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Motion sickness in virtual environments

DISSERTATION

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for the degree of

DOCTOR OF PHILOSOPHY

in Psychology

by

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ABSTRACT OF THE DISSERTATION

Motion sickness in virtual environment

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Doctor of Philosophy in Psychology

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With the increasing popularity of virtual reality, people are now experiencing motion sickness during use of head mounted displays (HMDs). This dissertation reviews the major theories on why certain body motions and visual inputs cause sickness. It then details three experiments which measure motion sickness when a person uses an HMD or a monitor to view virtual environments (VEs). In Experiment 1, seated subjects interacted with a VE using a monitor and using an HMD while physiological signals were recorded. We found that subjects reported severe motion sickness while using an HMD but not while viewing images on a monitor. In fact, half of the subjects chose to quit the experiment after six minutes of HMD use and reported feeling nauseous at that time. It was found that stomach activity, blinking, and breathing can be used to estimate post-immersion motion sickness severity and to classify which viewing condition a subject's data originated from. Experiment 2 tested postural instability theory, which proposes that a person must exhibit body instability before motion sickness can occur. Subjects either stood on a balance board or sat in a chair while they were immersed in a rotating tunnel simulation. They used a game controller to indicate changes in their perceived vertical. A minority of subjects showed significant changes in postural sway compared to a resting baseline. However, these subjects did experience changes in their perceived vertical; the world had tilted in the direction of visual rotation. We found that subjects with less postural sway reported greater sickness, which contradicts postural instability theory. In the final experiment, subjects navigated a virtual space station while wearing an HMD or viewing a monitor and stood on a balance board. While navigating through the VE, subjects were subjected to unexpected visual motion which produced the sensation of being pushed in virtual reality. Results showed that these visual perturbations caused significantly greater postural sway. Yet, motion sickness was reported similarly when subjects wore the HMD regardless of perturbation presence or absence. These results demonstrate clearly that postural instability caused by unexpected visual change is not a prerequisite of motion sickness.

1 Introduction

For most people motion sickness is a temporary discomfort most often felt during travel. With the rise in popularity of new virtual reality (VR) technologies, visually induced motion sickness has become one of the most critical areas of study for the continued growth of the industry. This body of work reviews the predominant theories on why certain body motions and visual inputs cause us to feel sick and discusses three experiments that measure motion sickness when a person uses virtual reality technology.

1.1 Theories of motion sickness

The noxious effects of motion sickness include primarily vomiting, nausea, and lightheadedness/dizziness. Other related physiological changes include reddening of the skin and increased sweating. Although these symptoms are largely agreed upon (Money, 1970; Reason, 1978; Treisman, 1977; Yates *et al.*, 1998a), no consensus has been reached about the cause of motion sickness.

1.1.1 The Poison Theory

Money and Myles (1975) called motion sickness an evolutionary abnormality, which is surprising because vestibulo-gastric illness occurs in a variety of species, not just humans. Treisman (1977) argues motion sickness is actually an adaptive response to a noxious stimulus. Vomiting makes little sense as a response to motion sickness unless there is a positive reason for it. The feelings elicited during motion sickness are similar to that of being poisoned by a neurotoxin and vomiting is a likely response to rid the body of such poison. Therefore, it seems plausible that motion sickness is an ancient defense against ingested poisoning.

However, some major problems exist with this theory. One fact is that babies and young animals such as puppies do not suffer from motion sickness. Some argue that this defense is

dormant because babies are often breast fed and breast milk is unlikely to have any toxins (Treisman, 1977). But this doesn't make sense because overwhelmingly babies' bodies are extremely sensitive to any form of toxin (Reason & Brand, 1975; Reason, 1978). It is unlikely that the symptoms of motion sickness would be uniquely considered unthreatening to the body. A more likely explanation is that because young animals are often carried around in unexpected ways by their mothers, they must not be too sensitive to odd and frequent controlled movements of their bodies by their mothers. Other work supporting the poison theory found that individuals who are more susceptible to motion sickness are more susceptible to toxins, chemotherapy and post-operative nausea and vomiting (Morrow, 1985). Money and Cheung (1983) performed labrynthectomy (removal of the vestibular system) on dogs and found an increased threshold to vomiting from ingestion of some but not all emetic drugs. This finding may be considered to support the poison theory of motion sickness. Yet the lack of similar responses to all emetic drugs by the animals fails to support the role of the vestibular system as a backup detector of toxins. Another problem with this explanation is that it does not account for how vomiting is beneficial to the body when it does not ease the symptoms of motion sickness.

Bowins (2010) suggests that motion sickness developed as a form of negative reinforcement to provide motivation to avoid movements that cause sensory conflict or postural instability. He also points out that an emetic response to toxins already passing through the blood brain barrier is redundant when the liver already exists for the purpose of poison filtration. If toxins have already crossed into the brain, then vomiting would be pointless to remove them. Additionally, not all instances of motion sickness lead to vomiting. In his view, the motion sickness response acts similarly to pain in terms of evolutionary fitness, informing the brain that the actions the body is performing are not optimal and should be stopped. Along the same line,

an update to the poison theory (Yates *et al.*, 1998b) concluded that motion sickness results from an aberrant activation of neural pathways that serve to maintain a stable internal environment and is not actually a poison response to eliminate toxins from the body. These pathways, which include vestibular inputs to the brainstem, are responsible for maintaining homeostasis and conflicting body state signals trigger atypical activation of these regions. In summary, although the poison theory of motion sickness makes sense at face value, it is not a completely satisfactory explanation of motion sickness.

1.1.2 Sensory Mismatch Theory

The sensory mismatch theory proposes that all forms of motion sickness result from a disagreement between the vestibular system and one of or both proprioception and vision. This conflict of sensory information is what gives rise to the unpleasant feelings associated with motion sickness.

The idea of sensory mismatch as the source of unpleasant feelings has been long studied and was described by Irwin in 1881 in his dialogues with sailors feeling dizziness and nausea from the visual vertigo of seasickness. He claimed that these feelings arose when two normally aligned sources of spatial information became opposed to one another in a way that was unexpected based on prior experience or what has been called the "exposure-history" (Held, 1961). The two premises of the sensory mismatch theory are as follows: 1) all scenarios that cause motion sickness include opposing motion-related information from the eyes, vestibular system, and other gravicepters, 2) that the vestibular system must be involved directly or indirectly (Reason & Brand, 1975). This is because prior work has shown that removal of the vestibular system almost completely eliminates susceptibility to motion sickness (K. E. Money, 1973).

The types of sensory mismatches that can cause motion sickness may be grouped into three categories according to Reason (1975): 1) mismatches of both visual and vestibular information, 2) visual information lacking agreement with visual information, and 3) visual information lacking agreement with vestibular information. Additionally, these same three categories can be considered for mismatches directly between the otoliths and the semicircular canals. Table 1.1 describes several example scenarios which result in each of the possible mismatches between the visual and vestibular systems that would likely elicit motion sickness. An important point is that although these scenarios may result in motion sickness in some individuals, they may not cause symptoms in all (see Table 1.1).

Table 1.1 Types of Vestibular Mismatch. Sensory mismatches and associated scenarios based on the categories described by Reason (1975).

Type of Mismatch	**Example Scenario**
Visual and Vestibular	Wearing a head mounted display that reverses visual field movement when the head is moved
Visual without Vestibular	Walking around in a virtual environment while being seated in reality
Vestibular without Visual	Reading a book while riding in a moving vehicle
Otolith and Canal	Rapid turning of the head in microgravity
Canal without Otolith	Caloric stimulation of the inner ear
Otolith without Canal	Low frequency oscillations in the vertical plane

1.1.3 Sensory Rearrangement Theory

Reason (1978) modified the sensory mismatch hypothesis propounded earlier (Reason & Brandt, 1975) by proposing that motion sickness is caused when conflicting sensory inputs diverge sufficiently from normal. This proposal is termed sensory rearrangement theory. The term sensory rearrangement was taken from Held's earlier work on the use of prism goggles to alter

visual perception (Held, 1961). Held proposed that as prism users learned to adapt to distortions of sensory information, the sensory rearrangements made were continuously recorded to update a correlation storage. The more the user wore the goggles, the less rearrangements were necessary to maintain a stable percept. For motion sickness, the modalities differ and so are discrepant. If the magnitude of this discrepancy is greater than prior experience, sickness is felt. Because of the structural limitations of the brain, information from prior experiences is only available from two sources: sensory systems and memory. For the brain to perform optimally, it must estimate what comes next based on these two sources of information. This idea is critical to understanding how the brain handles scenarios in which these sources of information disagree, such as during sensory rearrangements. To better understand how this process works, it is necessary to explain the concept of efference copies and reafference.

Helmholtz (1866) first proposed the idea of the efference copy when explaining how the brain issues motor commands to control eye movements. When the brain issues a motor command, a copy of this command is also stored. When the command is sent to move the eyeball, we perceive the world as still. This is because the brain has anticipated the resultant sensory information of the saccade from the efference copy. However, if one gently pushes on the corner of their eyeball to induce a slight rotation, the world appears to rotate. This is because no copies of the movement command are available with which to compare to.

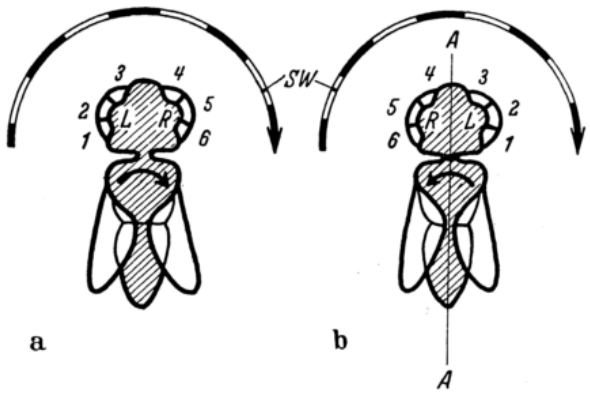

Figure 1.1 Diagram of fly behavior while a striped pattern is rotated from left to right. Image a shows the normal insect. Image b shows a fly whose head has been rotated about A-A 180 degrees. The arrow on the fly's thorax shows its turning direction. From VonHolst and Mittelsteadt (1950).

Later work by Von Holst and Mittelstaedt (1950) investigated how animals could distinguish between sensory information that was from themselves (reafference) or from additional sensations from the external world (exafference). They examined this by surgically rotating a fly's head 180 degrees only to find that the fly continuously moved around in the same direction as the flipped visual input (see Figure 1.1).

When a movement is planned, an efference copy is generated so that the brain may estimate the sensory feedback. This corollary discharge is compared with the actual sensory information produced from the motor command (the reafference). If these two signals do not match, a sensory discrepancy is produced and the brain can adjust future motor commands accordingly. It is because of this brain mechanism that it is nearly impossible to tickle ourselves even though the touch of others can elicit the tickle sensation. A graphical representation of this principle is shown below in Figure 1.2.

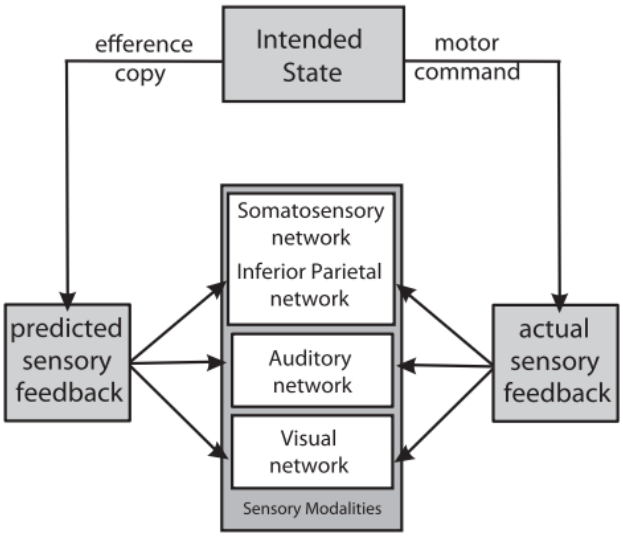

Figure 1.2 Brain sensory state estimation model. This model graphically shows the information flow of a motor command. A motor command is generated to reach some intended state and a copy of this command is retained. The copy is used to estimate sensory feedback which is then compared to the actual sensory feedback of the completed command in multiple brain regions. Image from Pynn & DeSouza (2013).s

Building on the reafference feedback model and Held's idea of a correlation storage, Reason (1978) concluded that motion sickness worked in a similar way to prism goggles, but changed the correlation storage to a "neural store" of prior sensory experiences. In the case of motion sickness, if predictions of reafferent input by the various sensory systems do not match those associated with some prior experience, the person will feel ill in proportion to the degree of mismatch with the prior exposure. Figure 1.3 below demonstrates this model.

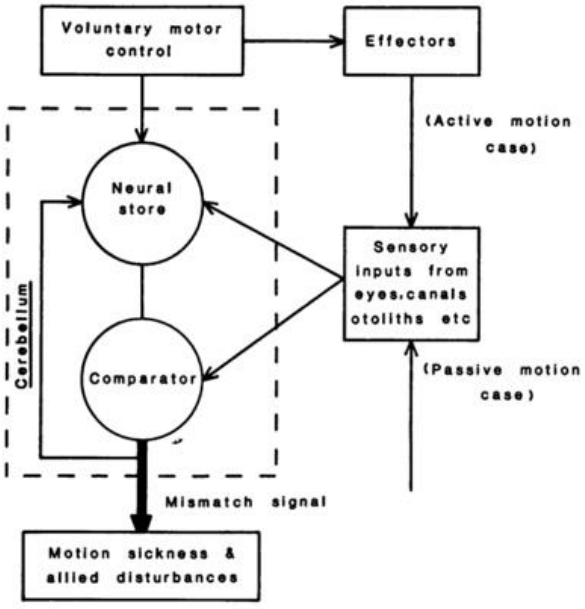

Figure 1.3 Neural Store Model. A motor command is sent to effectors and to an internal neural store of prior experiences. Sensory information is updated in the neural store and compared with expected sensory information. If a mismatch exists, motion sickness occurs and the neural store is updated. From Reason (1978).

Further work (Jelte *et al.*, 2008; Oman, 1982, 1990, 1991) brought in principles from engineering to try to explain mathematically sensory system integration using internal models. An internal model estimates expected sensory input based on the current environment and motor commands. This estimation is used to generate a cancellation signal for the expected information. During normal movements, the difference between the cancellation signal and the true exafferent feedback will be minimal, but in the case of a motion sickness inducing environment, such as seated movement in virtual reality, the difference may be large. The brain then uses this difference to update future actions to better match the unexpected exafference. Internal models have been exhaustively studied in the field of motor control, e.g. Kawato & Gomi, 1992; Wolpert & Kawato, 1998; Wolpert, 1995.

There is a consensus that the cerebellum plays a key role in generating internal models for the purpose of controlling arm and other limb movement. It has been shown that cerebellar output neurons called Purkinje cells project to the vestibular nucleus and are critically important for stable head movements (Blakemore *et al.*, 1999), but further work is needed to examine the connectivity between these regions and emetic control centers in the postrema area of the brainstem. A recent review by Oman and Cullen (2014) suggests that connections between vestibular-only neurons in the vestibular nucleus of the brainstem and the cerebellar sensory integration network are key.

In summary, the sensory rearrangement theory proposes that motion sickness is likely caused by a disagreement in information processed by sensory systems that are normally in agreement according to prior experience. The level of motion sickness experienced is correlated with how much discord exists between the current experience and the past experience. This comparison is modeled well by existing motor control theory models (Kawato & Gomi, 1992; Wolpert, 1995; Wolpert & Kawato, 1998).

1.1.4 Postural Instability Theory

The postural instability theory centers on the idea that maintaining body stability in the environment is critical and that prolonged instability leads to motion sickness. It was created as a direct rebuttal to sensory mismatch theory and ultimately claims that sensory mismatch neither exists nor does it lead to the consideration of postural instability. Developed by Riccio and Stoffregen, the theory argues that the dynamics of an animal's skeletomuscular system and its environment constrain postural control (Riccio & Stoffregen, 1988, 1991a). The authors make the interesting points that information regarding orientation and motion are different for individual perceptual/sensory systems and that perception is an emergent property of the entire

sensory system. This emergent information is specific to each animal-environment combination (Gibson, 1966; Riccio & Stoffregen, 1988). This means that intermodal specificity, or the stimulation across systems in a specific scenario, occurs in both normal and irregular (for example, microgravity or virtual reality) environments. Sensory conflict does not exist because there is no resolution to be made across sensory systems; the emergent information is simply specific to that scenario. For example, in a virtual rotating room environment, the visual motion of the rotating room will be uncorrelated with the motions necessary to maintain balance if the viewer is rotated. Riccio and Stoffregen claim that prolonged usage of this unstable control scheme will result in motion sickness until the appropriate scheme has been achieved and continuously used.

