased HR and skin conductance, but had a more complex effect on measures of HRV similar with decreased sympathetic shift in sympathovagal activity (LaCount et al., 2011).

1.4 Heart rate

The heart is the centre of the circulatory system, and its job is to pump blood throughout the body. Blood carries oxygen and a plethora of other essential

molecules and nutrients to the body organs. The left and right atria are smaller chambers that pump blood into the ventricles. The left and right ventricles have thicker walls and are therefore stronger. The left ventricle is the strongest because it is responsible for pumping blood out to the entire body. In a healthy heart, all four chambers work together in a continuous and coordinated effort to keep oxygen-rich blood circulating throughout the body. The heart has its own electrical system/natural pacemaker (sinoatrial node) that coordinates the work of the heart chambers (heart rhythm) and controls the frequency of beats. The frequency of the beats is also known as the HR. HR is directly related to the frequency of beats (i.e. how fast the heart is working), meaning that during exercise and situations where the heart needs to beat faster and harder, the HR is increased.

HR is dynamic and fluctuates throughout the day based on the activities being performed. HRV is the amount of HR fluctuations around the mean HR and can be used as a valuable tool to investigate the sympathetic and parasympathetic function of the ANS. HRV gives information about the sympathetic and parasympathetic autonomic activity and is occasionally used as an indicator of risk for sudden cardiac death. HRV measurements are non-invasive, easy to perform, and have good reproducibility in standardized conditions. Standardized conditions are important because HRV is influenced by factors such as respiratory rate and posture (Akselrod et al., 1985). HRV can be assessed by two methods: calculation of indices based on statistical operations

on R-R intervals (time domain analysis) or by spectral (frequency domain) analysis of an array of R-R intervals.

The link between HR and motion sickness was first observed by Crampton in 1955 – Crampton elicited motion sickness by moving the subject up and down vertically (like an elevator). The participants began the study with a 10-minute resting period, where baseline measurements were recorded. Participants were then moved vertically using the apparatus for one hour (or until vomiting). It was observed that after the exposure to the sickening stimulus, both the pulse rate and sweating rate had increased in those individuals experiencing motion sickness (Crampton, 1955). An example of this can be seen in Figure 3 and Figure 4. Similarly, Dahlman and colleagues (2009) more recently found an increase in HR during exposure to sickening stimuli (as described previously) (Dahlman et al., 2009).

Ohyama et al., performed a power spectrum analysis of HRV on the ECG recorded before, during, and after visual–vestibular conflict produced by a virtual environment. They found an increase in the power spectrum density of HRV in the low frequency and no significant change in the high frequency (Ohyama et al., 2007). It has been shown that the low frequency of the HRV is influenced by both the sympathetic nervous system activity and parasympathetic nervous system activity (Akselrod et al., 1981); whereas, the high frequency is only influenced by the parasympathetic nervous system activity (Eckberg, Kifle, & Roberts, 1980). In Ohyama and colleagues' study, there was no significant change in the power spectrum density of the HRV at the high frequency, implying

that there was no significant change in parasympathetic tone during motion sickness, suggesting increased sympathetic activity sickness (Ohyama et al., 2007).

The relationship between subjective ratings of sickness, more specifically the FMS, and autonomic outflow related to increasing symptoms following cybersickness has not yet been fully explored. While previous literature has shown that both the subjective ratings of sickness and HR are affected by cybersickness individually, we do not know whether there is a direct relationship between the two and whether one can be used to predict the other.

1.5 Hypothesis

There exists a gap in the academic literature regarding the weight of asking individuals to commit to a level of sickness (based on FMS) at regular intervals, and how that might affect their final cybersickness score. It's currently unknown whether or not asking FMS at regular intervals would result in a similar final FMS score. The aim of the present study is to address the gap in the existing literature about the autonomic outflow related to increasing symptoms following cybersickness and to investigate the association between HR, FMS, and prolonged exposure to a virtual environment. The hypotheses of this study are as follows: Positive correlation between subjective sickness scores and heart rate.

H1) As time in a head-mounted display virtual reality environment increases, self-rated cybersickness levels will rise exponentially before reaching a plateau.

H2) As time in a head-mounted display virtual reality environment increases, HR will increase linearly.

H3) Final cybersickness levels will be significantly higher when participants periodically self report sickness scores every 2 minutes.

H4) FMS scores and HR will be significantly positively correlated.

2. MATERIALS AND METHODOLOGY

2.1 Participants

A total of 30 young healthy adults were recruited from the University of Waterloo for this experiment. Of the 30 collected individuals, 4 subjects' data could not be analyzed due to excessive noise and very low amplitude, and 8 subjects' data merged with other collected individuals due to technical difficulties with the Consensys Pro, ultimately leaving only 18 participants' data for analysis. The merger of the participants' data led to the files being extremely large, which in turn would crash the application while attempting to export the data as an Excel file. To ensure that all options had been exhausted before excluding those participants, a ticket was submitted to SHIMMER Sensing. Additionally, I attempted to retrieve the files from the SHIMMER unit SD card on May 5th, 2020;

however, this attempt was unsuccessful. Upon inspection it was seen that the SHIMMER unit SD card was completely erased of all previous files.

The remaining 18 participants were ranging in age from 19 to 26 (10 females; mean = 23.2, s.d. = 2.12). These participants reported no auditory, visual, or vestibular disorders or symptoms. The study was approved through the University of Waterloo Research Ethics Committee and complies with The Code of Ethics of the World Medical Association (Declaration of Helsinki). All participants provided voluntary written consent.

2.2 Protocol

Upon the beginning of the experiment, the participants were asked to complete the MSSQ (Appendix A) and a gaming history questionnaire (Appendix C). The participants were then asked to stand while the ECG electrodes (4 lead placement) and GSR electrodes (base of index and middle fingers) were placed on their body (Figure 5). Before introduction to the virtual sickening stimulus, a 6-minute baseline reading of the HR and skin conductance was recorded while participants were in an upright free-standing posture and exposed to the virtual environment (a static video of the environment with no movements). Participants then began exploring the virtual environment for up to a maximum of 30 minutes using an XBOX controller (details below). Allocation to condition sequence was randomized; therefore, some participants were asked to rate their sickness levels based on the FMS scale every 2 minutes during their first VR exposure, and some were only asked at the beginning and end of their VR exposure. After their first exposure, the participants took a break for 30 minutes, or until their sickness

returned to a 0 on the FMS scale. Additionally, after each condition the participants were asked to complete the SSQ (Appendix B). Before each trial, participants were reminded that they should let the experimenter know if they feel uneasy, discomfort, or sickness and that they could withdraw from the experiment at any stage.

Experimental setup

The Oculus Rift CV1 head-mounted display (Oculus VR, Menlo Park, CA, USA) was utilized in the virtual reality portion of the experiment to expose participants to the VR environment. The VR hardware was running on a customized gaming PC (Aeon 3200 Gaming Desktop Computer featuring Intel Core i7-6700K Quad-core Processor) operating on Windows 10. Prior to the beginning of the tasks, the Oculus Rift system was calibrated for the height of each participant. A virtual boundary was set to define a physical space area of 8-by-8 feet that was covered with foam mats to prevent injuries in case of falls.

ECG setup

To record ECG during the experiment, SHIMMER^{TM} was used. SHIMMER was designed to be a wireless sensor platform for noninvasive biomedical research.

Various tests have been carried out to validate the SHIMMER ECG daughterboard as a valid tool for acquiring ambulatory ECG – The results indicated that the SHIMMER ECG is a valid tool for acquiring ECG from resting and non-resting human subjects (O'Donovan et al., 2009). The recorded data is

sent via Bluetooth to the base terminal of the SHIMMER and is then exported via Consensys Pro as an Excel document. The electrode placements were done following the SHIMMER ECG User Guideline Rev. 1.12 (as seen in Figure 5).

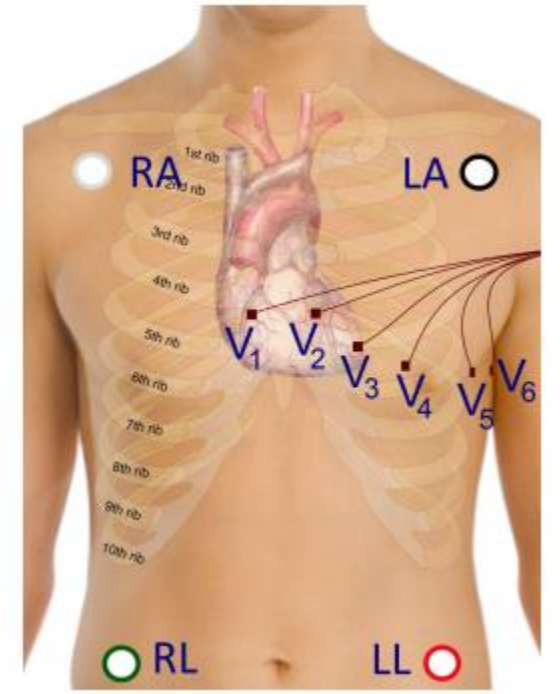

Figure 5: An example of how the electrodes should be positioned on the body. The electrodes for the bipolar limb leads (LA, RA, LL and RL) are represented by green nodes and wires, whilst the V1, V2, V3, V4, V5 and V6 positions for the unipolar leads, are represented by brown nodes and wires.

2.3 Procedure

Once a baseline recording of ECG and GSR was recorded, participants were immersed in a virtual environment where they were instructed to freely explore for 30 minutes. Participants had at least 30 minutes of a break between the two conditions in order to allow them to reach their baseline state (FMS score of 0) or until absence of sickness symptoms. ADR1FT (AD;https://www.oculus.com/experiences/rift/905830242847405/) was chosen as the

virtual environment of this study. AD was chosen as it was reported to have high levels of sickness by users of the Oculus Store (rated as "intense" or high incidence of sickness). AD was installed from the Oculus Rift library on the online interface and used for this experiment.

Figure 6: Screenshot of the ADR1FT environment depicting what the participants would see through the HMD.

AD immersed participants in a virtual spaceship where they played the role of an astronaut roaming around in a destroyed space station. In this environment participants were able to see the body, arms and legs of their virtual “self” (avatar). Participants could also see the outline of a virtual astronaut helmet. Importantly, cue conflict between self-motion and visual motion was high in this experience, as real head movement led to visual information consistent with moving the head within the space helmet. Cue conflict was also high because in order to move around, participants had to use different buttons on an XBOX controller. Movement instructions were explained and demonstrated to all

participants. Participants remained physically stationary, but they had the freedom to rotate their head. Participants were instructed to explore the environment during the 30-minute immersion time. A stopwatch was started when participants began the game. Subjects were asked to verbally report their perceived sickness levels using the FMS scale (0 to 20; where 0 represents no sickness at all and 20 indicates complete sickness) every 2 minutes (Figure 7A), or at the beginning and end of the trial (Figure 7B), depending on the condition. In order to make judgements on the appropriate symptoms, participants were cognizant of the fact that they should consider nausea, general discomfort, and stomach problems when making their judgments (Keshavarz et al., 2011).

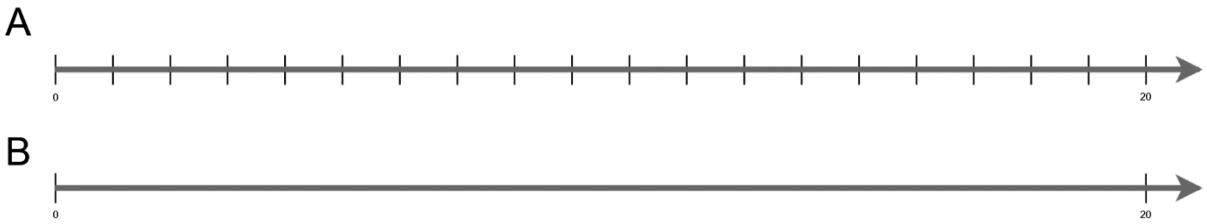

Figure 7: Visual representation of the two FMS conditions, where the horizontal arrow represents the time spent in VR and vertical lines represent when a subjective rating was recorded. A) In this condition individuals are asked to rate their sickness on a scale of 0-20 every two minutes. B) In this condition individuals are asked to rate their sickness on a scale of 0-20 only at the beginning and end of the trial.

2.4 Data analysis

Heart rate

Figure 8 depicts typical parameterization of HR response and HRV. QRS complex is typically the central and most dominant signal in the reading – main spike seen on an ECG waveform. PR indicates the transit time required for the electrical signal to travel from the sinus to the ventricles of the heart. AQ wave is

any downward deflection immediately following the P wave (atrial depolarization resulting in atrial contraction). An R wave follows as an upward deflection, and the S wave is any downward deflection after the R wave representing ventricular depolarization and contraction (Dong, 2016). The T-wave is normally a relatively small waveform representing ventricular repolarization. The most basic way to calculate the HR is to take the duration between two identical points of consecutive ECG waveforms such as the R-R duration. The R-R duration is then divided into 60 to calculate beats-per-minute. The resulting equation would be:

$$\textit{Equation 1: } Rate = \frac{60}{R{-}R\ interval}$$

Where R is the peak heart rate voltage and R interval is the time between two peak voltages. Beat-to-beat variability in RR intervals is referred to as HRV. The waveforms are labeled P (first short upward movement of the ECG tracing), and QRS complex (Q-larger upwards deflexion, R-a larger upwards deflexion, S-downwards wave) which shows ventricular depolarization and contraction.

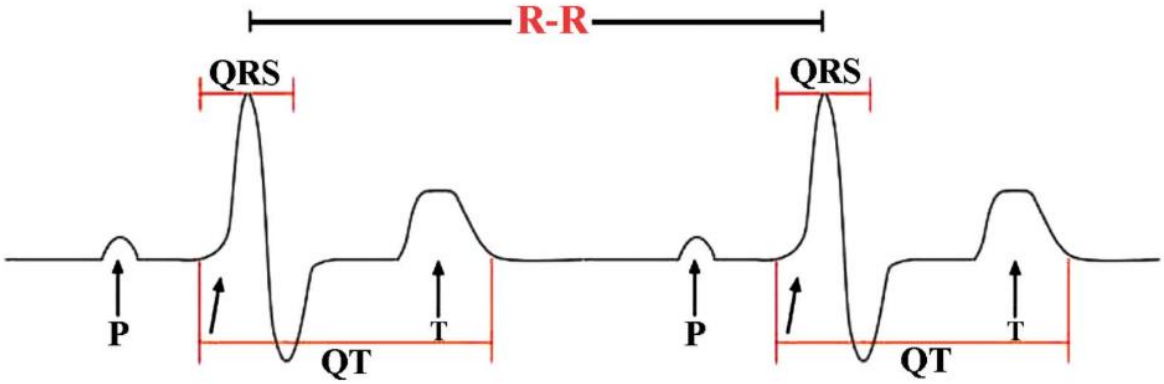

Figure 8: Jin-Guo Dong's review of HRV illustrating an example of ECG recording as the basis of measuring HR. A representation of HRV and different components of a heart beat. (Dong, 2016).