Based on this claim, postural instability is necessary for and must always precede motion sickness. Stoffregen and Riccio (1991) suggest that this notion is supported by the absence of motion sickness under water, because postural control underwater requires little effort. An important point is made that passengers of vehicles display more motion sickness than drivers. Unlike sensory conflict theory, which would state the driver is able to predict the expected mismatch from a quick turn during a stable drive, postural instability theory claims the driver is able to adjust his/her postural control in anticipation of the turn's acceleration (Stoffregen, 1985). Thus individual differences in motion sickness susceptibility are actually differences in postural control. Stoffregen and Smart (1998) analyzed postural sway data for standing subjects in a moving room with optical oscillations below 0.3 Hz and found that increases in postural sway occurred before the onset of motion sickness symptoms in half of subjects (see Figure 1.4). They also found that the subjects who showed the most instability were the ones who reported greater sickness symptoms.

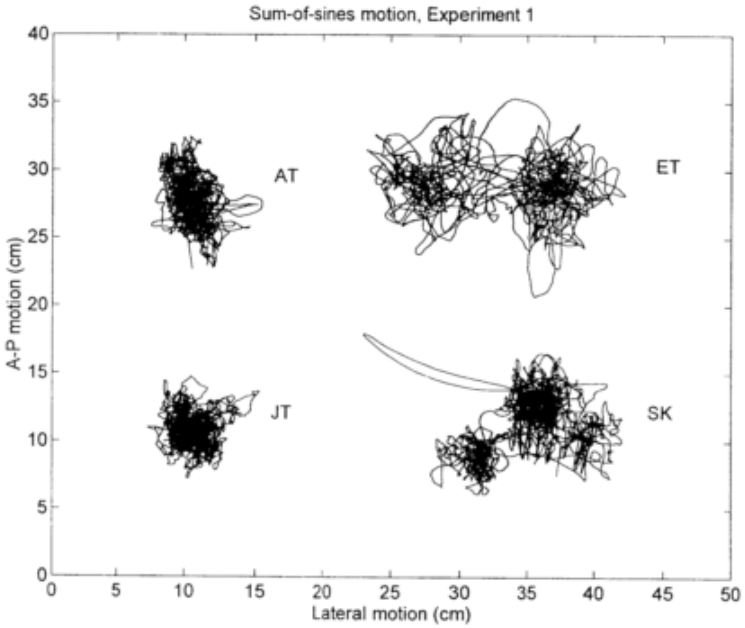

Figure 1.4 Postural sway data from stationary subjects who observed complex sum-of-sines optical motion. Subject ET developed motion sickness later in the experiment and SK developed motion sickness after leaving the lab. From Riccio & Stoffregen (1988).

Thomas and colleagues (2014) recorded head movements while subjects played a game on a tablet using either touch controls or rotation of the device to move around their avatar. They found that users who simply touched rather than rotated the tablet were five times more likely to report feeling sick and users who reported being sick moved their head more while playing. These results support the postural stabilization theory because users who could rotate the tablet and thus their head and body accordingly were reportedly less sick than those who simply played with touch controls. Motion sickness in such an environment is linked to the behavioral and thus postural goals of the user (Riccio & Stoffregen, 1991a).

Stott (1986) proposed three rules that if broken will lead to motion sickness: 1) motion of the head in one direction will result in motion of the external visual scene in the opposite direction, 2) rotation of the head not in the horizontal plane must include an angular change in

the direction of the gravity vector, and 3) any sustained linear acceleration is from gravity which points downward with an intensity of 1g. These rules were simplified to the general claim that motion sickness would result from any "conflict" between the expected and sensed vertical (Bos & Bles, 1998). In each of these cases, postural instability would indeed occur.

Warwick-Evans and colleagues (1998) tested the predictions of the sensory rearrangement and postural instability theories by having subjects watch a movie at either normal or two times normal speed while standing or lying down. Sickness was reported in all conditions but was significantly greater while subjects were lying down and while the movie was sped up. The authors followed up this experiment by showing the film at 20% reduced speed and found sickness in all conditions. These results suggest two conclusions: 1) the speed of the movie produced sensory conflict, but this conflict was inconsistently tied to sickness, and 2) subjects felt worse lying down which directly opposes postural instability theory.

In summary, the postural instability theory claims that sensory mismatch is impossible because no mismatches occur. Rather, the animal-environment interaction produces a unique emergent sensory stimulus that reflects the behavioral goals of the animal. When an animal is unable to achieve postural stability for a prolonged period, motion sickness occurs. When the animal can find a control scheme that yields stability, the symptoms will pass.

1.2 Measuring Motion Sickness in Virtual Reality

Virtual reality allows for more precise control over the visual stimulation shown to the user and so provides distinct advantages in the study of motion sickness. Because of the nature of VR hardware, cybersickness is primarily driven by sensory information from the visual display and the vestibular cues associated with moving a virtual avatar while remaining stationary in reality. In most VR setups, the user wears a head mounted display (HMD) (see Figure 1.5a) but other

systems, like the CAVE, exist which project images on walls around the user (see Figure 1.5b). Thus, cybersickness is only visually-induced and closing the eyes quickly alleviates symptoms.

(a) (b)

Figure 1.5 Two virtual reality systems. (a) The Oculus Rift Developer Kit 2 HMD and the (b) Antyclip CAVE. Images from engadget.com and antycipsimulation.com.

1.2.1 Questionnaires

Motion sickness questionnaires have the benefits of being inexpensive and convenient to administer. The most used questionnaire was developed by Reason and Brand (Reason & Brand, 1975; Reason, 1968) and remained unmodified until 1998 when Golding created an updated and simplified version of the Motion Sickness Susceptibility Questionnaire (MSSQ). The purpose of the MSSQ is to determine how susceptible a person is to becoming motion sick based on their experiences with motion sickness inducing environments. The susceptibility measures of the original MSSQ and the simplified MSSQ are nearly identical (r = 0.989) and the predictive value of motion sickness is given by correlations of around r = 0.45. These questionnaires demonstrate the variability in susceptibility across individuals, although a recent study found no significant correlation for the Big Five personality traits (*openness, conscientiousness, extraversion, agreeableness, neuroticism*) and motion sickness susceptibility (Nieto & Golding, 2006).

The MSQ and Pensacola Diagnostic Index (PDI) each provide a single value for motion sickness susceptibility which assumes the illness lies along a one-dimensional continuum. Gianaros and colleagues (2010) created the Motion Sickness Assessment Questionnaire (MSAQ) to examine motion sickness across four specific dimensions: gastrointestinal, central, peripheral, and sopite-related. Sopite symptoms include yawning, drowsiness, and disengagement from the environment. Scores on the MSAQ correlate strongly with other standard measures such as the PDI ($r = 0.81$) but provide a better assessment of separate illness factors. A *factor based* questionnaire called the Simulator Sickness Questionnaire (SSQ) was also developed specifically for measuring sickness in simulators (R. S. Kennedy, Lane, Berbaum, & Lilienthal, 1993). Scores on SSQ are broken down into three categories: nausea, oculomotor, and disorientation. The three scores have been shown useful in profiling what type of environment the user has experienced, for example sea sickness or virtual reality. A recent study found that sickness data collected from a large sample of VR users were well fit by the SSQ, with users who participated longer showing greater sickness scores across measures (Stanney *et al.*, 2003).

1.2.2 Physiological Measures

Although questionnaires are a useful way of measuring cybersickness susceptibility and the current symptoms felt by subjects, they can only provide limited predictive power. The nature of a questionnaire requires the user to break from their environment in order to respond which may decrease immersion in the VR and thus confound future responses. To solve this problem, some researchers have measured the correlates of the onset of cybersickness using physiological measures such as heart rate period (Kim, Kim, Kim, Ko, & Kim, 2005), respiration (Denise, Vouriot, Normand, Golding, & Gresty, 2009; Sugita et al., 2008), galvanic skin response (GSR) (Jäger, Gruber, Müri, Mosimann, & Nef, 2014; Kim et al., 2005), electrogastrogram (EGG) (Cheung & Vaitkus, 1998; Hu, Grant, Stern, & Koch, 1991; Oman, 1989), and skin pallor

(Holmes, King, Stott, & Clemens, 2002). However, individual variability in motion/cyber sickness susceptibility has been shown to be extensive (Barrett, 2004; Cheung & Vaitkus, 1998; Golding, 2006; Lackner, 2014) and little work has been done utilizing modern HMD technology.

1.3 Conclusion

Motion sickness involves multiple sensory systems which communicate with the vestibular system in order for the brain to compute movement of the head within its environment. But whether the ill feelings associated are due to an ancient poison defense mechanism, a mismatching of signals, or the instability of our posture is still up for debate. Cybersickness questionnaires provide limited usefulness and thus the development of physiological models that can accurately classify cybersickness symptoms at their earliest onset is of great interest. Understanding motion sickness is crucial to many industries, both civilian and military, and developing preventative solutions is necessary for the advancement of virtual reality technologies.

The following chapters present three experiments that measure cybersickness in the framework of the aforementioned motion sickness theories. The first experiment tested which non-neural physiological measures could be used to estimate cybersickness severity and classify sick and not sick individuals. The second experiment examined the validity of postural instability measures for motion sickness. The third experiment used unexpected visual motion to induce event related postural shifts and examine their effect on the genesis of motion sickness.

2 Use of physiological signals to predict cybersickness

This study was published in *Displays* at http://dx.doi.org/10.1016/j.displa.2016.07.002.

2.1 Introduction

Established surveys concerning motion sickness exist and are in common use (Bagshaw & Stott, 1985; Golding, 1998; R. S. Kennedy et al., 1993). One drawback of lengthy surveys is that they cannot always be administered while a subject is participating in an experiment. Yet brief judgments of motion sickness severity on a 1-4 scale (Bagshaw & Stott, 1985) provide useful information in such situations, although such judgments require the user to shift attention away from the experiment and toward how their body feels. Despite imperfections with these methods for evaluating motion sickness, the present study uses them to help determine the extent to which physiological measures can be used to predict cybersickness. Physiological indicators such as heart rate (Kim et al., 2005), respiration rate (Denise et al., 2009; Sugita et al., 2008), galvanic skin response (GSR) (Jäger et al., 2014; Kim et al., 2005), electrogastrogram (EGG) (Cheung & Vaitkus, 1998; Hu et al., 1991; Oman, 1990), and skin pallor (Holmes et al., 2002), and even temperature (Nalivaiko, Rudd, & So, 2014) have all been shown to be related to or predictive of cybersickness.

The following is an experiment in which cybersickness is measured while users navigate about a VE. Subjects viewed a VE using a display monitor or a head-mounted display (HMD). We hypothesized that cybersickness would be caused by the sensory mismatch that is created when subjects remain stationary in the real world but move around in the virtual world. Verbal reports of cybersickness were collected alongside continuous records of several physiological measures. Each subject participated in two VE viewing conditions: viewing the environment using a display monitor, and viewing the environment using an HMD. By contrasting results found when viewing a display monitor and those found when using an HMD, we can distinguish effects of arousal caused by environment interaction from physiological effects associated with

HMD use. Results show that physiological measures differ significantly between display monitor and HMD viewing conditions and can be used successfully to estimate the severity of cybersickness.

2.2 Methods

2.2.1 Virtual Environment

We chose a modified free-use level (Riman21, 2014) running on the Source Engine (Valve Corporation) to be the environment common to the two conditions: display monitor and HMD.

Figure 2.1 Screenshot of the virtual environment used in the experiment: a Half Life 2 game level that was run on the Source Engine.

A screenshot of the environment is shown in Fig. 2.1. During the display monitor condition, subjects viewed the environment on a Samsung S27A550H 27in LED display with a refresh rate of 60Hz and a resolution of 1920 x 1280 pixels. Subjects sat approximately 57 cm away from the display, which provided a field of view of approximately 60° of visual angle horizontally by 40° vertically. For the HMD condition, subjects wore an Oculus Rift (Oculus VR, Development Kit 2). The HMD has a resolution of 960 x 1080 pixels per eye with a refresh rate of 75Hz. The field of view is 100° horizontal by 100° vertical; head orientation is sampled at a rate of 1000 samples per second.

2.2.2 Questionnaires

Subjects started the experiment by completing the Motion Sickness Susceptibility Questionnaire (MSSQ), which was developed by Golding (Golding, 1998) to assess how susceptible a person is to motion sickness based on their past experience. It has two subsections. The first, called the MSSQA, concerns childhood experience of traveling and motion sickness before the age of 12. The second, called the MSSQB, concerns traveling and motion sickness over the last ten years. The questionnaire asks how often the subject felt sick or nauseated during different activities and is scored on a five point scale: 0 never, 1 rarely, 2 sometimes, 3 frequently, and 4 always (Bagshaw & Stott, 1985). The frequency of traveling in different vehicles is also tallied and used for calculating a final susceptibility score (see Golding 1998).

Subjects also filled out the Simulator Sickness Questionnaire (SSQ) which was developed by Kennedy and colleagues (R. S. Kennedy et al., 1993). The SSQ asks subjects to rate each of 16 symptoms on a 4-point scale: 0 absent, 1 slight, 2 moderate, and 3 severe. These ratings are used to generate scores on three sickness subscales: Nausea, Oculomotor, and Disorientation. Subjects filled out the SSQ after completing the display monitor condition and again after completing the HMD condition.

2.2.3 Procedure

All subjects completed the display monitor viewing condition before the HMD viewing condition. All rested during a five-minute break between conditions. Before recording physiological data, subjects were shown how to move around the VE using an Xbox controller that was connected to the computer controlling the VE. Subjects explored the VE freely during display monitor and HMD viewing sessions. For each of the two conditions, baseline resting data were collected for two minutes while the subject viewed the display and remained stationary in

the VE. Subjects then moved around in the VE for ten minutes. This period was followed by an additional two minutes devoted to collecting resting data.

Every two minutes, subjects were asked to rate verbally how they felt on a sickness scale: 1 no symptoms; 2 mild symptoms, but no nausea; 3 mild nausea, and 4 moderate nausea (Bagshaw & Stott, 1985). Subjects were told that, if at any time they felt too ill to continue, they were to inform the experimenter, who would help them exit the VE immediately. Subjects who terminated the experiment early for this reason were asked to rest before leaving the laboratory.

2.2.4 Physiological Recording

Physiological measures were recorded with a Biopac MP150 (BIOPAC Systems, Inc.). Signals were recorded using modules for electrocardiogram (ECG), electrogastrogram (EGG), electrooculogram (EOG), photoplethysmogram via pulse oximeter (PPG), breathing rate, and galvanic skin response (GSR). Each subject's ECG was recorded using three Ag/AgCl 11mm surface electrodes (EL507, BIOPAC Systems, Inc.) located approximately one inch below the left and right collarbone and underneath the right ribcage below the costal margin, respectively. Each subject's stomach contractions were measured using EGG. The EGG was recorded using three Ag/AgCl 11mm electrodes located below the left costal margin, two finger widths underneath the left costal margin, and below the right costal margin, respectively. We used two Ag/AgCl 11mm electrodes to determine when blinks occurred. These electrodes were positioned above the left eyebrow and 1cm below the lower eyelid, respectively. Each subject's pulse was measured using PPG. Recordings were made at the volar surface of the distal phalanx of the 4th finger of the left hand. Breathing rate was measured with a sensor band wrapped around the subject's chest approximately 5cm below the armpits. GSR was recorded from two Ag/AgCl 11mm electrodes on the volar surface of the distal phalanges of the 3rd and 5th fingers of the left

hand, respectively. Ag/AgCl electrodes were peel-and-stick disposable gel electrodes. GSR electrodes used a pre-applied conductive paste. Data were recorded through the Acknowledge 4 (BIOPAC Systems, Inc.) software package and stored for offline analysis.

2.2.5 Physiological Analysis

Physiological data were acquired at a rate of 250 samples per second. Data were segmented offline into seven epochs, each containing 30,000 samples or two minutes of data. These epochs corresponded to the initial baseline period, ten minutes of VE interaction, and the final rest period, for both conditions.

EGG samples were bandpass filtered from 0.005 to 0.2 Hz to help assess faster-than-normal stomach contraction activity (tachygastric activity, 4 – 9.5 cycles per minute (cpm)) and slower-than-normal activity (bradygastric activity, ≤ 2 cpm). The signal was then spectrally decomposed using a Fast Fourier Transform with a Hamming window to yield a frequency resolution of 0.5 cycles per minute. The percentages of band power for tachygastric and bradygastric activity were computed by dividing power in their respective frequency bands by the total power in the .005 to 0.2 Hz band.

The respiration signal was bandpass filtered to preserve energy in the frequency band 0.1 – 1 Hz. We followed work by Kim and colleagues (Kim et al., 2005) in using a peak detection algorithm to determine the number of breaths taken per minute. The PPG pulse signal was bandpass filtered from 0.1 – 10 Hz and detrended to remove any piecewise polynomial trend. We also used a peak detection algorithm to identify PPG peaks; these were used to measure amplitude changes due to vasodilation of the fingertip. The peak detection algorithm was based on the Matlab function *findpeaks* and was set to find local peaks within a sliding window whose length was defined after visual inspection of individual subject data. Because the respiration

signal can create EGG artifacts, the raw breath signal was used to visually remove contaminated EGG segments. ECG samples were bandpass filtered from 0.5 – 30 Hz to remove high frequency muscle activity (C.T. Lin et al., 2007). A peak detection algorithm was used to determine average beats per minute and the heart rate period. EOG data were bandpass filtered from 0.1 – 5 Hz to smooth out artifacts from saccadic eye movements. The number of blinks per experiment epoch was computed using a peak detection algorithm. Skin conductivity was measured in units of microsiemens and averaged over each experimental epoch. These epochs were normalized by the baseline resting epoch to account for individual differences in resting skin conductance. Normalization was performed by dividing the data from all epochs by the data from the baseline epoch. Head rotation information that was provided by the HMD in quaternion form was transformed into yaw, pitch, and roll measured in degrees. The standard deviations of these measures were computed to quantify variability in head rotation away from a fixed position.

2.2.6 Statistical Methods

We want to know whether there are significant differences in physiological measures found during display monitor and HMD use and how these differences contribute to cybersickness. Verbal reports of cybersickness were recorded every two minutes and summary sickness measures were recorded after each of the two conditions using the SSQ. Physiological data were recorded continuously during both conditions.

Physiological data were first examined using a 2 X 7 repeated measures ANOVA with display (monitor or HMD) and time (Rest 2 min, 0-2 min, 2-4 min, 4-6 min, 6-8 min, 9-10 min, Rest 2 min) as factors. Only data from the nine subjects who completed the experiment were submitted to the ANOVA. Greenhouse-Geisser corrections were implemented when the assumption of sphericity was violated. Second, we performed stepwise multiple linear regression

analysis that used physiological data from 19 subjects to estimate the SSQ cybersickness ratings described in Section 2.1. Regression analysis made use of normalized physiological data taken from the 2-4 minute epoch in the HMD viewing condition. Finally, we assessed the reliability of physiological measures by using linear discriminant analysis (LDA) to train a model to classify data from 18 subjects as originating from the display monitor or HMD condition. LDA used physiological data taken from the two conditions' 4-6 minute epochs.

2.2.7 Participants

Twenty individuals (14 men, 6 women) over the age of 18 participated in the study. None of the participants reported any vestibular or neurological dysfunction. A modified version of the video game questionnaire developed by Green and Bavelier (Green & Bavelier, 2006) was administered to each subject. Questionnaire results show that each subject in the present experiment had previous experience playing video games. Informed consent was obtained prior to the experiment in accordance with protocol HS# 2014-1090, approved by the Institutional Review Board at UC Irvine.

2.3 Results

In what follows, we first present ANOVA results which reveal the differences between the physiological measures and cybersickness severity ratings that are found in the display monitor and HMD viewing conditions, respectively. Second, we present the results of regression analyses that were performed to estimate cybersickness severity ratings using physiological measures. Finally, we use classification methods to show that physiological measures alone can be used to determine whether or not a person was using an HMD in this experiment.

2.3.1 Comparison of physiological data in display monitor and HMD conditions

Data were aggregated across subjects and the seven experimental epochs. Data from the monitor viewing and HMD conditions are plotted in gray and black, respectively. Error bars show the standard error of the mean.

2.3.1.1 *Verbal Motion Sickness Rating*

Longer durations of HMD use were associated with reports of greater motion sickness (see Fig. 2.2). An ANOVA indicates that there is a main effect of display condition $F(1,7) = 27.323$, $p = .001$, $\eta_p^2 = .796$, and a main effect of time epoch, $F(6,42) = 13.494$, $p < .000$, $\eta_p^2 = .658$. A significant interaction effect is also found between display type and time epoch, $F(6,42) = 13.494$, $p < .000$, $\eta_p^2 = .658$. Follow-up comparisons among motion sickness ratings reported during HMD use show that all motion sickness ratings during time segments after the initial 0-2 minute interval are significantly greater than those reported during the baseline period.

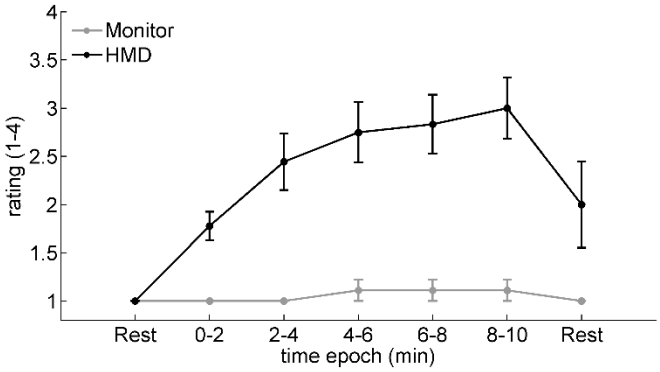

Figure 2.2 Plot of subject averages for verbally-reported sickness rating per epoch. Time epoch varies along the horizontal axis while motion sickness rating varies along the vertical axis. A motion sickness rating of 1 corresponds to "no symptoms", while a rating of 4 corresponds to "moderate nausea" (see Section 2.3). The data show clearly that reports of motion sickness increase dramatically during HMD use but not during display monitor viewing.

Seventeen of the 20 subjects reported no symptoms (rating 1) during the monitor viewing condition. Two of the 20 subjects reported feeling mild symptoms, but no nausea (rating 2).

Finally, a single subject reported feeling mild nausea (rating 3). All subjects reported feeling no symptoms (rating 1) during the final rest period of the monitor viewing condition and during the initial rest period of the HMD viewing condition. In contrast to the results for the display monitor viewing condition, fully eleven of the 20 subjects exited the experiment early during the HMD viewing condition due to motion sickness. Of these eleven subjects, one exited during the 2-4 min epoch, five exited during the 4-6 min epoch, and a further five exited during the 6-8 min epoch. These subjects reported a mean sickness rating of 3 ($\sigma = 1.170$) just prior to exit. Only nine of the 20 subjects completed the HMD viewing condition.

2.3.1.2 **Electrogastrogram (EGG)**

Studies by Kim and colleagues (Kim et al., 2005) and Lien and colleagues (Lien et al., 2003) show that tachygastric band power increases with motion sickness. Whether bradygastric stomach activity decreases with motion sickness is less clear (Cheung & Vaitkus, 1998). Fig 2.3 shows for a single subject a raw EGG data trace (Fig 3A), corresponding power spectra (Fig 3B), and percent band power (Fig 3C). These illustrative data show that there is somewhat more tachygastric activity and considerably less bradygastric activity in the HMD viewing condition.

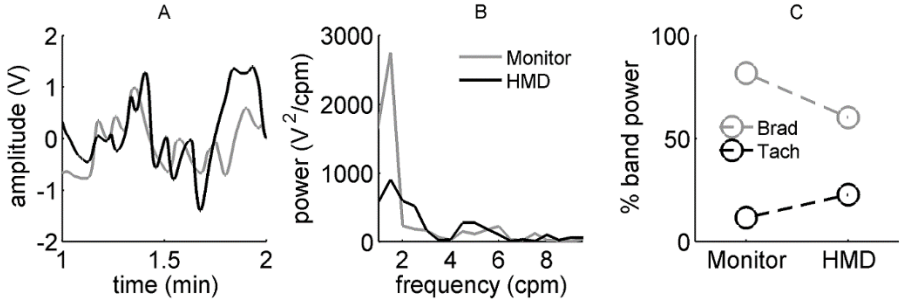

Figure 2.3 A. Plot of raw EGG traces from one subject for minute-long periods during the monitor viewing condition (gray) and the HMD viewing condition (black), respectively B. Power spectra of the data shown in A. C. Normalized power in the bradygastric (0.5-2Hz) band and in the tachygastric (4.5-9 Hz) band respectively.

Fig 2.4 shows how tachygastric band power varies with time epoch in display monitor and HMD viewing conditions. An ANOVA for the tachygastric band data from the nine subjects who completed the experiment indicates that there is a highly significant main effect of display $F(1,7) = 12.235$, $p = .010$, $\eta_p^2 = .636$. Fig 2.5 shows how bradygastric band power varies with time epoch in display monitor and HMD viewing conditions. An ANOVA for the bradygastric band data indicates that there is a highly significant main effect of display $F(1,7) = 14.320$, $p = .007$, $\eta_p^2 = .672$. We found no effect of time epoch in these ANOVAs.

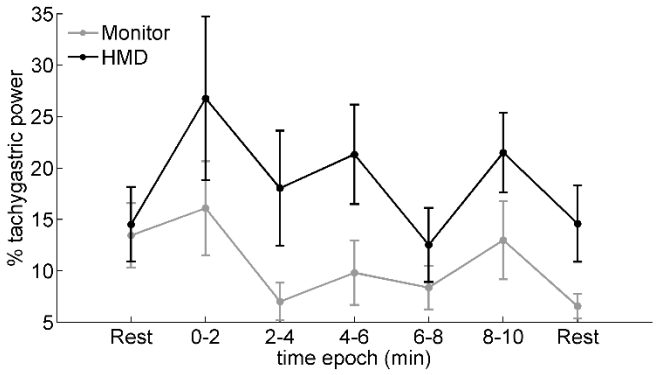

Fig. 2.4. Plot of subject averages for percent tachygastric power over time for display monitor viewing (gray) and HMD viewing (black) conditions. Epoch varies along the horizontal axis while (normalized) percent tachygastric power varies along the vertical axis. The data show that there was more tachygastric activity during HMD use than during monitor viewing. Error bars in this figure and in figures 5-12 show the standard error of the mean for the nine subjects who completed the entirety of both conditions.

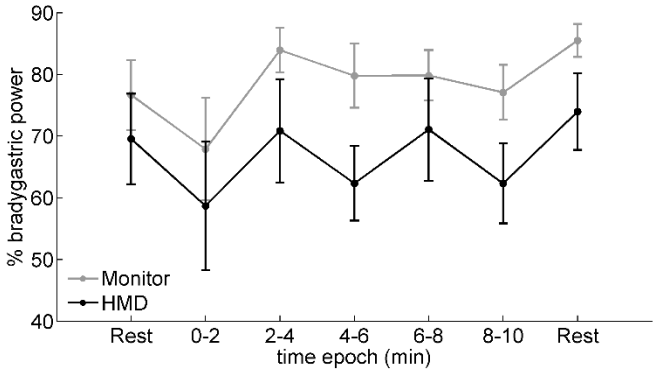

Fig. 2.5. Plot of subject averages for percent bradygastric power over time. Time epoch varies along the horizontal axis while (normalized) percent bradygastric power varies along the vertical

axis. The data show that there was less bradygastric activity during HMD use than during display monitor viewing.

2.3.1.3 *Electrooculogram (EOG)*

More blinks per epoch are found during HMD use as shown in Fig. 2.6. An ANOVA indicates that there is a main effect of display $F(1,7) = 7.822$, $p = .027$, $\eta_p^2 = .528$. There is also a main effect of time epoch $F(6,42) = 5.017$, $p = .017$, $\eta_p^2 = .417$. A significant interaction effect shows longer HMD use results in increasing number of blinks per epoch, $F(6,42) = 6.019$, $p < .000$, $\eta_p^2 = .462$.

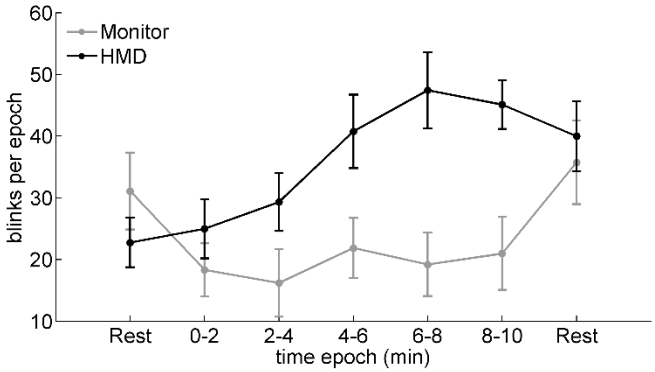

Fig. 2.6. Plot of subject averages for number of blinks per time epoch. Time epoch varies along the horizontal axis while number of blinks varies along the vertical axis. The data show that blinking increased with prolonged HMD use.

2.3.1.4 *Galvanic skin response (GSR)*

An ANOVA indicates that there is a main effect of time epoch on skin conductivity $F(6,42) = 8.200$, $p = .005$, $\eta_p^2 = .539$ as shown in Fig. 2.7. There is a near significant interaction effect between display type and time epoch $F(6,42) = 3.587$, $p = .052$, $\eta_p^2 = .339$. Follow up comparisons find that all proceeding epochs show increased skin conductivity compared to the initial rest period.

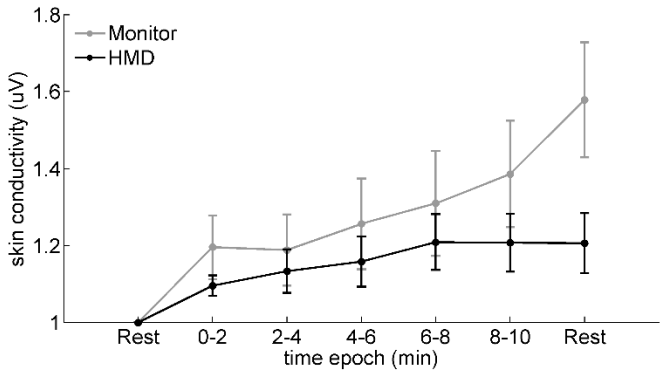

Fig. 2.7. Plot of subject averages for skin conductivity over. Time epoch varies along the horizontal axis while skin conductivity (normalized) varies along the vertical axis. The data show skin conductivity increased with time and suggest that there is less conductivity with HMD use than with monitor viewing.

2.3.1.5 *Electrocardiogram (ECG)*

Time between heart beat peaks is less during HMD use as shown in Fig. 2.8. An ANOVA indicates that there is a near significant main effect of display $F(1,7) = 5.219$, $p = .056$, $\eta_p^2 = .427$. There is a significant main effect of time epoch $F(6,42) = 5.672$, $p = .016$, $\eta_p^2 = .448$. Follow up comparisons show that there is less time between heart beat peaks with longer game playing.

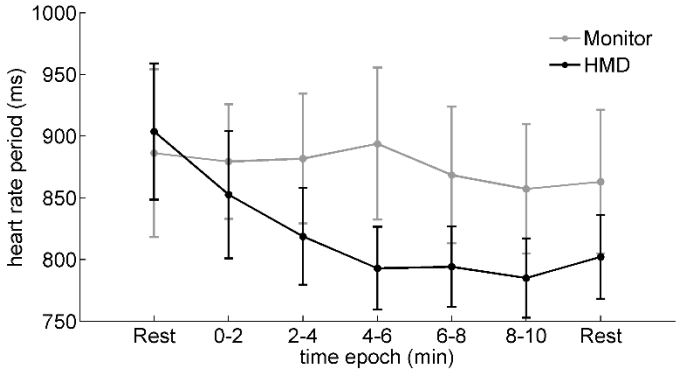

Fig. 2.8. Plot of subject averages for average time between heart beat peaks per epoch. Time epoch varies along the horizontal axis while the average time between beat peaks varies along the vertical axis. The data showed decreased time between beats with prolonged game playing and suggest that this duration is shorter during HMD use than during monitor viewing.

There are more beats per minute during HMD use (see Fig. 9). An ANOVA indicates that there is a main effect of display type F (1,7) = 6.228, p = .041, η_p^2 = .471. There is also a main effect of time epoch F(6,42) = 6.460, p = .000, η_p^2 = .480. Follow-up comparisons show that heart rate increases as time spent in the VE increases. No significant differences were found in ECG variability with respect to display type or time epoch.

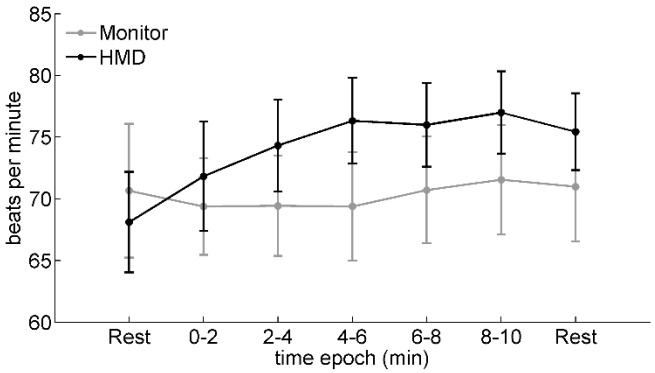

Fig. 2.9. Plot of subject averages for average heart beats per epoch. The horizontal axis denotes the times of each time epoch and the vertical axis shows the number of beats per minute. The data showed that number of beats per epoch increases during HMD viewing.

2.3.1.6 ***Respiration***

Subjects take more breaths per segment during level interaction than at rest (see Fig. 2.10). An ANOVA indicates that there is a main effect of time epoch, F(6,42) = 9.780, p = .000, η_p^2 = .583. Follow-up comparisons show a significant increase in breathing during gameplay and a subsequent decrease to the baseline level during the final rest period. Variability in time of breath occurrence within single time epochs was examined as a function of display type and epoch time. No significant differences were found.