Each participant's change in HR was adjusted to be represented as a change in their HR compared to their baseline HR recordings. To achieve this, all the subsequent HR averages calculated were subtracted by that individual's baseline HR average. The following equation was fit to HR recordings as a function of VR exposure time:

$$\textit{Equation 2: } f = y0 + a * x$$

Where *y0* is average y-intercept, and *a* is the average slope.

MSSQ

The MSSQ originally developed by Golding (1998) consists of two parts: MSSQ A which inquire participants about their previous motion sickness experiences during childhood, and MSSQ B which inquire participants about their previous motion sickness experiences during adulthood. Both sections required the participants to recall their motion sickness experiences in various real-world settings (e.g., car, train, boats). Each answer was given a numerical value as such: never =0, 1 to 4 trips =1, 5 to 10 trips =2, 11 or more trips =3 (Golding, 1998).

MSSQ scores were calculated using the original method initially developed by Golding (1998). The following are the equations used to calculate an MSSQ score from the participants responses.

$$\textit{Equation 3: } MSSQ\ A = \frac{9*(total\ sickness\ score\ child)}{9*(number\ of\ transportation\ types\ experienced)}$$

$$\textit{Equation 4: } MSSQ\ B = \frac{2.64*(total\ sickness\ score\ adult)}{9*(number\ of\ transportation\ types\ experienced)}$$

The numerator of Equation 4 (“total sickness score adult”) is calculated from the question 9 and 10 on MSSQ B. The number of transportation types experienced is calculated from question 8.

SSQ

The raw SSQ values were calculated according to the original calculation method developed by Kenned and colleagues (1993). 27 symptoms which are commonly experienced by users of virtual reality systems were placed in 3 different categories. A score was first calculated for each of the three categories: Nausea, Oculomotor, and Disorientation (symptoms included in each category can be viewed in the table provided in Appendix B). The nominal responses of none, slightly, moderately or severely had numerical scores of 0 to 3 respectively. To calculate the scores for each category, the raw scores were multiplied to the weight factors specific to each group. The weight factors were 9.54, 7.58, and 13.92 for Nausea, Oculomotor and Disorientation, respectively. The total score was obtained by multiplying the sum of the raw sub scores by 3.74 (Kennedy et al., 1993). These calculations were done using Sigmaplot 12.5.

FMS

The FMS scores were collected in integer form (0 to 20) from participants at the end of every 2 minutes during condition 1, and in the condition 2 FMS scores were only acquired at the beginning and at the end of the trial. Keshavarz (2011) revealed significant and high correlations between the FMS ratings and the SSQ scores. FMS scores reached a correlation of r = 0.785 with the total

SSQ scores, which proved a strong relationship between these two variables. Additionally, the highest correlation was observed between the peak FMS rating and the score on the SSQ subscale of Nausea (r = 0.828), which was inline with the creation purpose of the FMS rating (Keshavarz et al., 2011). Thus far in the thesis, the raw FMS data is being used without any data transformation. The following equation was fit to FMS scores as a function of VR exposure time:

$$\textit{Equation 5: } f = y0 + a * x + b * x\text{^}2$$

Where *y0* is average y-intercept, *a* is average slope, and *b* is average curvature. To achieve the best fit, *a* was constrained to be above 0 (*a* > 0).

Multiple Linear Regression

A multiple linear regression is a statistical technique that uses several explanatory variables to model the linear relationship between the independent variables and dependent variable (response outcome). One advantage of using multiple regression is the ability to determine the relative influence of one or more predictor variables on the outcome variable. Not only does this method have predictive capabilities, it also includes a statistical significance test to judge whether the predictive contribution is statistically significant. It is important to note that this predictive model makes assumptions. For example, a linear relationship is assumed between the dependent variable and the independent variables. These calculations were completed using RStudio 1.14.

The independent variables used for the multiple linear regression within this study were past motion sickness history (measured using MSSQ), change in HR, and past experiences with VR. These independent variables were used to see whether an overall prediction could be made about the outcome variable (FMS). Additionally, for each predictor variable, the t-statistic was used to evaluate whether there was a significant association between the predictor and the FMS.

3. RESULTS

The GSR data recorded was extremely noisy and unreliable. Many filtration processes were attempted; however, no data was salvageable. Due to the placement of the electrodes on the base of middle and index fingers, and participants playing with an XBOX controller, signal noise and movement artifacts were common. Although pilot testing had proven to be successful, it could be that poor electrode placement and movement of the electrodes during the trials contributed to noisy data. Therefore, none of the GSR was analyzed for the purpose of this study.

Figure 9 shows the progression of each participant's sickness measured using self-rated FMS. For all but one participant, there was an exponential increase in sickness as exposure time in VR increases.

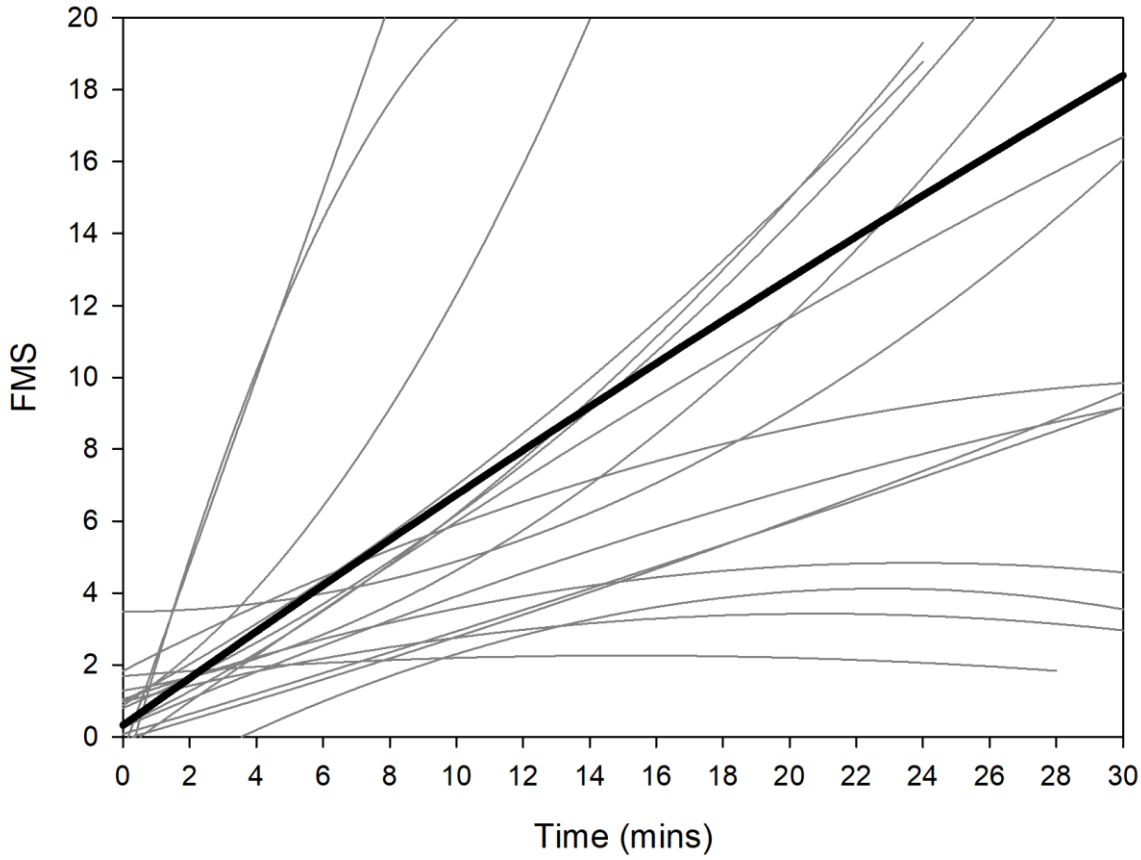

Figure 9: Participants' sequential self-reported FMS scores as a function of VR exposure time. Individual participants' quadratic regression, fitted by equation 4, are represented by grey lines. The solid black line shows the overall average for all participants (average y-intercept (y0), average slope (a), and average curve (b) parameters).