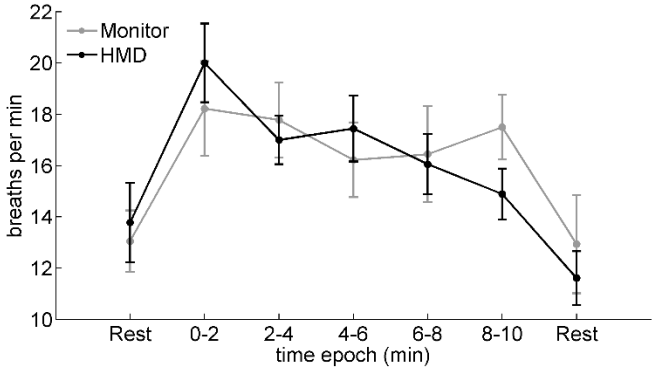

Fig. 2.10. Plot of subject averages for average breaths per epoch. Time epoch varies along the horizontal axis while number of breaths varies along the vertical axis. The data showed breathing rate increased during game playing compared to rest for both HMD use and monitor viewing.

2.3.1.7 *Photoplethysmogram (PPG)*

No significant effects were found for changes in pulse amplitude during level interaction. A plot of subject-averaged pulse amplitude per epoch for both conditions is shown in Fig. 2.11.

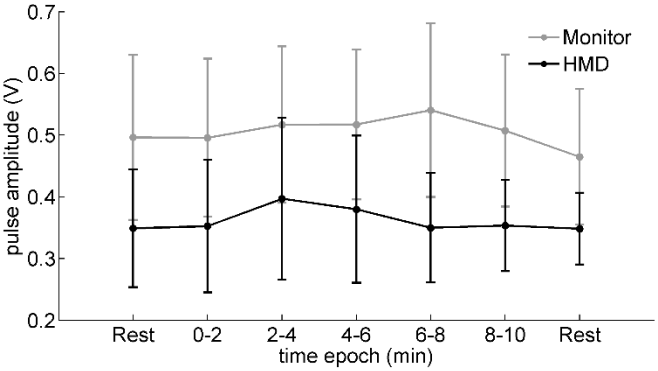

Fig. 2.11. Plot of subject averages for average pulse amplitude per epoch. Time epoch varies along the horizontal axis while amplitude varies along the vertical axis. No change in pulse amplitude with time is evident for either viewing condition.

2.3.1.8 *Head Rotations*

Greater yaw and pitch variation occurred during VE navigation with the HMD compared to rest (see Fig. 2.12). An ANOVA for yaw indicates that there is a significant effect of time epoch $F(6,42) = 8.225$, $p < .000$, $\eta_p^2 = .540$. Follow-up comparisons found yaw variation during VE navigation differed significantly only from that found during the rest period. An ANOVA for

pitch indicates that there is a significant effect of time epoch $F(6,42) = 6.200$, $p < .000$, $\eta_p^2 = .470$. Follow-up comparisons found that yaw variation during VE navigation differed significantly between the 0-2 min and 2-4 min gaming periods and for all gaming conditions compared to the rest periods.

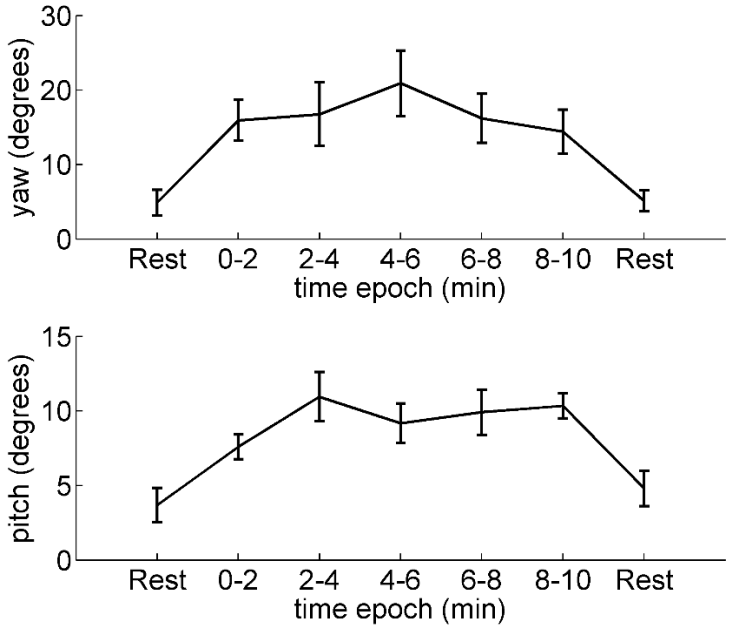

Fig. 2.12. Plot of subject averages for yaw and pitch variation per epoch during HMD viewing. Time epoch varies along the horizontal axis while standard deviation of head rotation varies along the vertical axis. The data showed increased yaw and pitch variability during level interaction compared to rest.

Summary ANOVA results are shown in Table 2.1. These results show clearly that physiological measures differ substantially between the display monitor viewing and HMD viewing conditions.

Table 2.1

Summary of ANOVA results for the nine subjects who completed the display monitor viewing and HMD viewing conditions of the experiment.

Type of Measure	**Summary of Significant Results**

% EGG tachygastric power	more activity during HMD viewing
% EGG bradygastric power	less activity during HMD viewing
Blinks per epoch	greater during HMD use and increased with time
Skin conductivity	increased with time compared to baseline
N-N Peak difference	less during HMD use and decreased significantly with time
Heart beats per epoch	more beats per minute during HMD use
Breaths per epoch	more breaths during VE interaction than rest
Sickness rating	greater during HMD use and increased with time
Yaw and Pitch variation	greater during VE interaction than rest

2.3.2 Regression Models for Cybersickness and Symptom Subscales

We wanted to see if physiological changes caused by HMD use can be used to estimate sickness scores on the SSQ. First, we calculated two-tailed Pearson correlation coefficients between physiological measures during the HMD condition, the MSSQ, and post-condition SSQ scores (see Table 2.2). The physiological measures used were the differences between baseline measurements and those taken during the 2-4 min epoch.

We found significant correlations between bradygastric power and the SSQ scores for Cybersickness and Disorientation subscales (see Table 2.2). Significant correlations were also found between mean blinks and the SSQ Oculomotor subscale score. A highly significant correlation between childhood susceptibility (MSSQA) and SSQ Oculomotor subscale score was also found. We also found that childhood motion sickness susceptibility scores (MSSQA) are significantly correlated with the time at which subjects exited the VE, $r = -.459$, $p = .042$, suggesting that those who report greater childhood susceptibility to motion sickness succumb to HMD-related cybersickness earlier.

Table 2.2
Pearson correlations between physiological measures, MSSQ scores, and the SSQ. *$p < .05$, **$p < .001$ (two-tailed). Significant correlations were found between bradygastric power and SSQ Disorientation, and SSQ Cybersickness. Significant correlations were also found between mean blinks and SSQ Oculomotor scores. A highly significant correlation between childhood susceptibility (MSSQA) and SSQ Oculomotor score was also found. N = 19.

Measure	SSQ Nausea	SSQ Oculomotor	SSQ Disorientation	SSQ Cybersickness
% Tach. Power	.260	.001	.390	.277
% Brad. Power	-.335	-.402	-.502*	-.479*
Mean blinks	.243	.497*	.110	.309
Mean GSR	.195	-.101	.131	.113
Mean Heart Rate Interval	-.05	.105	.082	.041
Mean Beats	.092	-.073	.000	.021
Mean Breaths	-.242	-.313	-.227	-.299
Mean Pulse Amp	-.124	.223	.096	.048
Yaw Variation	-.240	.029	-.357	-.245
Pitch Variation	-.127	.023	-.241	-.148
Roll Variation	.033	.104	-.145	-.011
MSSQA (child)	.079	.611**	.304	.344
MSSQB (adult)	.180	.363	.218	.282

Second, we used regression to determine which physiological changes help to estimate cybersickness symptom scores on the post-immersion SSQ. Only variables with correlations to SSQ scores that were greater than 0.2 were submitted to the regression.

The mean SSQ score after exiting the monitor viewing condition was 8 with a maximum score of 67.32. The mean SSQ score after exiting the HMD condition was 71.81 with a maximum score of 123.42. Greater SSQ scores were reported after the HMD condition than after the monitor viewing condition: nausea ($t(19) = 10.302$, $p < .000$), oculomotor ($t(19) = 9.222$, $p < .000$), and disorientation ($t(19) = 7.606$, $p < .000$). Kennedy (R. S. Kennedy et al., 1993) measured over 1000 flight simulation subjects and found an average SSQ score of 9.8 and a maximum of 108.6, with scores above 30 sitting in the 90th percentile. The average SSQ score reported after exiting the HMD condition was 71.81, demonstrating that subjects in our experiment were feeling substantial cybersickness.

2.3.2.1 *SSQ Cybersickness Score*

Bradygastric power, breathing rate, and blinking rate showed adequate predictive power for inclusion in the regression. It was found that increases in cybersickness symptoms can be estimated from changes in bradygastric stomach activity and breathing. These two variables explained 37.4% (adjusted $R^2 = .296$) of the variance, $F(3,18) = 4.786$, $\sigma_{est} = 23.34$, $p = .023$ (see Table 2.3).

Table 2.3
Stepwise Regression of Physiological Measures on SSQ Cybersickness Score. Criterion to enter = 0.2.

Measure	***β***	***t***	***Std. Error***	***p***
Bradygastric Power (%)	-.541	-2.700	14.45	.016
Breaths	-.385	-1.922	11.95	.073

2.3.2.2 *SSQ Nausea Subscale Score*

Bradygastric activity and breathing rate showed adequate predictive power for inclusion in the regression. Increases in nausea symptoms were only weakly estimated from changes in bradygastric stomach activity and breathing; these variables explained 20.1% (adjusted $R^2 = .101$) of the variance, $F(2,18) = 2.015$, $\sigma_{est} = 31.45$, $p = .116$ (see Table 2.4).

Table 2.4
Stepwise Regression of Physiological Measures on SSQ Nausea Subscale Score. Criterion to enter = 0.2.

Measure	***β***	***t***	***Std. Error***	***p***
Bradygastric Power (%)	-.383	-1.69	19.47	.110
Breaths	-.303	-1.337	16.11	.200

2.3.2.3 *SSQ Oculomotor Subscale Score*

MSSQA score, blinks, pulse amplitude and breathing rate showed adequate predictive power for inclusion in the regression. Increases in oculomotor symptoms were estimated from changes in blinking, pulse amplitude, breathing, and the MSSQ childhood score; these variables explained 74.7% (adjusted $R^2 = .674$) of the variance, $F(4,18) = 10.310$, $\sigma_{est} = 9.79$, $p = .000$ (see Table 2.5).

Table 2.5
Stepwise Regression of Physiological Measures on SSQ Oculomotor Subscale Score. Criterion to enter = 0.2.

Measure	***β***	***t***	***Std. Error***	***p***
MSSQA	.517	3.802	.109	.002
Blinks	.518	3.689	1.438	.002
Pulse Amplitude	-.304	-2.209	3.280	.042
Breaths	-.277	-2.029	5.007	.062

2.3.2.4 *SSQ Disorientation Subscale Score*

Bradygastric power ratio and breathing rate showed adequate predictive power for inclusion in the regression. Increases in sickness symptoms were estimated from changes in slow wave stomach activity and breathing; these variables explained 34.9% (adjusted $R^2 = .268$) of the variance, $F(2,18) = 4.288$, $\sigma_{est} = 35.40$, $p = .032$. (see Table 2.6).

Table 2.6
Stepwise Regression of Physiological Measures on SSQ Disorientation Subscale Score. Criterion to enter = 0.2.

Measure	***β***	***t***	***Std. Error***	***p***
Bradygastric Power (%)	-.553	-2.704	21.91	.016
Breaths	-.315	-1.540	18.13	.143

Summary results for the three regression models are shown in Table 2.7.

Table 2.7
Summary of variables and performance for regression models used in estimation of SSQ scores. Criterion to enter = 0.2, N = 19.

SSQ Score Predicted	Contributing Variables	β Direction	R^2	*Adjusted* R^2
Cybersickness	% Bradygastric activity Breaths	- -	.374	.296
Nausea	% Bradygastric activity Breaths	- -	.201	.101
Oculomotor	MSSQA Blinks Pulse Breaths	+ + - -	.747	.674
Disorientation	% Bradygastric activity Breaths	- -	.349	.268

2.3.3 Linear discriminant analysis (LDA) for subject condition classification

We used LDA to determine whether one can distinguish between display monitor viewing and HMD viewing using differences in recorded physiological measures. The variables used included only physiological measures (EGG, GSR, EOG, PPG, ECG, and breathing rate) from the middle epoch (4-6 min); verbal motion sickness rating data were not included.

Cross validation was performed by randomly selecting nine of eighteen total subjects to provide data for training and using data from the remaining nine for testing. Each subject's data was grouped according to condition: monitor or HMD. The model attempted to classify which condition the test set data belonged to. To examine test-retest reliability of the model, we ran this data selection and classification process 1000 times. We found that the model was able to classify 77.8% ($\sigma = 9.290$) of subject data samples correctly. These results show that the data from the display monitor and HMD viewing conditions differ in a manner reliable enough to allow use of data from one group of subjects to classify data from a different group.

2.4 Discussion

The primary aim of this study was to determine whether physiological changes caused by HMD use can be used to predict cybersickness. It is known that HMD-based navigation of a VE while remaining seated in the real world can cause cybersickness (Kim et al., 2005). This is because the visual information displayed by the HMD conveys movement which conflicts with the vestibular signals experienced by the seated user (Akiduki et al., 2003; Nishiike et al., 2013; Oman, 1990; Reason, 1978; Reason & Brand, 1975). We recorded physiological signals while subjects navigated a VE using either a display monitor or an HMD. Independent variables included display type (display monitor or HMD) and time of measurement (epoch). Our dependent variables were physiological measures, verbal sickness reports, and questionnaire scores.

We found that HMD use is associated with more tachygastric stomach activity and with less bradygastric stomach activity. Cheung and Vaitkus (Cheung & Vaitkus, 1998) found that changes in stomach activity may reflect a reaction by the autonomic nervous system to an uncomfortable environment. Increased fast-wave stomach contraction activity during optokinetic drum exposure has been reported previously by Hu and colleagues (Hu et al., 1991) and during VE immersion by Kim and colleagues (Kim et al., 2005). We found also that changes in bradygastric stomach activity are negatively related to cybersickness scores on the SSQ. An opposite result for bradygastric activity was found by Lien and colleagues (Lien et al., 2003), who studied motion sickness caused by circular vection. Cheng and Vaitkus (Cheung & Vaitkus, 1998) did not find this correlation due to within-subject variability of stomach activity.

Subjects blinked more when they wore the HMD; the number of blinks increased with immersion time. This effect was first reported by Kim and colleagues (Kim et al., 2005), who

suggested that increased blinking found during VE immersion is correlated with negative mood states as well as with fatigue. Our results support this suggestion; the blinking behavior found in our study estimates ratings on the SSQ oculomotor discomfort subscale which has questions concerning fatigue. The display monitor version of the task also evoked less blinking activity than the HMD condition. Ponder (Ponder & Kennedy, 1927) reported that less blinking activity may be due to decreased eye strain or tension; this suggests that in our experiment the monitor viewing condition was more comfortable than the HMD condition.

Although the previous studies by Kim and colleagues (Kim et al., 2005) and Hu and colleagues (Hu et al., 1991) reported that skin conductance increased during navigation in VEs and similar tasks, we believe that the skin conductance increase found in this study may be due largely to increased arousal caused by interaction with the VE rather than to cybersickness. GSR increases substantially in both display monitor and HMD viewing conditions (see Fig. 7). Increased skin conductivity due to increased arousal is well documented (Darrow, 1936; Montagu & Coles, 1966). Golding reported that measuring GSR from the forehead may provide a better estimate of changes due to motion sickness, especially when subjects are sweaty (Golding, 1992). Unfortunately our equipment allowed only for measurement of fingertip GSR.

The increased heart rate and decreased time between heart beats during HMD use suggests that the sympathetic activity of the autonomic nervous system increases in response to an uncomfortable environment (K. Money, Lackner, & Cheung, 1996). This effect is in agreement with many similar studies which have used virtual reality technology (Chelen, Kabrisky, & Rogers, 1993; Hu et al., 1991; Kim et al., 2005; Ohyama et al., 2007), although the viability of heart rate changes in cybersickness prediction remains unclear.

Increases in breathing rate were found in both conditions. These are indicated by increases in the number of breaths taken per epoch and are thus likely due to increased arousal. An earlier study by Wang and Perry (Wang & Perry, 2006) showed that video game interaction using a display monitor can elicit increased breathing due to arousal. Denise and colleagues (Denise et al., 2009) found that controlled breathing during an oscillating motion sickness task can attenuate the development of motion sickness. Our regression analysis shows that there is a negative interaction between breathing rate and cybersickness symptom severity (β = -.541, see Table 3). This interaction suggests that individuals who tend to reduce their rate of breathing during HMD use may not feel as ill. Learning how to control one's breathing may prove to be a good way to reduce the onset of cybersickness. It is important to note that breathing rate alone is not highly correlated with SSQ scores. In fact, variability in individual subject scores combined with other physiological measures allows for good estimation of SSQ scores.

Although head orientation variables yaw and pitch varied more during VE interaction than during rest, these measures did not provide significant predictive power. Because our VE encouraged users to look around actively, this increased variability is not surprising and demonstrates that users were immersed in the VE.

Many subjects also reported an increase in their upper body temperature and that they felt clammy during the HMD viewing condition. Holmes and colleagues (Holmes et al., 2002) found that changes in facial skin pallor were associated with motion sickness, and work by Kim (Kim et al., 2005) and Bertin and colleagues (Bertin et al., 2005) found related sickness effects coupled with decreases in skin temperature. Yet in these studies skin temperature was measured only on the fingertips and not the upper body. In our experiment, it may be the case that there was uncontrolled variability in room temperature. Finally, we found no effect of viewing condition

on plethysmogram measures. One reason may be due to the assumption that subject arterial pressure was constant throughout the experiment. Online measurement of arterial pressure may provide a better estimate of cutaneous vascular tone, although others studies have reported PPG changes during virtual immersion without the use of arterial pressure (Jäger et al., 2014; Kim et al., 2005).

The experimental design in the present study lets us distinguish physiological changes associated with cybersickness from physiological changes due to arousal. A strength of this design is that we can compare physiological changes and cybersickness ratings in monitor and HMD viewing conditions for the same VE. Motion sickness ratings during the display monitor viewing condition show that there is no motion sickness for 19 of the 20 subjects (see Fig 2). While it is certainly the case that playing a first person shooter on a flat display can cause motion sickness, as shown by Bos and de Vries (Jelte E Bos, de Vries, van Emmerik, & Groen, 2010), we feel it likely that the lack of cybersickness among our subjects while viewing the monitor is due to the relatively small display size (60° x 40°) and prior gaming experience of our subjects (see Section 2.7). In contrast, the average motion sickness score among our subjects in the HMD condition was a 3 (some nausea, see Fig 2). There is a large difference in the cybersickness generated by the two viewing conditions. We thus have an ideal testbed to determine which physiological measures can be used to estimate cybersickness severity.

A weakness in the design of the present study is that the HMD viewing condition always followed the display monitor viewing condition. This opens up the possibility that measured differences are due to condition order effects. The time between display monitor and HMD viewing conditions was only nine minutes. Barrett (Barrett, 2004) reported that it may take several days for severe motion sickness symptoms to diminish. Yet no severe motion sickness

was experienced in the display monitor viewing condition. Ji and colleagues (Ji, So, & Cheung, 2009) had subjects who reported symptoms as moderate or higher on the SSQ rest for 15 minutes. Golding and colleagues (Golding et al., 2009) found that most subjects recovered from motion sickness after a period of five minutes in an optokinetic stimulation experiment. The three subjects in the present experiment who reported some symptoms but no nausea (rating 2) or mild nausea (3) during the display monitor viewing condition all reported no symptoms (rating 1) during the rest period at the end of the display monitor viewing condition and during the rest period that began the HMD viewing condition. The nine minute period between conditions was likely long enough for the three subjects to recover fully before the onset of HMD use. Nevertheless, we performed the regression analyses and LDA on the data from the 19 subjects who reported no nausea at any time during the display monitor condition; no noteworthy impact on model performance or significance values was found.

We feel that any order effects in the present experiment pale in significance when compared to the large difference in cybersickness experienced in these two conditions. Cybersickness severity ratings in our experiment show that the display monitor viewing condition did not produce any cybersickness whatsoever, with the exception of a single subject, while the HMD condition produced cybersickness in all subjects. Eleven of the 20 subjects dropped out during the HMD viewing condition because they felt too sick to continue. No subjects dropped out during the display monitor viewing condition.

We do not know which aspects of HMD use elicit cybersickness. The cybersickness found in the HMD condition may be due to vection from a larger field of view, to lack of head movement during visually-perceived virtual movements, or to some combination of the preceding (LaViola, 2000). Results confirm our expectation that navigating a VE while using an

HMD induces substantially greater cybersickness than does navigation while using a display monitor. Verbal reports of cybersickness severity increase with prolonged HMD use but not during prolonged viewing of the display monitor. Indeed, half of our subjects dropped out as the HMD viewing condition progressed. Inclusion of both of these viewing conditions is critical because a study by Drummond found that, in some individuals, watching a wide screen display can cause simulator sickness (Drummond, 2005). Yet the present results show that display monitor use does not induce simulator sickness, so that we can compare measures during display monitor and HMD viewing conditions to distinguish effects due to arousal from those associated more directly with cybersickness.

2.5 Conclusion

In summary, the results suggest that changes in physiological measures during use of an HMD to navigate a VE can be used to estimate cybersickness severity. Discriminant analysis show that physiological data from display monitor and HMD conditions can be distinguished when using data from half of the subjects to classify data from the other half, so confirming that these changes in physiology are related to HMD use. Changes in stomach activity, blinking behavior, and breathing suggest that the mismatch between signals from the real and virtual worlds activate the autonomic nervous system as a response to an uncomfortable situation. It is likely that individual differences in physiological measures and cybersickness scores may account for lower variance explained by the regression models. This is an important factor to consider for further research investigating detection of the onset of cybersickness. The time course of EGG presents a problem for use with online estimation of cybersickness, suggesting the use of alternative, faster measures such as EEG. EEG has been used successfully for cybersickness estimation in prior studies (Chen et al., 2010; Kim et al., 2005; Ko, Wei, Jung, & Lin, 2011; Chin Teng Lin,

Tsai, & Ko, 2013; Park et al., 2008; Wei et al., 2011), but results have been mixed. A combination of neurophysiological and non-physiological measures may be necessary to best estimate the development of cybersickness during VE immersion.

3 Cybersickness without the wobble: experimental results speak against postural instability

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3.1 Introduction

Dichgans and colleagues (1972) found that the perceived direction of gravity depends on the motion occurring in the observer's visual field. For rotations about the line of sight, they found that the perceived vertical direction tilts in the direction of visual stimulus rotation and that this tilt increases with rotation speed. Earlier work found that seated individuals who viewed a tilted room felt an illusory self-tilt about body roll or pitch axes (Asch & Witkin, 1992; Kleint, 1936; Witkin & Asch, 1948). Howard and Childerson (1994) found that exposure of seated subjects to a rotating furnished tunnel produced the sensation of tumbling, and Allison and colleagues (1999) found that this sensation increased with field of view and tunnel rotation velocity.

In many individuals, this kind of vection is associated with visually induced motion sickness (VIMS). Vection is an illusory phenomenon which occurs when self-motion is felt by a stationary observer. The classic example of vection is the feeling of moving backwards in a stopped train while train cars alongside you pull forward, creating the illusion of self-motion in the backwards direction (Helmholtz, 1896). This perception occurs when the visual and vestibular systems receive information that are in conflict (Hu et al., 1991).

Postural instability theory is centered on the idea that maintaining stability of the body is critical and that prolonged instability may lead to VIMS (Riccio and Stoffregen 1991). For example, if a stationary subject views a rotating tunnel, then vection from the perceived motion of the rotating tunnel is uncorrelated with the motions necessary to maintain balance. Stoffregen and Smart (1998) claim that postural instability is a prerequisite for VIMS to occur. Although many studies support this claim (Apthorp & Palmisano, 2014; Flanagan, May, & Dobie, 2004; Reed-Jones, Vallis, Reed-Jones, & Trick, 2008; Smart, Stoffregen, & Bardy, 2002; TA Stoffregen & Hettinger, 2000; Villard & Flanagan, 2008), others have found that the relationship between postural stability and VIMS is less clear (Akizuki et al., 2005; Guerraz & Bronstein, 2008; Häkkinen, Vuori, Puhakka, Postural, & Participants, 2002; Y. Wang, Kenyon, & Keshner, 2010).

The relationship between vection and VIMS has been debated in the literature. While previous studies have found evidence that the strength of reported vection is positively correlated with the severity of VIMS (Bonato, Bubka, & Palmisano, 2008; Bubka & Bonato, 2006; Classen, Bewernitz, & Shechtman, 2011; Diels & Howarth, 2011; Flanagan et al., 2004; Golding et al., 2009; Hettinger, Berbaum, Kennedy, Dunlap, & Nolan, 1990; Keshavarz, Hettinger, Kennedy, & Campos, 2014; Lee, Yoo, & Jones, 1997; Smart et al., 2002; TA Stoffregen & Smart, 1998), others have found only weak or no correlation between vection magnitude and VIMS severity (Golding, Doolan, Acharya, Tribak, & Gresty, 2012; Keshavarz & Hettinger, 2014; Lawson, 2001). For example, Fushiki (2009) exposed subjects to upward or downward moving random dot patterns and measured vection onset times and postural stability before, during, and after stimulus exposure. Postural sway was increased only after participants reported vection and became stronger after stimulus presentation than before.

The current experiment used a head-mounted display (HMD) to immerse subjects in a rotating VE to induce vection. Subjects' perception of vertical was recorded alongside measures of postural sway. Based on results by Dichgans and colleagues (1972), we hypothesized that the perceived vertical would be offset in the direction of VE rotation and that the magnitude of this offset would increase with rotation speed. We also hypothesized that our subjects would feel cybersickness, a type of VIMS felt during VE immersion, due to the sensory mismatch caused by stationary viewing of a virtual rotating stimulus and possibly by postural instability. We collected self-reports of cybersickness during VE immersion and simultaneously recorded changes in subjects' posture using a Wii balance board (Clark et al., 2010). A seated condition was used to test whether or not cybersickness would occur while subjects had postural stability. Results show that our virtual stimulus produced data similar to that of Dichgans' physical monocular stimulus (Dichgans et al., 1972) and also produced cybersickness. Furthermore, perceived vertical settings did not differ significantly between seated and standing HMD use. Finally, changes in postural sway were associated with cybersickness in only a minority of subjects. These results demonstrate a weak link between postural instability and cybersickness.

3.2 Methods

Subjects wore an HMD and viewed a virtual tunnel that rotated clockwise or counter-clockwise about the line of sight at six different speeds from trial to trial. Subjects rotated a virtual arrow to indicate their perceived vertical and rated their level of cybersickness. In the first condition subjects sat comfortably in a chair. The second condition was administered on a second day; the same subjects stood on a Wii balance board so that changes in their postural sway could be measured while they were immersed in the VE.

3.2.1 Virtual environment and equipment

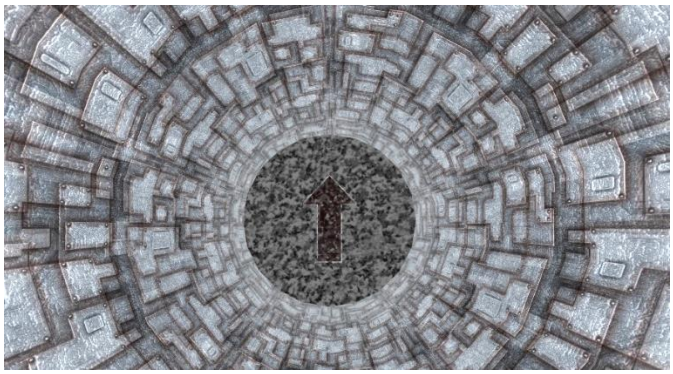

Fig 3.1. Screenshot of the VE used in seated and standing conditions. The tunnel rotated about a central disk upon which an arrow appeared intermittently for use in perceived vertical settings. The disk's texture was used to minimize the screen door effect reported by HMD users in a pilot study. Subjects used the analog stick on an Xbox controller to point the black arrow along the direction of their perceived vertical.

The VE was developed in the Unity 5 game engine and was deployed on a desktop PC. The VE included a cylindrical tunnel that rotated about the line of sight (see Fig 3.1). Subjects viewed the VE through an Oculus Rift (Oculus VR, Development Kit 2), which has a resolution of 960 x 1080 pixels per eye with a refresh rate of 75Hz. The field of view was 100 x 100 degrees of visual angle. Internal tracking of head rotations and translational movements occurred at 1KHz. Changes in posture were recorded with a Nintendo Wii balance board. Data from the Wii balance board and HMD were sampled at a rate of 100 Hz and sent wirelessly to a separate recording computer.

The central disk's texture was chosen to minimize the screen door effect that is sometimes visible in the HMD and which may provide orientation artifacts. The screen door effect occurs when an HMD wearer is able to shift their focus from the VE to the grid of pixels forming the actual display. Minimization of the screen door effect was important because a user

who attends to the HMD's pixel array may be biased by the array orientation when making their perceived vertical settings.

3.2.2 Procedure

Subjects were first instructed how to use an Xbox controller in the experiment. Subjects sat comfortably in a chair in the seated condition. For the standing condition, subjects were instructed to place their feet on marked locations on a Wii balance board. The HMD was then placed over the subject's eyes and was adjusted until the image looked clear.

Before each block of trials, the subject was asked to fixate on the central disk and to remain still for 30 seconds. These data were used to measure the subjects' natural head position and, if standing, the distribution of weight across the feet. After the subject pressed a button on the controller, the walls of the virtual tunnel began to rotate clockwise or counter-clockwise at one of six fixed speeds for 15 seconds. The six speeds were 6, 17, 28, 38, 49, and 60 deg/sec. After fifteen seconds, a black arrow appeared at a random orientation on the central disk. The subject then had an additional 15 seconds to rotate the arrow to point up along their perceived vertical and to press a button. Subjects were allowed to change freely their perceived vertical selection within these 15 seconds, although few took advantage of this. After the trial ended, the screen turned to gray and subjects were given a text prompt to select how they felt on a sickness scale: 1 no symptoms; 2 mild symptoms, but no nausea; 3 mild nausea, and 4 moderate nausea (Bagshaw & Stott, 1985). Subjects completed 8 blocks of 6 trials each for the seated and standing conditions. Subjects viewed every possible speed-direction combination four times for both seated and standing conditions. To ensure ease of response entry, when a subject pressed the response selection button, the color of the arrow changed to blue for confirmation and to red if the subject had not yet responded and only five seconds remained in the trial. Time to respond

was also measured for each trial to assess whether or not user decision time was affected by stimulus rotation speed or direction.

Subjects were told that if at any time they felt too sick to continue the experiment, they were to inform the experimenter who would help them exit the VE immediately. Subjects who terminated the experiment early for this reason were asked to rest before leaving the laboratory. A single subject dropped out of the experiment because of cybersickness. This person felt too ill to continue after completing half of the trials in the standing condition. This person's data were not used. Subjects were recruited to come in on two separate days to run the seated and standing conditions of the experiment. This was done to ensure that any motion sickness that might have occurred during one experiment condition would be gone by the time of the second experiment.

3.2.3 Questionnaires

Subjects began the experiment by completing the Motion Sickness Susceptibility Questionnaire (MSSQ) (Golding, 2006). The MSSQ assesses how susceptible a person is to motion sickness based on their past experience. It asks how often the subject felt nausea during different activities and is scored using a five point scale: 0 never, 1 rarely, 2 sometimes, 3 frequently, and 4 always. The amount of time spent traveling in different types of vehicles is tallied and used for calculating the final susceptibility score (for more detail see Golding 2006).

Subjects filled out the Simulator Sickness Questionnaire (R. S. Kennedy et al., 1993) after completing the experiment. The questionnaire contains a list of 16 symptoms that subjects rate on a 4 point scale: 0 absent, 1 slight, 2 moderate, and 3 severe. These ratings are tallied to create scores for three sickness subscales: Nausea, Oculomotor, and Disorientation. A total cybersickness score is then computed from these three subscales.

3.2.4 Analysis

3.2.5 Behavioral data

Perceived vertical settings, cybersickness ratings, and times to respond were grouped according to VE rotation speed and direction in seated and standing conditions for all subjects.

3.2.6 Wii and HMD data

The Wii balance board uses four sensors to record the user's weight. All postural sway measurements are reported as changes in weight distribution across these sensors. Data from the backward two sensors were summed and then subtracted from the sum of the forward two sensors' data to create a single Forward-Backward (FB) time series. Data from the left two sensors were summed and then subtracted from the sum of the right two sensors' data to create a single Right-Left (RL) time series. The means of the FB and RL time series from the resting period before each block were subtracted from all subsequent trials in that block to take into account the baseline posture.

Standard deviations in body posture and head position time series in the FB and RL directions were computed over the 30 sec baseline and trial periods. These were used to assess postural sway (Koslucher et al., 2012). We used *t*-tests for groups with unequal numbers of observations to assess differences in sway between stimulus trial and baseline periods.

Cross correlations were computed between the HMD position and balance board signals in the FB and RL directions on each trial for every subject (N = 13). These were computed to ensure that variations in body postural sway included movements of the head. The cross correlations used lags every 0.01 sec in the range -30 to 30 sec. We computed a 95% confidence interval at each of these lags by calculating the cross correlation between the HMD signal from one trial and the postural signal from an unmatched trial. This process was repeated individually for every

subject to create a 1000 sample confidence distribution at each lag on every trial (Horton, D'Zmura, & Srinivasan, 2013).

We wanted to see if postural and head position information at trial onset could be used to determine the direction of the stimulus rotation within individual subjects. First, we grouped all trials for the two fastest stimulus rotation speeds (49 and 60 deg/sec) according to rotation direction: CW or CCW. Second, we summed samples from the first second of data from each trial to get a direction index. FB data from trials that summed to a positive value show a shift in the forward direction, while FB data from trials that summed to a negative value show a shift in the backwards direction. We computed similar sums for RL data. Finally, we performed a two-tailed *t*-test between these two bins for CW and CCW trials for each subject.