Table 1

	R^2	*y0*	*a*	*b*
P1	0.981	-0.343	0.665	$-3.24e^{-3}$
P2	0.035	1.685	0.076	$-2.53e^{-3}$
P3	0.966	0.978	0.502	$1.00e^{-2}$
P4	0.982	-0.0735	0.267	$1.84e^{-3}$
P5	0.978	0.800	0.400	$1.37e^{-2}$
P6	0.977	1.494	0.441	$6.89e^{-3}$
P7	0.339	-1.659	0.507	$-1.11e^{-2}$
P8	0.988	1.282	0.149	$1.86e^{-2}$
P9	0.917	1.835	0.476	$-6.96e^{-3}$
P10	0.957	-1.179	3.319	-0.12
P11	0.898	0.875	0.592	$5.51e^{-2}$
P12	0.420	0.973	0.234	$-5.60e^{-3}$
P13	0.792	1.042	0.319	$-6.74e^{-3}$

P14	0.961	0.078	0.278	$8.75e^{-4}$
P15	0.870	0.271	0.397	$-3.37e^{-3}$
P16	0.903	3.481	$4.243e^{-11}$	$1.40e^{-2}$
P17	0.994	-0.400	2.600	$-2.72e^{-9}$
P18	0.981	0.319	0.444	$1.45e^{-2}$
Average	**0.829 ± 0.065**	**0.637**	**0.648**	**$-1.34e^{-3}$**

Participants' FMS score R-squared (R^2), y-intercept (*y0*), slope (*a*), and curve (*b*) parameters as a function of VR exposure time.

Figure 10 shows each participant's HR changes (corrected to baseline) as a function of VR exposure time. All participants' HR increased as they played through AD.

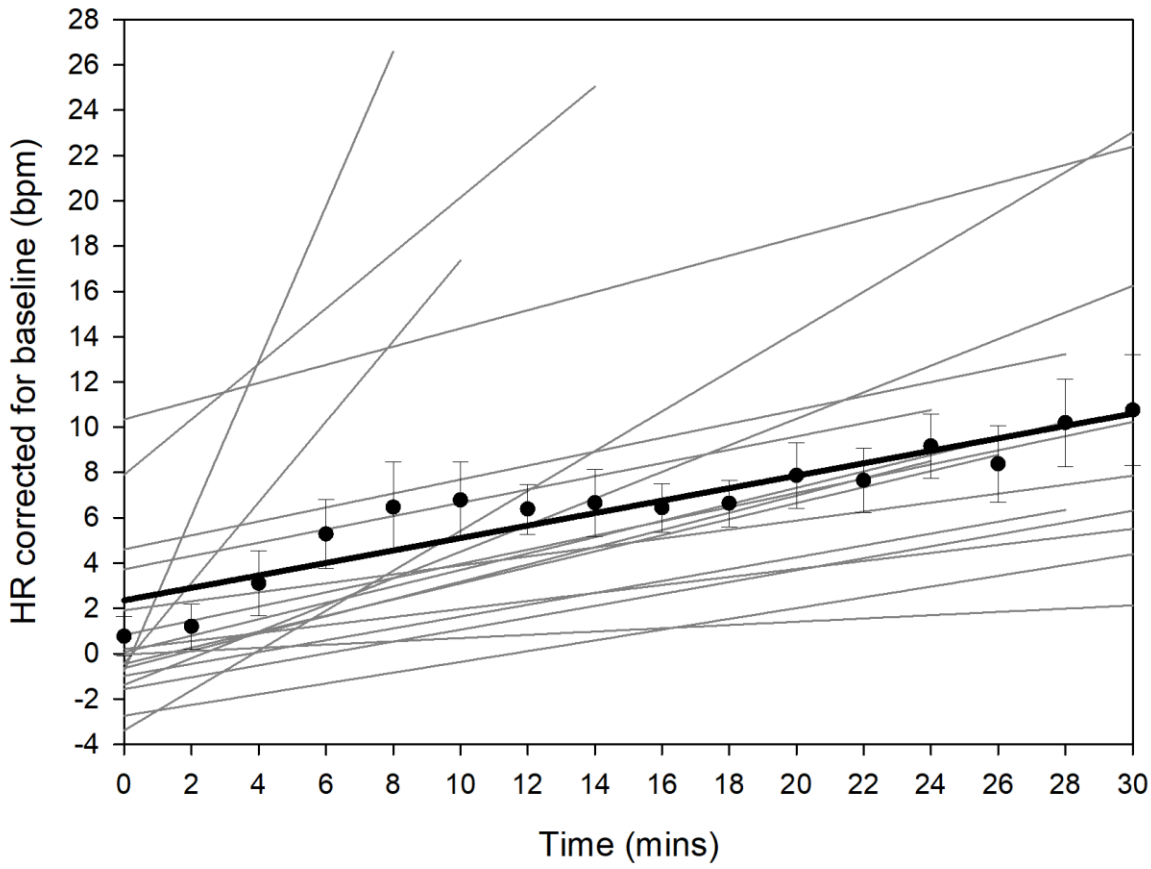

Figure 10: Participants' HR (corrected to baseline) as a function of VR exposure time. Each participant is represented by their own colour with data fitted by equation 2 (solid lines). The dotted black line shows the overall average for all participants (average y-intercept (y0), average slope (a) parameters).

Table 2

	R^2	*a*	*b*
P1	0.749	0.829	0.314
P2	0.616	4.608	0.308
P3	0.293	3.729	0.293
P4	0.770	-1.565	0.263
P5	0.928	-0.446	0.355
P6	0.977	-0.976	0.262
P7	0.816	-1.373	0.587
P8	0.777	0.069	0.363
P9	0.667	1.918	0.198
P10	0.937	-0.433	1.780
P11	0.545	7.900	1.225
P12	0.922	0.204	0.177
P13	0.169	-0.033	0.072
P14	0.848	-3.384	0.881
P15	0.430	-2.738	0.238
P16	0.651	10.355	0.401
P17	0.969	-0.760	3.420
P18	0.894	-0.631	0.381
Average	**0.859 ± 0.055**	**2.357**	**0.275**

Participant's HR R-squared (R^2), slope (*a*), and curve (*b*) parameters as a function of VR exposure time.