We wanted to determine whether postural sway and head movement are associated with cybersickness. Subject data were first divided into two groups. Those subjects with an SSQ cybersickness score greater than the median score were placed into the "less comfortable" group, while the remaining subjects were placed into the "more comfortable" group. Second, we grouped all trials for the two fastest stimulus rotation speeds (49 and 60 deg/sec) according to rotation direction: CW or CCW. We selected these trials because the motion sickness ratings at these two speeds were correlated with end-of-experiment SSQ cybersickness scores. Finally, we performed a two-tailed *t*-test to assess any difference between the FB variability in trials for the less comfortable subjects and variability in trials for the more comfortable subjects. Variability for each trial was defined as the standard deviation in FB postural sway (e.g., Koslucher et al. 2012).

3.2.7 Participants

Fifteen subjects (4 F, 11 M) over the age of 18 participated in the study. Informed consent was obtained prior to the experiment in accordance with protocol HS# 2014-1090, approved by the Institutional Review Board at UC Irvine. All participants indicated that they had previous experience playing video games on a wide screen display. None of the participants reported any vestibular or neurological dysfunction.

3.3 Results

3.3.1 Questionnaires

The MSSQ assesses how susceptible a person is to motion sickness based on their past experiences as a child and over the past ten years. The subject-averaged MSSQ total score was 22.9 (sd = 20.07), which indicates that our subjects are amongst the 30^{th} percentile, which is a lower-than-average susceptibility (Golding, 1998).

The SSQ was used to assess cybersickness symptoms immediately at the ends of both seated and standing conditions. It provides nausea, oculomotor discomfort, disorientation, and total sickness scores. For the seated condition, the subject-averaged SSQ score for nausea was 15.9 (sd = 17.7), for oculomotor discomfort was 19.20 (sd = 18.31), for disorientation was 24.13 (sd = 27.01), and for cybersickness was 22.19 (sd = 20.46). For the standing condition, the subject-averaged SSQ score for nausea was 34.34 (sd = 39.79), for oculomotor discomfort was 17.18 (sd = 19.53), for disorientation was 22.27 (sd = 37.13), and for cybersickness was 27.93 (sd = 33.27). A paired samples *t*-test determined that SSQ scores did not differ significantly between the seated and standing conditions. Significant correlations were found in the seated condition between the MSSQ total score for susceptibility and SSQ subscale scores for nausea, *r*

= .522, p = .046, oculomotor discomfort, r = .657, p = .008, disorientation, r = .572, p = .026, and cybersickness, r = .665, p = .007.

We used the variability in subjects' SSQ cybersickness scores to create two post-hoc subject groups: more comfortable and less comfortable (see Section 3.2). The seven subjects whose score was less than the median SSQ cybersickness score of 18.7 were placed into the "more comfortable" group and the remaining subjects were placed into the "less comfortable" group.

3.3.2 Behavioral measures

We ran three 2x6x2 mixed-design ANOVAs to compare the effects of VE rotation in two directions and at six angular velocities on subject estimates of perceived vertical, on cybersickness ratings, and on times to respond.

3.3.2.1 *Perceived vertical settings*

There was a significant main effect of direction on perceived vertical settings, $F(1, 13) = 50.439$, $p < .000$, and a near significant main effect of speed, $F(5, 65) = 2.296$, $p = .055$ (see Fig 3.2). There was a three-way interaction between condition, direction, and speed, $F(5,65) = 2.571$, $p = .035$. Follow-up comparisons found that this effect was driven by the difference between rotation speeds 17 and 60 deg/sec. These results show that the perceived vertical offset directions match the direction of stimulus rotation in the seated and standing conditions, which agrees with the original result of Dichgans and colleagues (1972). Yet the perceived vertical offsets did not increase as stimulus rotation speed was increased, a discrepancy discussed in Section 5.

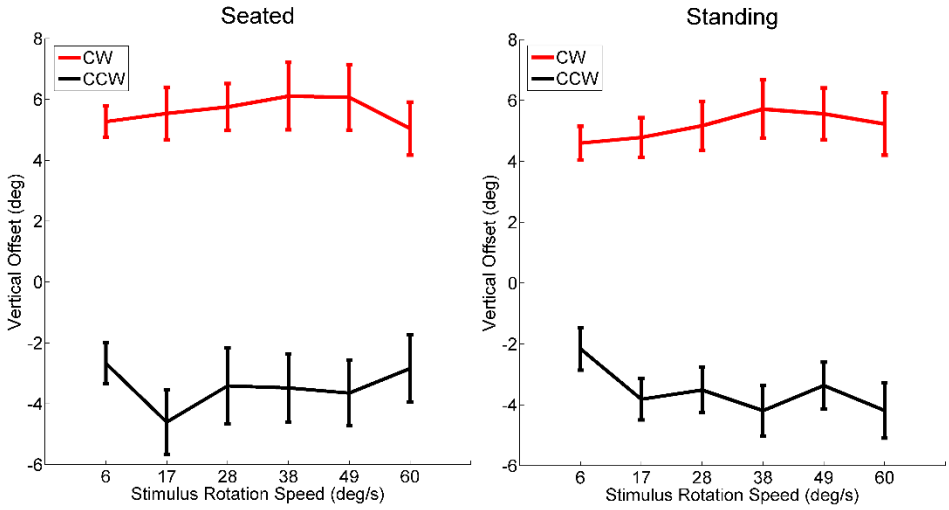

Fig 3.2. Plot of perceived vertical settings for the different stimulus rotation speeds during the seated (left panel) and standing (right panel) conditions. Subject- and trial-averaged data from clockwise (CW) trials are shown in red and from counterclockwise (CCW) trials are shown in black. Subjects' perceived vertical settings followed the stimulus rotation direction, but did not increase with speed. Error bars show one standard error of the mean.

3.3.2.2 *Cybersickness ratings*

There was a significant main effect of tunnel rotation speed on cybersickness ratings, $F(1.346,17.494) = 5.051$, $p = .029$ (see Fig 3.3). One might expect postural instability to be greater for standing than for seated subjects and, according to postural instability theory, for cybersickness ratings to increase more for standing than for seated subjects. The results do not support this expectation. We correlated the SSQ results for seated and standing conditions with the cybersickness ratings for those conditions at each stimulus rotation speed. We found that SSQ cybersickness scores are positively correlated with cybersickness ratings during the standing condition for the two fastest CW rotations (49 deg/sec CW, $r = .674$, $p = .008$, for 60 deg/sec CW, $r = .828$, $p = .000$) and for the two fastest CCW rotations (49 deg/sec CCW, $r = .598$, $p = .024$, and 60 deg/sec CCW, $r = .738$, $p = .003$). The increase in cybersickness with rotation speed shown here in Fig 3 is not accompanied by change in perceived vertical settings

(see Fig 2). This shows that perceived vertical settings and cybersickness ratings are not correlated in this experiment.

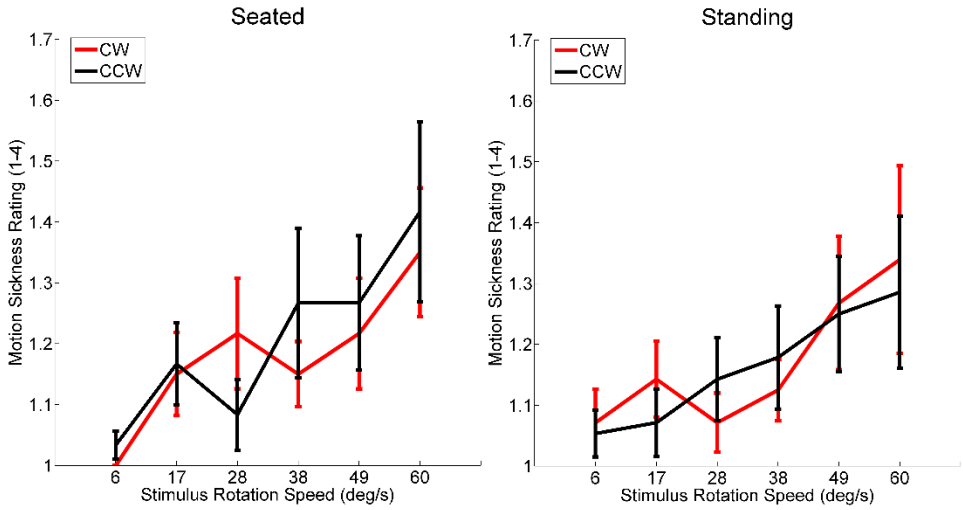

Fig 3.3. Plot of motion sickness ratings for the different stimulus rotation speeds during the seated (left panel) and standing (right panel) conditions. Subject- and trial-averaged data from clockwise (CW) trials are shown in red and from counterclockwise (CCW) trials are shown in black. Motion sickness ratings increase with speed similarly for both the seated and standing conditions. Error bars show one standard error of the mean.

3.3.2.3 *Times to respond*

Subjects viewed the rotating stimulus on each trial for 15 seconds before the arrow appeared, at which time they could make their perceived vertical setting. Times to respond show that subjects made the setting after the arrow was visible for five seconds on average. However, the time that subjects took to respond did not differ significantly for stimulus speed, direction, or experimental condition.

3.3.3 Postural data analyses

We analyzed changes in posture to test whether postural instability theory is consistent with results. HMD data from one subject and HMD and posture data from another subject were unavailable due to signal loss in the recording.

3.3.3.1 *Body and head variation in baseline and trial periods*

We used standard deviations of FB and RL samples to measure postural sway (see Fig 3.4). Standard deviations were computed for each subject for each trial (four left bars in each panel) and for each subject's baseline period (four right bars in each panel). Postural sway magnitude differed across subjects. Some subjects showed very small changes in head and body positions (e.g., S14), and others showed substantially larger changes (e.g., S1). For each subject, 48 standard deviations were found for the trial periods: one standard deviation per trial. For each subject, 8 standard deviations were found for the baseline periods: one standard deviation per baseline. These multiple measurements let us compute standard errors of the mean (displayed as error bars in Fig 4) and to assess differences in postural sway between virtual environment rotation and resting baseline periods using *t*-tests for unequal number of observations. Postural sway was significantly greater during stimulus rotation in the FB direction for S3, $t(54) = 2.30$, $p < .05$, and in the RL direction for S1, $t(54) = 1.78$, $p < .05$. For data averaged across fourteen subjects, we found no statistically significant differences in head or body sway in either direction between stimulus rotation and baseline periods.

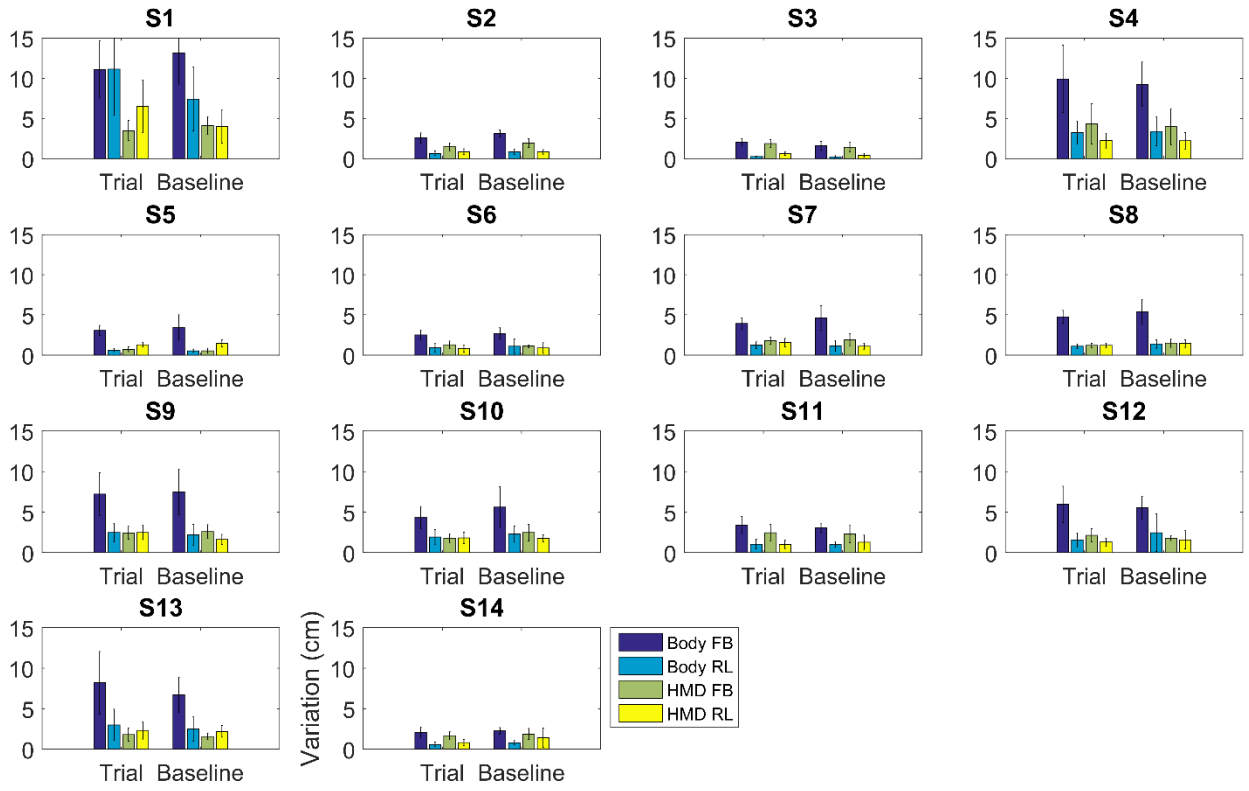

Fig 3.4. Comparison of pre-trial baseline and within-trial variation in body posture (FB, dark blue; RL light blue) and head position (FB, green; RL yellow) for 14 subjects. Variation for head position is in units of cm and variation for body posture is in units of kg. Variation during stimulus exposure was similar to variation during the baseline periods. Data show that some individuals had greater overall variation in their body posture and head position. Error bars show the standard error of the mean for 48 trials and for 8 baseline periods.

3.3.3.2 *Head and body movement correlation*

Cross correlations were computed between HMD position data and Wii board posture data for all trials for each subject to examine the relationship between head position and postural sway (see Fig 5). The subject-average peak correlation in the FB direction was 0.745 (sd = 0.13) at a lag of 25 ms (sd = 42.74). This peak was significantly above the 95% confidence interval for 11 of the 13 subjects. The subject-average peak correlation in the RL direction was 0.704 (sd = 0.14) at a lag of 63.077 ms (sd = 178.16). This peak was significantly above the 95% confidence interval for only two of the 13 subjects. The results for the FB direction show that changes in head

position and body posture are closely coupled, with body posture changes associated with near-immediate changes in head position. This is not the case for the RL direction. RL movements of the head and body on different trials are more correlated than the average found for head and body movements on identical trials (see Fig 3.5 lower-right panel).

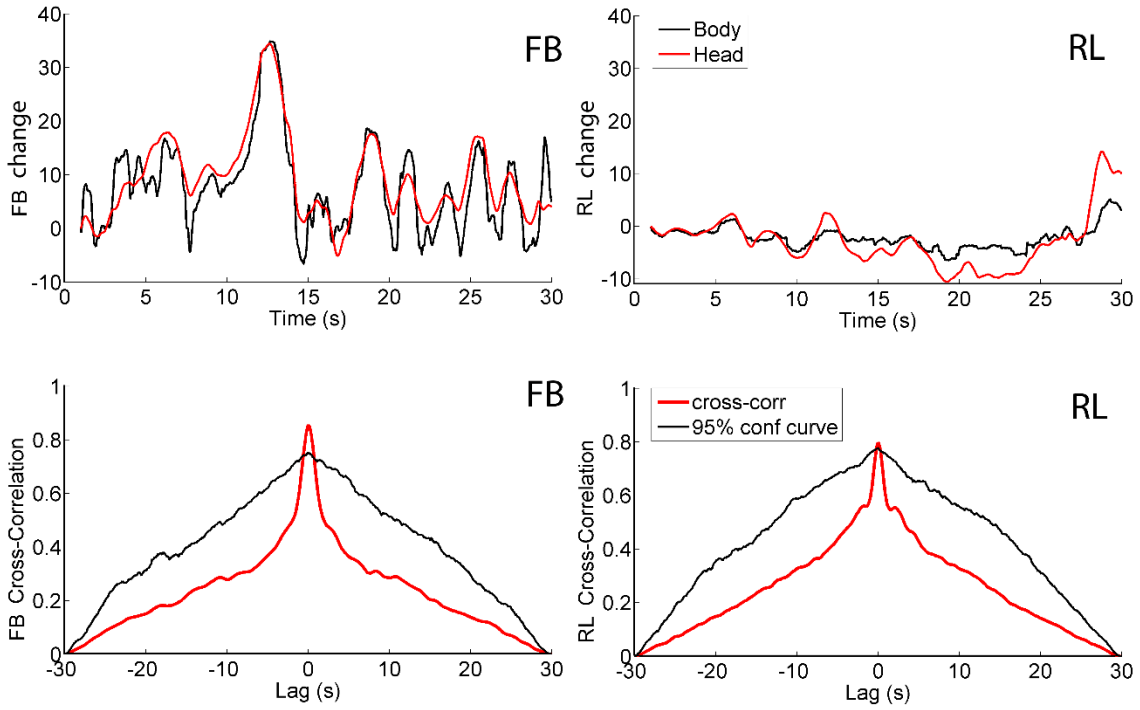

Fig 3.5. Top panels: Raw body posture (black line) and head position (Red line) data from a representative subject in the FB (top-left) and RL (top-right) directions. Change for the HMD data are in units of (scaled) cm while change for the posture data are in units of kg. HMD data in the upper plots are scaled by a factor of twenty to enhance visual comparison. Bottom panels: trial-averaged cross correlations between head and body movements in the FB (bottom-left) and RL (bottom-right) directions. The red lines in the bottom panels show the mean cross correlations over all trials. The black lines in the lower panels show the 95% confidence intervals from correlations between head and body on unmatched trials. Each cross correlation used lags separated by 0.01s from -30 to 30 sec. A clear peak in correlation is seen at lag zero sec, which demonstrates that FB movement in the body and head are closely related. Cross-correlations found for head and body data from the same trial in the RL direction did not exceed those generated when using head and body data from different trials

3.3.3.3 *Stimulus evoked postural change*

Only three subjects showed significant differences between their CW and CCW FB postural data immediately after stimulus onset. The remaining 12 did not exhibit these differences. Data from a representative subject who showed these differences are displayed in Fig 3.6. Plots of data for a representative subject who did not show these differences are shown in Fig 3.7. Identical scales are used in Figs 3.6 and 3.7 for purposes of comparison. Data from the majority of subjects resembled those shown in Figure 3.7. There was no significant shift in FB posture at stimulus onset for the majority of subjects, which suggests that postural instability is not a prerequisite of cybersickness in this experiment. No subjects showed significant differences between their CW and CCW FB head position data during the first second after stimulus onset.