Figure 11 shows each participant's final FMS score for each condition (FMS asked every 2 minutes and FMS asked at the beginning and end). A paired t-test found that final FMS scores following continuously being asked throughout the experiment (average: 13.61; s.d.: 7.29) was not statistically different than only being asked at the beginning and end of the VR exposure (average: 13.89; s.d.: 6.543; t(17)= -0.369, one-tailed p=0.358; two-tailed p=0.717; effect size = 0.0401). Based on these means and standard deviations from a small sample, a power analysis revealed that a total of 3000 participants would be required for the one-tailed result to reach significance with Power equal to 0.8.

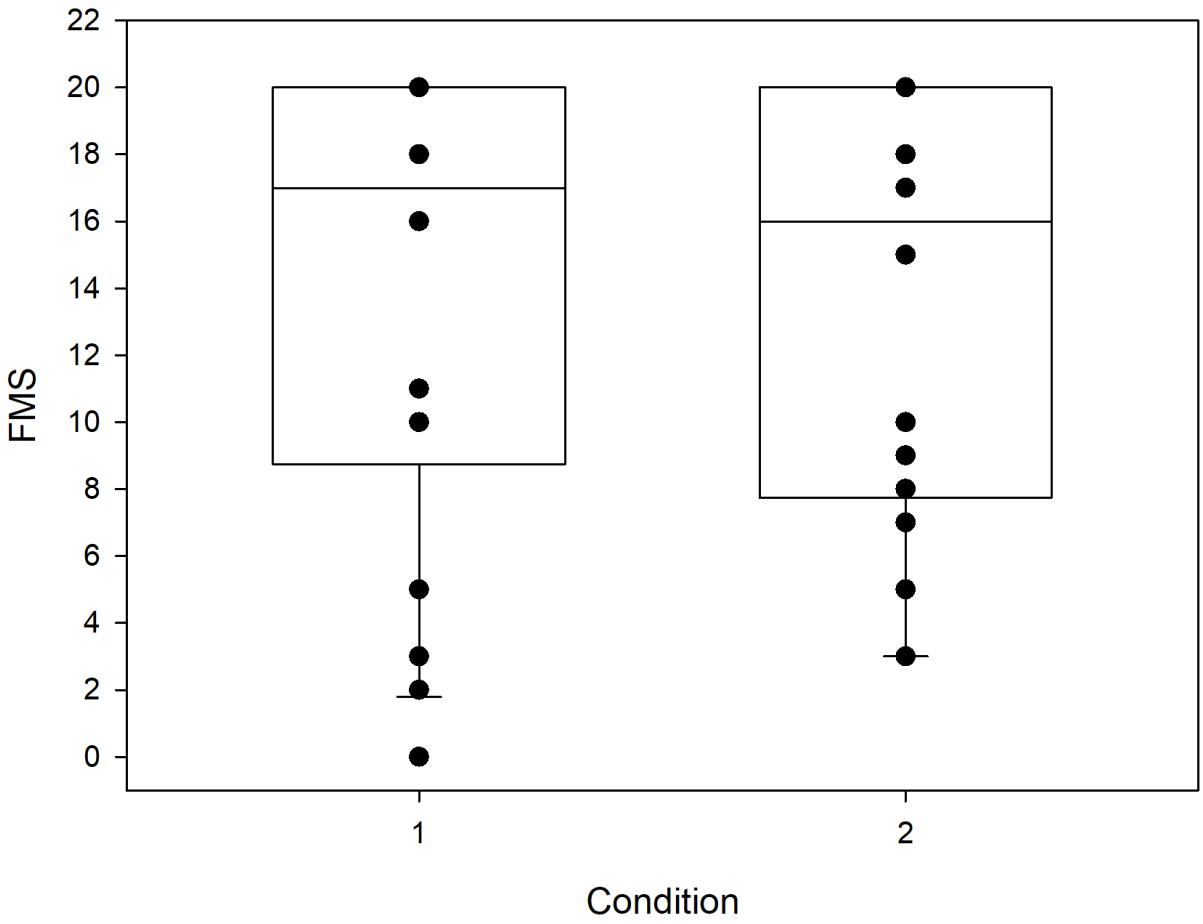

Figure 11: Participants' FMS as a function of the two conditions. Each participant is represented by a different point, and the box represents the average of each condition.

Figure 12 shows a Pearson correlation between HR slope as a function of FMS slope ($R^2 = 0.658$, $r = 0.811$, $p = 0.0000444$).

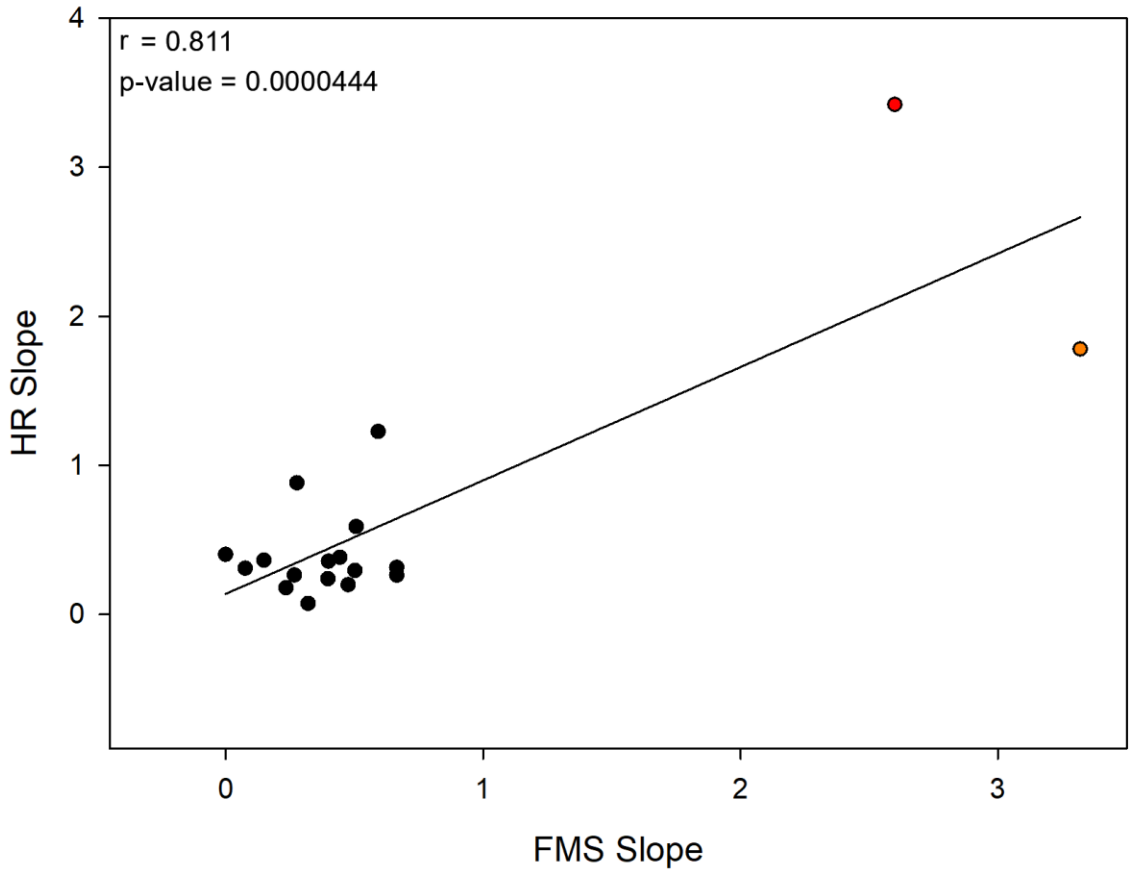

Figure 12: Pearson correlation between HR slope as a function of FMS slope. Each participant is represented by each point and the solid black line is the line of best fit (R^2 = 0.658). P2 (orange) and P17 (red) have been coloured in as they are considered to be outliers.