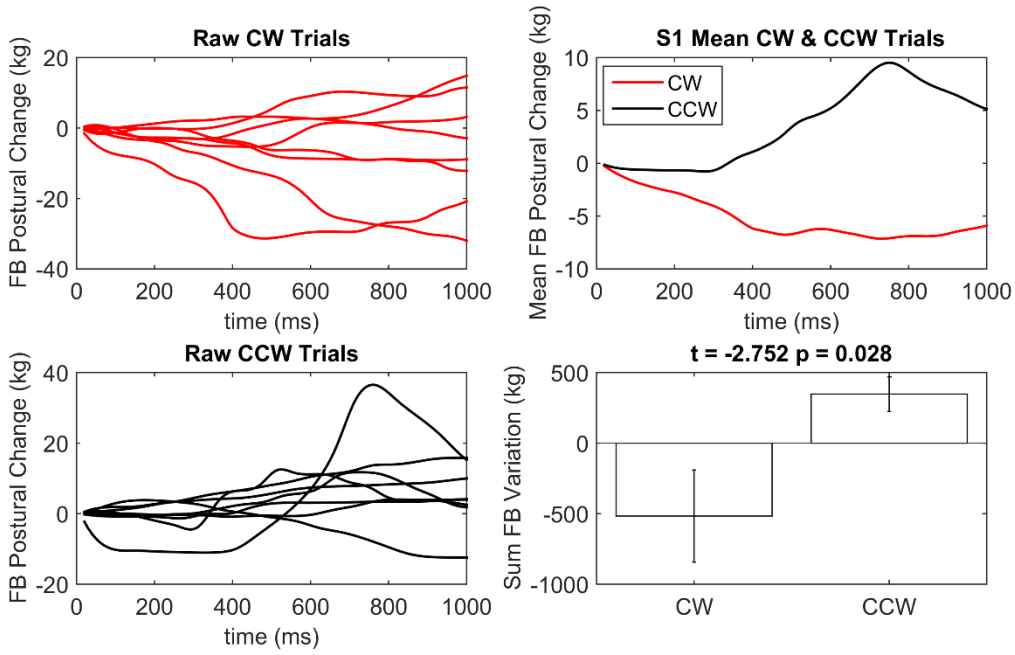

Fig 3.6. Postural change data from a subject from the minority who show a significant change in posture in response to stimulus rotation onset. The upper-left panel shows the FB postural change during viewing of CW stimuli rotating at the two fastest speeds (49 and 60 deg/sec) (red lines). The lower-left panel shows the FB postural change during viewing of CCW stimuli rotating at 49 and 60 deg/sec (black lines). The upper-right panel shows the mean FB postural changes during CW and CCW stimulus viewing. The lower-right panel shows the significant

difference between the distribution for summed CW trial FB postural change and CCW postural change.

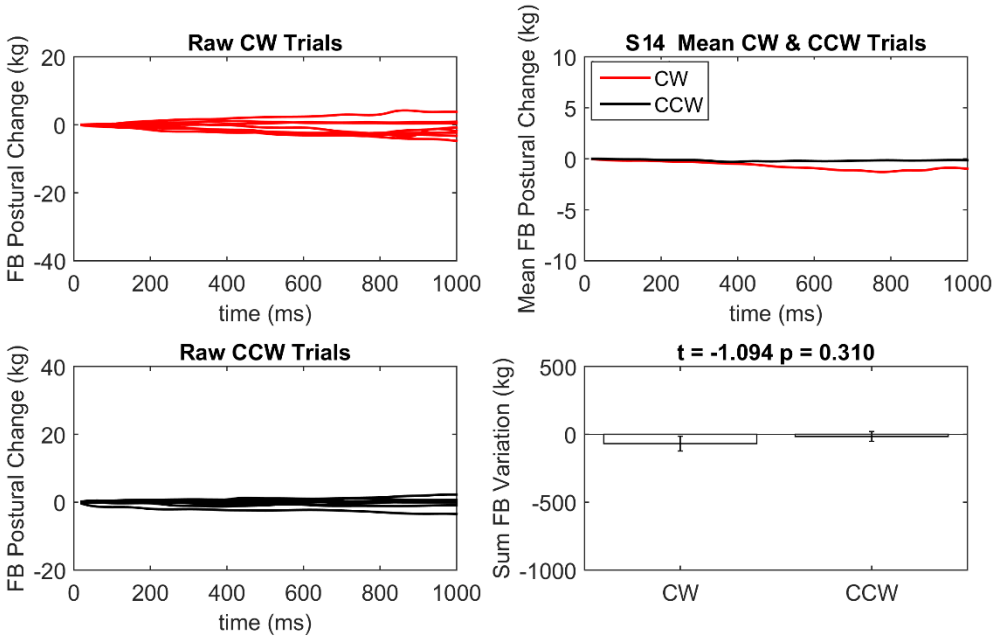

Fig 3.7. Postural change data from a subject from the majority who do not show a change in posture in response to stimulus rotation onset. The scales in these plots are identical to the scales used in the plots of Fig 3.6. The upper-left panel shows the FB postural change during viewing of CW stimuli rotating at the two fastest speeds (red lines). The lower-left panel shows the FB postural change during viewing of CCW stimuli rotating at 49 and 60 deg/sec (black lines). The upper-right panel shows the mean FB postural changes during CW and CCW stimulus viewing. The lower-right panel shows that the distribution for summed CW trial FB postural change and CCW postural change are not significantly different.

3.3.3.4 *FB and RL variation across trials*

FB postural sway was significantly lower for the less comfortable subjects than for the more comfortable subjects (see section 3.2), $t(111) = -2.3$, $p = .023$ (see Fig 3.8). This result is not what one would expect were postural instability theory correct. Neither RL postural sway nor head position differed significantly between less comfortable and more comfortable subjects.

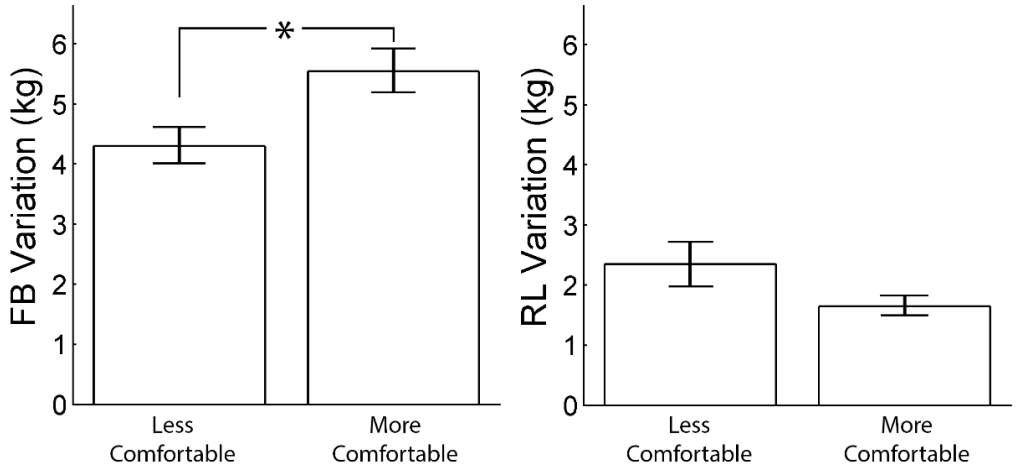

Fig 3.8. Subject-averaged postural variation over all trials at stimulus speeds of 49 and 60 deg/sec in the FB direction (left plot) and RL direction (right plot). The data show that the less comfortable subjects had significantly less (t = -2.3, p = .023) FB variation than the more comfortable subjects. There was no significant difference between subject groups for variation in the RL direction. Error bars show the standard error of the mean for 14 subjects.

3.4 Discussion

Results from this experiment show that cybersickness can occur in the absence of postural instability. We replicated the study of Dichgans and colleagues (1972) using virtual reality technology with the expectation that both cybersickness and postural sway would increase with rotation speed. We did not find this result. Instead, our results with perceived vertical settings, response times, balance board postures, and cybersickness ratings show that cybersickness increased without appreciable postural sway in the majority of subjects (see Figs 3.3, 3.7, and 3.8).

Dichgans and colleagues (1972) found that the perception of vertical is influenced by a visual environment that rotates about the line of sight. Our results follow theirs in showing that the perceived vertical direction is offset in the direction of the visual environment's rotation. Yet, we failed to replicate the strong increase in perceived vertical offset with stimulus rotation speed. Average peak offsets in the present study were about six degrees but reached 15 degrees in the

original Dichgans study. This may be due in part to the fact that they used a larger visual field: 130 vs 100 deg. The original results lead us to believe that our choice of 60 deg/sec was fast enough to elicit a maximum offset in the perceived vertical direction. The difference in results may also be due to different methods of stimulus presentation. Dichgans and colleagues (1972) had subjects view the rotating stimulus monocularly and increased its speed every 30 seconds over a six minute period. It may have been the case that rotatory motion aftereffects of earlier stimuli influenced later settings (e.g., Freud 1963). Our experiment interleaved changes in rotation direction and speed from trial to trial. We found no significant variation in the times subjects took to respond, and feel it is unlikely that aftereffects from previous trials played a substantial role in perceived vertical estimates.

Cybersickness ratings were found to increase with rotation speed. This may be caused by vection that is induced by viewing the stimulus rotation. A positive relationship between vection strength and VIMS strength is well documented in the literature (Bonato et al., 2008; Bubka & Bonato, 2006; Classen et al., 2011; Diels & Howarth, 2011; Flanagan et al., 2004; Golding et al., 2009; Hettinger et al., 1990; Keshavarz et al., 2014; Lee et al., 1997; Smart et al., 2002; TA Stoffregen & Smart, 1998). However, a weakness of our design is that we did not explicitly ask subjects to rate their level of vection. In fact, our data show that only perceived vertical direction was influenced significantly by the stimulus and perceived vertical offset magnitude was not. This suggests that the relationship between vection strength and perceived vertical differs from the relationship between vection strength and cybersickness. It may be possible for individuals to become habituated to any vection produced by the stimulus, yet still feel cybersickness. Diels and Howarth (2011) exposed subjects to a rotating cloud of dots and found that although subjects reported feeling some VIMS symptoms, vection incidence actually decreased momentarily as

sickness increased steadily. VIMS in the absence of vection was also found by Ji and colleagues (2009).

Our data show that sickness ratings increase with speed similarly during the seated and standing conditions, with some subjects reporting nausea (sickness rating 3). It may be that proprioceptive information felt from being seated in a chair or information from shifts in postural sway while standing on the balance board contributed little to estimation of perceived vertical. The visual information provided by the HMD was so compelling that it outweighed information provided by proprioception and gravity. Past work has found that visual information in many scenarios trumps conflicting information from the other senses (e.g., Slutsky and Recanzone 2001; Recanzone 2009).

Motion sickness ratings at the two fastest rotation speeds were significantly correlated with the end-of-experiment SSQ cybersickness scores. This is interesting because trials at the two fastest speeds were interleaved throughout the experiment. Those individuals who felt cybersickness during these trials likely have a lower threshold for cybersickness and ultimately reported feeling worse at the end of the experiment.

Postural stability measures did not correlate with SSQ scores for individual subjects. Cobb (1999) found that self-reported symptoms of postural instability were correlated with simulator sickness in a VE, but that post-immersion SSQ scores and post-immersion postural stability measures were not. This suggests that a user's subjective sense of discomfort may be a better measure of cybersickness than their objective postural stability. This suggestion is strengthened in the present experiment by the fact that there was little difference in the variation of body posture and head position between the data from stimulus rotation and resting baseline periods (see Fig 3.4). Our stimulus paradigm was strong enough to produce cybersickness, but

was likely too weak to elicit significant changes in postural stability. The maintenance of postural stability in the current experiment may be related to the briefer exposure times to stimulus rotation. Kennedy and colleagues (1995) suggest that exposure to VEs for less than three hours will not induce postural instability.

Separating subjects by median SSQ score showed that less comfortable subjects had less FB variation in postural sway than more comfortable subjects during trials at the two fastest rotation speeds (see Fig 3.8). Subjects with less FB sway felt worse than subjects with more. It may well be that the majority of subjects exhibited "VR lock" during which they minimized motion in an attempt to avoid cybersickness. Subjects who maintained fluid body motion reported less post-experiment cybersickness. On average, the less comfortable subjects showed greater RL variation than the more comfortable subjects, but this trend was insignificant. While we were initially surprised by greater levels of postural sway along the FB than along the RL direction (see Figs 4 and 8), earlier studies have reported similar findings (e.g., Koslucher et al. 2012).

The cross-correlation results show that movements of the head were closely related to movements of the body in the FB direction only. A minority of subjects demonstrated an initial postural shift in response to stimulus onset. For these subjects, it may have been the case that their postural reference frame shifted in alignment with the stimulus, if only briefly. Our data show that although some individuals change body posture at stimulus onset, most do not. In conclusion, the results of this experiment suggest that postural instability is neither a prerequisite nor a symptom of cybersickness.

4 Effects of unexpected visual motion on postural sway and motion sickness

4.1 Introduction

Visually-induced motion sickness (VIMS) is thought to occur when visual, vestibular, and proprioceptive information does not align with what an individual's brain anticipates given their prior experience navigating the external world (K. E. Money & Myles, 1975; Reason, 1978; Reason & Brand, 1975). It has also been suggested that postural instability is a prerequisite for motion sickness to occur (Apthorp & Palmisano, 2014; Flanagan et al., 2004; Reed-Jones et al., 2008; Riccio & Stoffregen, 1991b; Smart et al., 2002; TA Stoffregen & Hettinger, 2000; Villard & Flanagan, 2008). However, others have found that participants who navigate virtual environments while sitting become sick without any prior instability (Mark S. Dennison, Wisti, & D'Zmura, 2016; Kim et al., 2005). A recent study by Dennison and D'Zmura (2016) found that when standing participants were exposed to a virtual rotating room, the participants who showed more postural sway actually reported feeling more comfortable in the experiment than the participants who exhibited less postural sway.

According to sensory mismatch theory, the degree to which cybersickness develops depends greatly on the moment-to-moment discrepancy between what subjects expect to feel and what they actually feel. The reasoning is that the brain predicts the sensory consequences of well-practiced actions such as walking, riding a bike, or driving a car (D. Wolpert et al., 1995; D M Wolpert, Miall, & Kawato, 1998; Daniel M Wolpert & Flanagan, 2010). These predictions are part of the brain's internal model for maintaining stability. When the prediction is wrong, instability often occurs.

The brain's predictions may also reflect the expected sensory information caused by external sources. Work by Norman and colleagues (2016) used EEG to measure the brain

response to voluntary finger movements and the brain response to involuntary finger movements controlled by a robotic exoskeleton. Their work found that an event-related desynchronization (ERD) was produced both when the movement was produced voluntarily by the brain, and when the movement was expected to occur from the exoskeleton. This result suggests that internal models may also be used in the prediction of expected sensory information from motor actions caused by the outside environment.

The present study seeks to understand how self-reported motion sickness severity and postural sway change during distinct moments of substantial sensory mismatch, called visual perturbations, while individuals navigate a virtual environment (VE). The VE was viewed either with a head-mounted display (HMD) or on a desktop monitor. We recorded changes in postural sway using a Wii balance board (Clark et al., 2010) and changes in position and orientation of the HMD. The experiment had three viewing conditions: HMD viewing with perturbations (HMD-Push), monitor viewing with perturbations (Monitor-Push), and HMD viewing without perturbations (HMD-NoPush). In each of these conditions, self-reports of motion sickness severity were collected. We hypothesized that motion sickness severity would be strongest in the HMD-Push condition and weakest in the Monitor-Push condition, and that postural instability would be greatest while suffering visual perturbations while wearing an HMD. We found that although postural instability increased in the HMD-Push and Monitor-Push conditions, in which perturbations were present, significant motion sickness occurred in the HMD-Push and HMD-NoPush conditions. These results suggest that although HMD wearers are more sensitive to visually-induced perturbations, the resulting postural instability is not related directly to motion sickness severity.