4. DISCUSSION

It was predicted that we would see an increase in FMS scores over time, as seen in previous studies. Our results from 18 participants suggest that most subjects' sickness levels do increase with exposure to sickening virtual environments. Additionally, it was predicted that we would see a similar increase in HR over time, also seen in previous studies. All participants' HR levels increased compared to their baseline with exposure to sickening virtual environments. Though all HR's increased over time, there were a lot of individual

differences present. Many researchers have suggested that the difference in sickness levels in subjects could be related to individual differences. Some of these individual differences could be related to functional differences of participants' cardiovascular system, however, as stated previously, Laboissière and colleagues have suggested that the sensory re-weighting mechanism has the ability to explain the differences in individual variances in motion sickness sensitivity (Laboissière et al., 2015). Sensory re-weighting phenomenon refers to the relative contribution of different sensory systems (visual, vestibular, auditory, and proprioceptive) on the representation of the external environment. It has been shown that quantitative estimates of sensory weights change depending on the availability of sensory information from visual or proprioceptive systems (Peterka & Health, 2002). Based on these findings, it is easy to see how sensory re-weighting can play a role in HR and FMS responses and individual differences in response to cybersickness.

Individuals relying on incoming visual information and prioritizing visual information may have a greater response to cybersickness. However, to fully understand the effects of sensory re-weighting on cybersickness a separate study needs to be completed. Figure 13 shows all previously seen graphs with results from two subjects highlighted. The red-coloured participant (P17) and the orange-coloured participant (P2) behave differently from other participants such that they not only reached 20 on the FMS scale very quickly, but their HR also increased very rapidly.

To understand whether P2 and P17 were outliers we performed a Generalized Extreme Studentized Deviate (ESD). ESD was chosen over Grubbs test and Tietjen-Moore test as they require a specific number of suspected number of outliers, whereas ESD is used to detect one or more outliers in a dataset that follows a normal distribution. ESD testing showed that P2 and P17 were outliers compared to the rest of the population. While these individuals' data were different from majority of the participants and were outliers compared to the rest of the data, their data is important to further investigate.

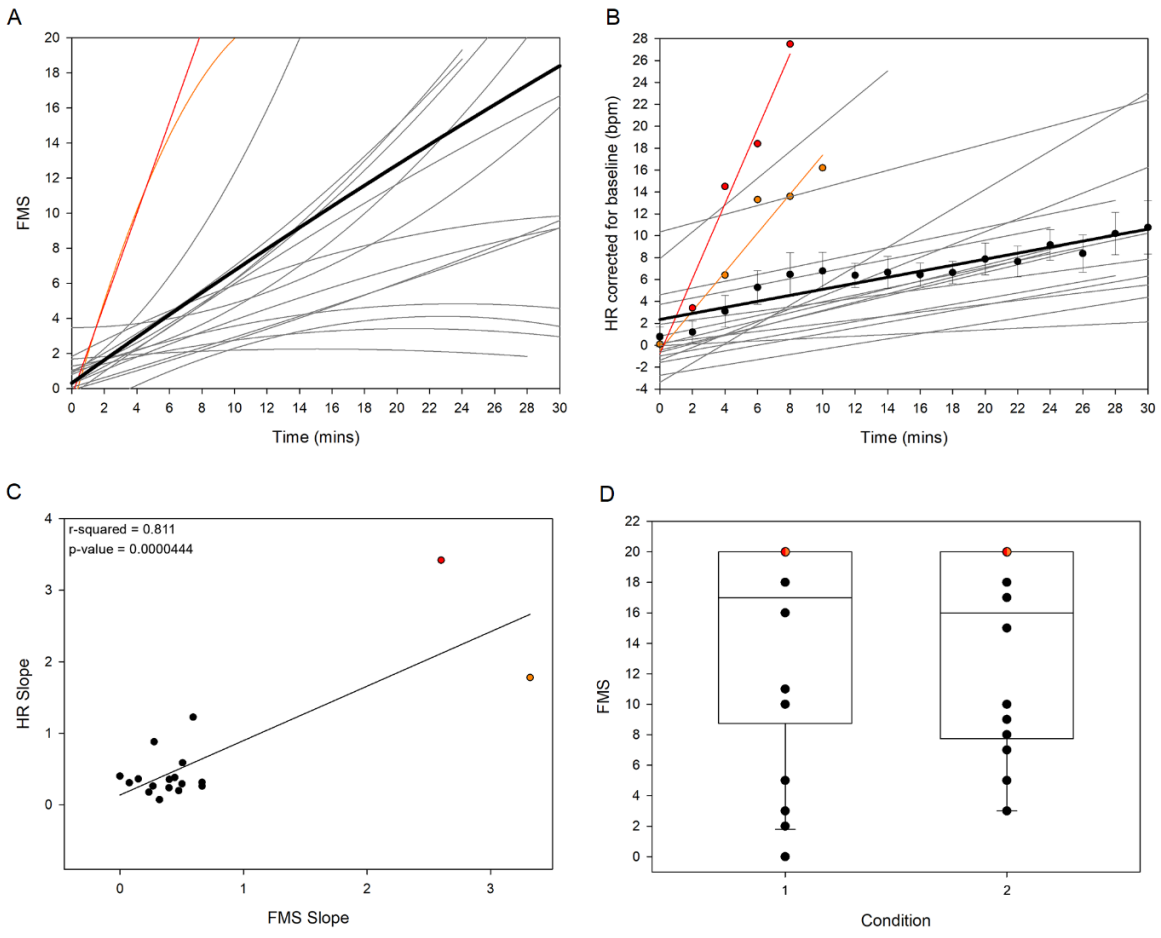

Figure 13: All previously seen figures from the results section with two subjects highlighted. A) Participants' sequential self-reported FMS scores as a function of VR exposure time. B) Participants' HR (corrected to baseline) as a function of VR

exposure time. C) Pearson correlation between HR slope as a function of FMS slope. D) Participants' FMS as a function of the two conditions.

In hypothesis 3 we predicted that sickness levels would be higher if participants were asked about their sickness levels periodically throughout the experiment. To test for this, a paired t-test was done on the final FMS scores of the two conditions. Results showed that there were no statistical differences in the final FMS scores between the two conditions, suggesting that by committing to a sickness rating continuously throughout the exposure, the participants were not more likely biased to a higher final FMS. We had hypothesized that having subjects continuously monitor their symptoms would make them more aware of their body's response, which in turn would lead them to rate their sickness score higher. Another reason behind that hypothesis was that participants could have felt the need to rate themselves higher on the sickness scale if they had noticed their ratings remain at the same level over time. Alas, the data did not show a statistical difference in final FMS scores between the two conditions, thereby rejecting our third hypothesis that by continuously asking for perceived ratings of sickness the participants would be more likely to report a higher final sickness level. This result suggests that future studies may be able to reliably use FMS without the worry that it may be over-estimating sickness.

Our final hypothesis was tested by correlating HR slopes and FMS slopes of all participants. The correlation coefficient was high which would typically suggest a high correlation between HR slopes and FMS slopes. However, visually inspecting Figure 12 shows that P2 and P17 data points are different

than the other participants. Although these two participants behave differently from the other participants, they behave similarly to each other. Additionally, both P2 and P17 reach their final FMS scores approximately around the same time in both trials. As stated previously, these individuals are outliers; however, they should not be excluded. These results can be interpreted in two different ways: 1) the data is as we see it, meaning there are two distinct types of responders (slow and fast), and 2) the responders fall on a continuum, and we just haven't captured that with participant sample. Since we cannot exclude P2 and P17 and based on the heterogenous responses seen, participants could be classified as slow and fast responders. The figure below (Figure 14) shows the correlation between HR slopes and FMS slopes after P2 and P17 were removed; thereby just showing the slow responders' group. The correlation of the slow responders group has a much smaller coefficient and was not significant, suggesting that there was not a visible relationship between HR slopes and FMS slopes of that group, or our sample was not able to capture the true relationship.

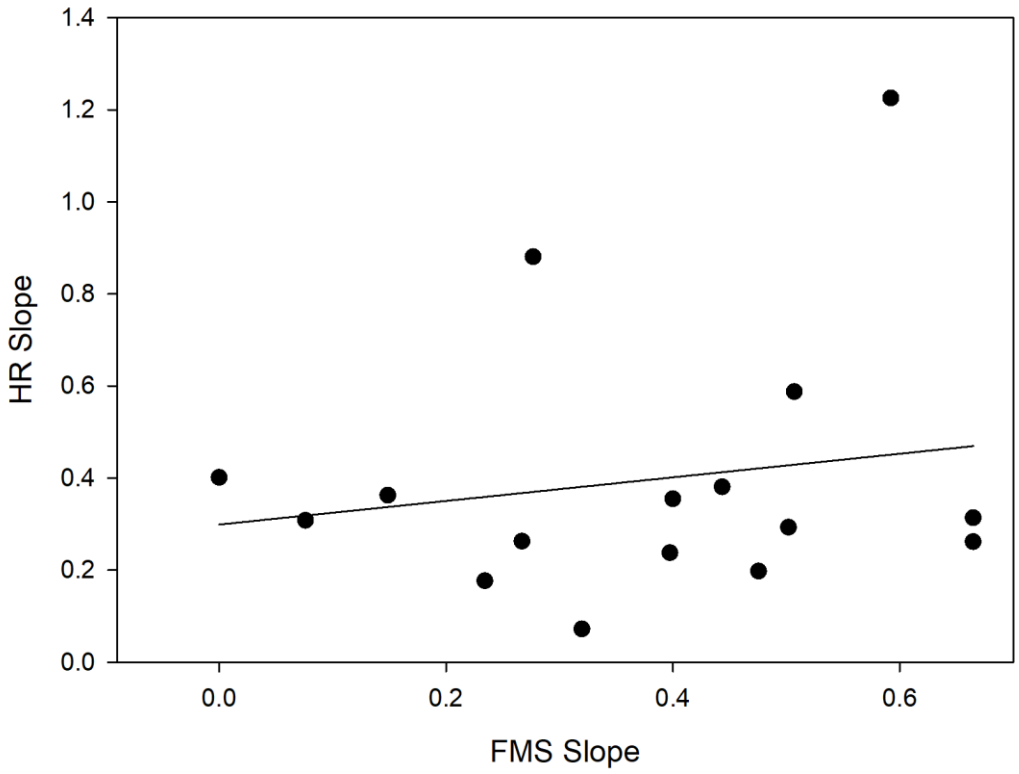

Figure 14: Pearson correlation between HR slope as a function of FMS slope of the "Slow Responders" group (P2 and P17 removed). Each participant is represented by each point and the solid black line is the line of best fit (R = 0.177, p-value = 0.153, R^2 = 0.0312).

Being able to differentiate the type of responders is an important step towards being able to predict cybersickness. A simple multiple linear regressions model was used on the data from the "slow responders" group to see if prediction of final FMS was at all possible. The variables used in the predictive model were change in HR, VR experience, and past sickness history (MSSQ). Although not statistically significant, this predictive model, thus far, explains 71% change in final FMS score (Table 3). An argument can be made that even though the p-value is greater than 0.05, this predictive model shows that certain variables can

be used in predicting sickness and that there is still merit in continuing with such work.

Table 3

	Estimate	*Standard error*	*t Value*	*Pr(>|t|)*
(Intercept)	7.149	5.067	1.411	0.231
MSSQ	0.013	0.352	0.037	0.972
VR Experience	6.458	6.739	0.958	0.392
HR Change	0.114	0.285	0.400	0.710

Multiple Linear Regression results of the “slow responders” group. R^2: 0.710; F-statistic: 3.271; p-value: 0.1411; Residual Standard Error: 4.828, 40.2% error rate.

Given that there is a small predictor capability with this simple model, we suggest that future experiments use larger sample sizes and also possibly use machine learning as a means of determining whether HR, HRV, and GSR can predict the SSQ and FMS scores reported by participants. This would not only allow us to potentially better predict FMS, but also factor out how repeatedly asking participants to self-report their sickness affects their sickness and FMS ratings. Machine learning is the process of an algorithm learning from the data it has been provided and deciding or making a prediction about something related to the data. It is a subset of artificial intelligence as it heavily relies on patterns in data and statistical inferences to make predictions.

There is already precedent for using machine learning to predict sickness in VR. A study done in 2018, Jin and colleagues built three machine learning models and evaluated their performances: The Convolutional Neural Network (CNN) trained from scratch, the Long Short-Term Memory Recurrent Neural

Networks (LSTM-RNN) trained from scratch, and the Support Vector Regression (SVR). Although they did not measure any physiological data, they measured head movement, motion in a scene, scene texture, and colour in a scene (Jin, Fan, Gromala, & Pasquier, 2018). The participants were asked to play five store-bought VR games, where each gameplay lasted for three minutes. Upon the completion of each game, the participants were asked to complete an SSQ to measure their self-rated sickness. To train and evaluate the three models, Jin and colleagues (2018), applied repeated random sub-sampling validation, where the augmented dataset composed of a total of 2,400 thirty-seconds data that was shuffled 10 times. Table below shows the coefficient of determination and mean square error of each model.

Table 4

	R^2	*MSE*
CNN	0.462	0.036
LSTM-RNN	0.868	0.009
SVR	0.793	0.014

Recreation of a table published by Jin and colleagues (2018). This table shows the R^2 (coefficient of determination) and MSE (mean square error) of the three machine learning models used in their study (Jin et al., 2018).

Their results indicated that the best prediction of cybersickness was done by the LSTM-RNN, providing a viable solution for cybersickness prediction for interactive VR games (Jin et al., 2018). The authors suggested that a possible explanation for LSTM-RNN outperforming the other two models was its ability to remember information and find patterns across time to make predictions, which is suitable for the problem of predicting cybersickness based on the time-series events of VR gameplay.

Based on these results, several limitations should be acknowledged. First, it is not possible to collect and record every form of physiological reaction to sickness. Based on previous studies, and certain assumptions, we have decided to focus solely on certain physiological recordings. The second limitation is related to our sampling – our primary participants will likely consist of university students, which may reduce the results' external validity. Third, we rely heavily on self-reported data, which has its own potentials, but is limited by the fact that it rarely can be independently verified. And finally, the increase in HR during exposure to virtual environments could be related to excitement and not all due to cybersickness.

Even though we were not able to make any significant predictions in this study, we know that there may be two different types of responders. We can use this knowledge to design studies that would tease out that relationship and get closer to being able to predict cybersickness. Previous research has shown a relationship between certain physiological data and level of sickness, but such physiological reactions have never been used to predict cybersickness. Using machine learning will allow us to incorporate the physiological data with the self-rated data to not only find a relationship, but to look ahead and predict one's outcome. By understanding cybersickness, we will be able to start predicating and eventually preventing this condition.

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5. APPENDIX

Appendix A

Motion Sickness Susceptibility Questionnaire Short-form (MSSQ-Short)

1. Please State Your **Age** ..... Years. *2*. Please State Your Sex (tick box) **Male** [1] **Female** [2]

This questionnaire is designed to find out how susceptible to motion sickness you are, and what sorts of motion are most effective in causing that sickness. Sickness here means feeling queasy or nauseated or actually vomiting.

Your CHILDHOOD Experience Only (before 12 years of age), for each of the following types of transport or entertainment please indicate:

3. **As a CHILD (before age 12),** how often you **Felt Sick or Nauseated** (tick boxes):

	Not Applicable - Never Travelled	**Never Felt Sick**	**Rarely Felt Sick**	**Sometimes Felt Sick**	**Frequently Felt Sick**
Cars					
Buses or Coaches					
Trains					
Aircraft					
Small Boats					
Ships, e.g. Channel Ferries					
Swings in playgrounds					
Roundabouts in playgrounds					
Big Dippers, Funfair Rides					
	t	0	1	2	3

Your Experience over the LAST 10 YEARS (approximately), for each of the following types of transport or entertainment please indicate:

4. **Over the LAST 10 YEARS,** how often you **Felt Sick or Nauseated** (tick boxes):

	Not Applicable - Never Travelled	**Never Felt Sick**	**Rarely Felt Sick**	**Sometimes Felt Sick**	**Frequently Felt Sick**
Cars					
Buses or Coaches					
Trains					
Aircraft					
Small Boats					
Ships, e.g. Channel Ferries					
Swings in playgrounds					
Roundabouts in playgrounds					
Big Dippers, Funfair Rides					
	t	0	1	2	3

For more background information and references to the original Reason & Brand MSSQ and to its revised version the 'MSSQ-Long', see Golding JF. Motion sickness susceptibility questionnaire revised and its relationship to other forms of sickness. Brain Research Bulletin, 1998; 47: 507-516. Golding JF. (2006) Predicting Individual Differences in Motion Sickness Susceptibility by Questionnaire. Personality and Individual differences, 41: 237-248.

Appendix B

No_____ Date_____

SIMULATOR SICKNESS QUESTIONNAIRE

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.

Appendix B (Cont'd)

Simulator Sickness Questionnaire***

Kennedy, Lane, Berbaum, & Lilienthal (1993)***

Validation of the French-Canadian version of the SSQ developed by the UQO Cyberpsychology Lab :

- Total : items 1 to 16 (scale of 0 to 3).
  - « *Nausea* » : items 1 + 6 + 7 + 8 + 12 + 13 + 14 + 15 + 16.
  - « *Oculo-motor* »: items 2 + 3 + 4 + 5 + 9 + 10 + 11.

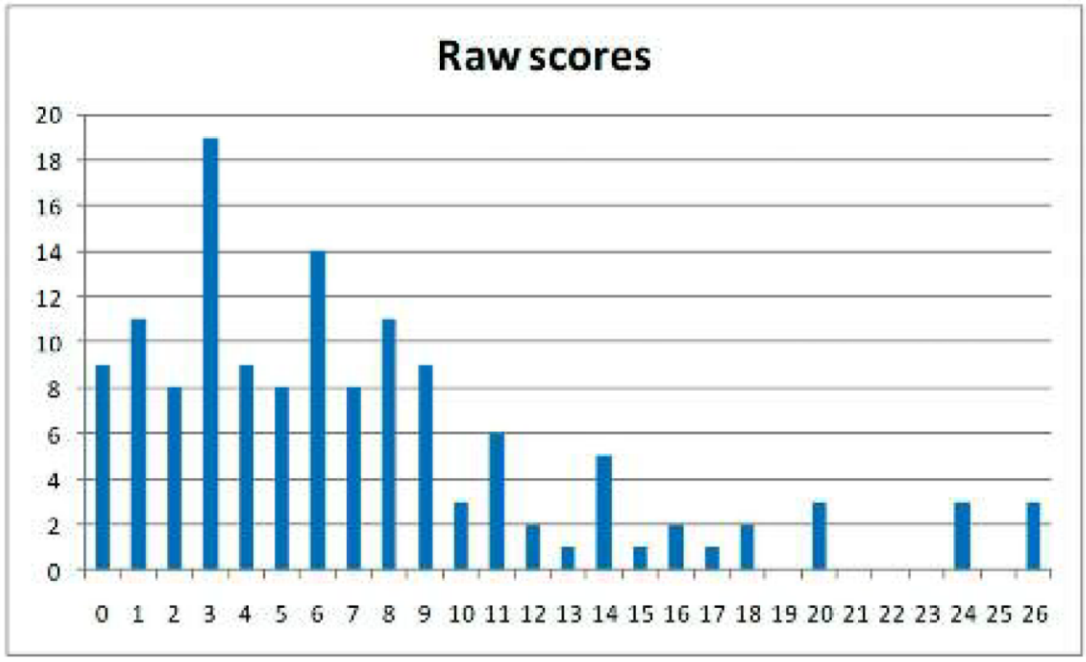
Please refer to the following articles for more information about the French-Canadian validated version :

BOUCHARD, S., Robillard, & Renaud, P. (2007). Revising the factor structure of the Simulator Sickness Questionnaire. Acte de colloque du *Annual Review of CyberTherapy and Telemedicine*, *5,* 117-122.

BOUCHARD, S., St-Jacques, J., Renaud, P., & Wiederhold, B.K. (2009). Side effects of immersions in virtual reality for people suffering from anxiety disorders. *Journal of Cybertherapy and Rehabilitation*, 2(2), 127-137.

BOUCHARD, S. Robillard, G., Renaud, P., & Bernier, F. (2011). Exploring new dimensions in the assessment of virtual reality induced side-effects. *Journal of Computer and Information Technology*, *1*(3), 20-32.

Based on results from Bouchard, St-Jacques, Renaud, & Wiederhold (2009), below are the mean scores reported:



Note. For the original scoring version, consult : 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.

Appendix C

Date: Participants ID:

Gaming Experience Questionnaire

1. Do you like to play video games?
   - Yes ☐
   - No ☐

2. Which age did you start playing video games? (please tick one)
   - 1-10 years old ☐
   - 11-15 years old ☐
   - 16-20 years old ☐
   - 21-25 years old ☐
   - +26 years old ☐

3. How many days do you play games in one week? (please tick one)
   - 0 days ☐
   - 1-2 days ☐
   - 3-4 days ☐
   - 4-6 days ☐
   - Everyday ☐

4. How much time on average do you spend a week playing video games? (please tick one)
   - 0 hours ☐
   - 1-5 hours ☐
   - 6-10 hours ☐
   - 11-15 hours ☐
   - +15 hours ☐

5. Have you ever used any Virtual Reality devices (Oculus, HTC Vive, etc..)?
   - Yes ☐
   - No ☐

6. If yes, how many hours of experience with Virtual Reality do you have? (please tick one)
   - 0 hours ☐
   - 1-5 hours ☐
   - 6-10 hours ☐
   - 11-15 hours ☐
   - +15 hours ☐

7. Have you ever gotten motion sick playing video games?
   - Yes ☐
   - No ☐