4.2 Methods

4.2.1 Virtual environment and equipment

The virtual environment (VE) was a space station containing long, turning corridors and elevators leading to multiple floors. Our VE was custom made in the Unity5 game engine. Visual perturbations occurred approximately every two seconds in the HMD-Push and Monitor-Push conditions and were absent in the HMD-NoPush condition. These perturbations lasted for thirteen frames or 260 milliseconds (ms) and would push the participant's virtual body in either the forward, backward, right, or left direction. These directions were always computed relative to the direction that the participant was looking in the VE.

Fig 4.1. Screenshot of the virtual environment used in the experiment.

A screenshot of one of the corridors from the environment is shown in Fig 4.1. For both HMD conditions, participants wore an Oculus Rift (Oculus VR, Development Kit 2). This HMD has a resolution of 960 x 1080 pixels per eye with a refresh rate of 75Hz. The field of view is 100° horizontal by 100° vertical. Head orientation is sampled at a rate of 1000 Hz. For the Monitor-Push condition, participants viewed the VE on a Samsung S27A550H 27in LED display with a refresh rate of 60Hz and a resolution of 1920 x 1280 pixels. Participants stood at

approximately 57 cm away from the monitor. This provided a field of view of approximately 60° of visual angle horizontally by 40° vertically.

Postural sway measures were taken by having participants stand without shoes on a Wii Balance Board. Data from the balance board were sent wirelessly to the data collection computer. Data collection utilized Lab Streaming Layer developed at UC San Diego's Swartz Center for Computational Neuroscience (SCCN).

4.2.2 Procedure

The experiment had three viewing conditions, each of which were run in separate sessions on different days: HMD-Push, Monitor-Push, and HMD-NoPush. The randomized order in which participants completed these conditions was counter-balanced. Participants completed each condition on separate visits to ensure that any motion sickness from the prior condition had passed. On the first experiment run, participants were instructed how to control their virtual body using an Xbox controller and how to stand on the balance board. In all three conditions, participants were tasked with exploring the VE to find and destroy target canisters like the one shown in Fig 4.2. The task purpose was to ensure that participants actively explored the VE.

Fig 4.2. Participants navigated through the VE and destroyed canisters like the one pictured here.

Participants had exactly ten minutes to find all the targets. They were not allowed to return to any rooms once the doors had closed. One and a half minutes of baseline data were

collected at the beginning of the session while the participant remained still on the balance board and in the VE. Every thirty seconds thereafter, participants were asked to rate how they felt on a sickness scale: 0 no symptoms; 1 mild symptoms, but no nausea; 2 mild nausea, and 3 moderate nausea. This scale is based on work by Bagshaw and Stott (1985). A heads-up display appeared in front of the participant's view and allowed for the input of their sickness rating with the controller. Participants were told that, if at any time they felt too ill to continue, they were to inform the experimenter, who would help them exit the experiment immediately and rest before leaving the laboratory.

4.2.3 Questionnaires

Participants first completed the Motion Sickness Susceptibility Questionnaire (MSSQ) (Golding, 2006). This questionnaire assesses how susceptible a person is to motion sickness based on their experience. It asks how often the participant felt nausea during different activities and is scored using a five-point scale: 0 never, 1 rarely, 2 sometimes, 3 frequently, and 4 always. The amount of time spent traveling in different types of vehicles is totaled and used for calculating the final susceptibility score (for more information see Golding 2006).

Before and after each experiment condition, participants filled out the Simulator Sickness Questionnaire (R. S. Kennedy et al., 1993). This questionnaire contains a list of 16 symptoms that participants rate on a 4-point scale: 0 absent, 1 slight, 2 moderate, and 3 severe. These ratings are used to compute scores for three separate sickness subscales: Nausea, Oculomotor, and Disorientation. A total score is also provided.

Finally, participants completed a video game and VR experience survey. This survey asks how many hours an individual plays video games and uses VR technology each week.

4.3 Analysis

4.3.1 Behavioral data

We assessed how motion sickness changes as a function of experiment time and viewing condition. Motion sickness ratings were collected every thirty seconds resulting in twenty-one separate measures for each condition and participant. These data were then submitted to a repeated measures ANOVA with time and experiment condition as factors. Greenhouse-Geisser corrections were implemented. To further examine the relationship among motion sickness, visual expectation, and postural stability, we divided the participants into two groups. Participants with an SSQ score greater than the median score were placed into the "less comfortable" group, while the rest of participants were placed into the "more comfortable" group (see Sections 4.4.2 and 4.4.3).

4.3.2 Wii and HMD data

The Wii balance board records the user's weight using four different sensors. Postural sway is reported as changes in the distribution of weight across these sensors. Data from the two sensors at the back of the board were summed and then subtracted from the sum of the two sensors at the front of the board to create a single Forward-Backward (FB) time series measure. Data from the left two sensors were summed and then subtracted from the sum of the right two sensors' data to create a single Right-Left (RL) time series measure. This process was identical to that described by Dennison and D'Zmura (2016).

Data for each participant were segmented into twenty-one epochs of duration 30 sec. The standard deviation of body postural sway in the FB and RL directions was then determined for each epoch. These standard deviations were used to assess changes in postural sway as a function of time in the experiment (Koslucher et al., 2012). Sway data for each direction were submitted

to a repeated measures ANOVA with time and experiment condition as factors. Greenhouse-Geisser corrections were implemented.

We computed cross correlations between the balance board and HMD position signals to determine whether these describe similar movements for the body and head. These cross correlations were performed for data in the FB and RL directions for each perturbation event in the HMD-Push and Monitor-Push conditions. This process matches closely that of Dennison and D'Zmura (2016), but there are two differences: (1) we use lags every second in the range -39 to 39 sec, and (2) correlations between HMD position data on one trial and uniformly-distributed noise of equal duration were computed for control purposes. These control correlations generate a 95% confidence interval that is used to test the significance of correlations between HMD and sway data drawn from the same trial.

We wanted to determine whether postural sway is influenced by the presence of visual perturbations presented during navigation while wearing an HMD or viewing a monitor. To do this, data were segmented into 2.5 second epochs ranging from 500ms before the onset of a visual perturbation to two seconds afterwards. This process produced 296 events for each condition, or 74 perturbation epochs for each of the four directions (forward, backward, left, and right). For the HMD-NoPush condition, 296 segments of 2.5 seconds each were chosen pseudo-randomly to serve as a control. For each epoch, the average of the data from 500 ms before perturbation onset was subtracted from all data points after perturbation onset. Postural sway data were then averaged across participants for each perturbation direction and condition. For each time point in the epoch, a two-tailed *t*-test for unequal groups was performed to determine if the time course of the postural response differed between experiment conditions.

4.3.3 Participants

20 participants (5 F, 15 M) over the age of 18 participated in the study. Data from two participants in two conditions were lost due to a network malfunction. Informed consent was obtained prior to the experiment in accordance with protocol HS# 2014-1090, approved by the Institutional Review Board at UC Irvine. All participants indicated that they had previous experience playing video games on a wide screen display. None of the participants reported any vestibular or neurological dysfunction. Two participants exited the experiment early because of severe motion sickness.

4.4 Results

4.4.1 Questionnaires

The participant-averaged MSSQ total score was 53.83 (sd = 40.84), which indicates that our participants' scores lie in the 50th percentile, which is average susceptibility (Golding, 1998). The SSQ was given to determine changes in motion sickness symptoms before and after each experiment condition. The questionnaire gives nausea, oculomotor discomfort, disorientation, and total sickness scores.

Table 4.1
Mean and standard deviation for SSQ symptom and total scores provided before participants started each experiment condition.

SSQ Symptom Group	*HMD-Push*	*Monitor-Push*	*HMD-NoPush*
Nausea	4.24	0.95	1.91
Oculomotor	4.63	3.03	3.03
Disorientation	3.09	0.70	1.39
Total Score	4.78	2.06	2.62

Table 4.2
Mean and standard deviation for SSQ symptom and total scores provided after participants finished each experiment condition.

SSQ Symptom Group	*HMD-Push*	*Monitor-Push*	*HMD-NoPush*
Nausea	72.61	11.93	48.65
Oculomotor	50.95	12.13	29.56
Disorientation	77.33	7.66	34.80
Total Score	74.38	12.72	43.01

The data in Tables 4.1 and 4.2 show that the average SSQ total score increased by nearly 70 for the HMD-Push condition, 11 for the Monitor-Push condition, and 40 for the HMD-NoPush condition. We used the HMD-Push post-experiment SSQ scores to create two post-hoc groups for each condition: more comfortable and less comfortable. For each experiment condition, participants whose score was greater than the median score for that condition were placed into the "less comfortable" group and the remaining participants were placed into the "more comfortable" group.

4.4.2 Motion sickness ratings

There was a significant interaction effect between experiment condition and exposure time on motion sickness ratings, $F(40,880) = 3.785$, $p < .000$. When splitting the data up by sickness group, the interaction effect between condition and time remained for less comfortable participants, $F(40,340) = 2.012$, $p = .04$. The data in Fig 4.3 clearly show that motion sickness ratings increase the longer participants remain in the VE, with ratings in the HMD-Push and HMD-NoPush conditions being significantly greater than in the Monitor-Push condition. Less comfortable participants reported greater motion sickness ratings over time than more comfortable participants in the HMD-Push condition, $F(20,300) = 4.851$, $p = .001$, the Monitor-Push condition, $F(20,360) = 7.662$, $p < .000$, and the HMD-NoPush condition, $F(20,360) = 10.835$, $p < .000$.

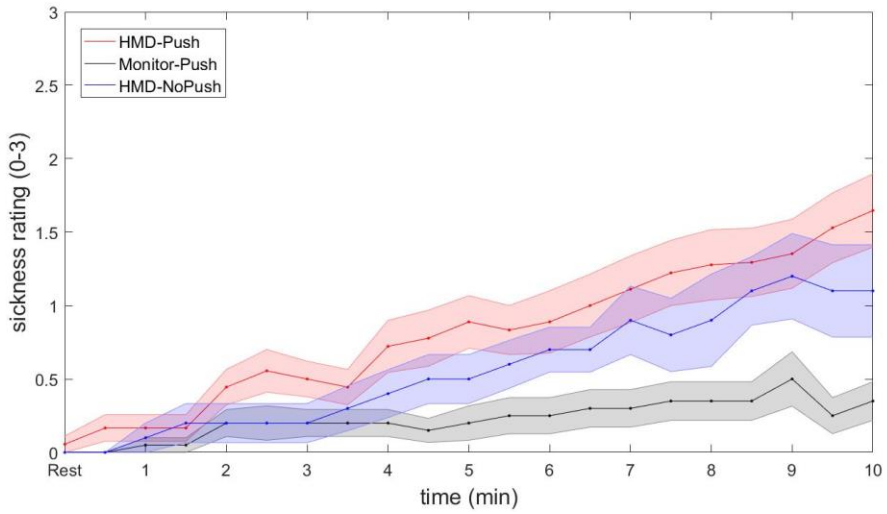

Fig 4.3. Subject-averaged motion sickness ratings over time for the three experiment conditions. Sickness was greatest in the HMD-Push (red) and HMD-NoPush (blue) conditions. Minimal sickness occurred in the Monitor-Push condition (black). Shaded regions show one standard error of the mean.

4.4.3 Analysis of Posture Data

We analyzed changes in postural sway to determine its relationship with visual perturbations and motion sickness. Data from one participant in the HMD-Push condition and another participant in the Monitor-Push condition were lost due to a network malfunction.

4.4.3.1 *Postural sway over experiment duration*

There was a significant main effect of experiment time on postural sway in the FB direction, $F(20,840) = 4.911$, $p < .000$, and the RL direction, $F(20,840) = 4.315$, $p < .000$. When splitting the data up by sickness group, the main effect of duration remained for less comfortable participants, $F(20,800) = 7.753$, $p < .000$, and more comfortable participants, $F(20,820) = 5.404$, $p < .000$. Sway data show that for the HMD-Push and Monitor-Push conditions, participants have increased postural sway in both the FB (see Fig 4.4) and RL (see Fig 4.5) directions the longer they navigated the VE. Postural sway data did not significantly differ between the Rest period and end period (10 min) in the HMD-NoPush condition. We found no significant effect of

sickness group on postural sway in any of the three viewing conditions. However, the data trended to show that less comfortable participants swayed less in the HMD-Push and HMD-NoPush conditions.

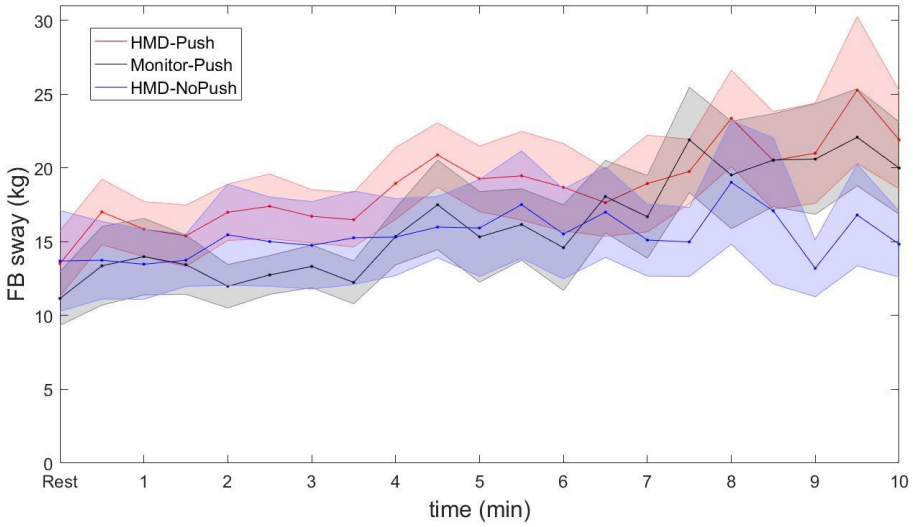

Fig 4.4. Postural sway over time for the FB direction. Sway magnitude during the HMD-Push (red) and Monitor-Push (black) conditions increased with time compared to Rest, whereas it remained similar to Rest during the HMD-NoPush (blue) condition.

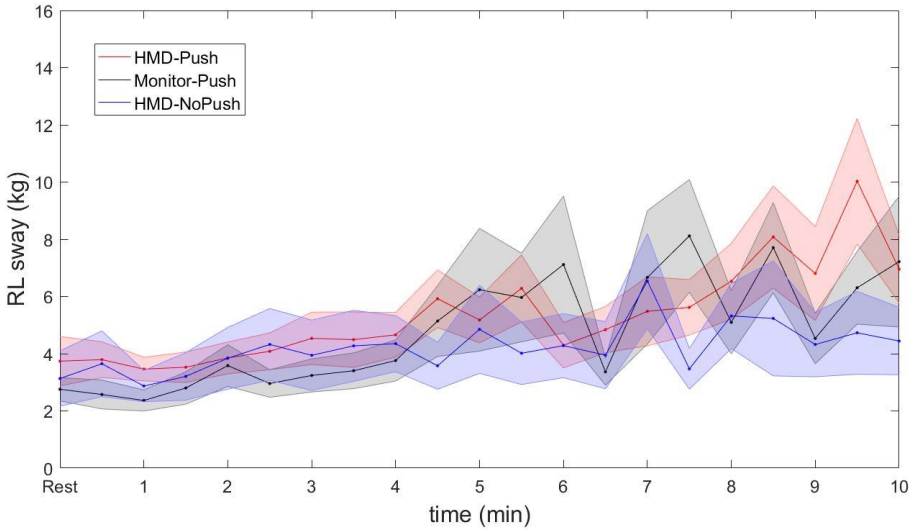

Fig 4.5. Postural sway over time for the RL direction. Sway magnitude during the HMD-Push (red) and Monitor-Push (black) conditions increased with time compared to Rest, whereas it remained similar to Rest during the HMD-NoPush (blue) condition.

4.4.3.2 *Head position and body movement correlation*

Cross correlations were computed between HMD position data and Wii board posture data for all visual perturbation instances for each participant. This was done to measure the relationship between head position and body sway. The results for both the FB and RL directions show that changes in head position and body posture are positively correlated, with body posture changes associated with immediate changes in head position. Fig 4.6 shows raw data from the head and the body in the FB and RL in the FB direction (left four panels) and RL (right four panels) direction when a representative participant is subject to unexpected visual perturbations that simulate forward, backward, rightward, and leftward pushes. The balance board measurements for the body are shown in blue, while the HMD measurements for the head are shown in red. These data show that head position shifts (plotted in units of cm) and body posture shifts (plotted in units of kg) are correlated and occur at about the same points in time after the push onset (time 0 sec). Only one participant showed changes in head position and body posture that were negatively correlated (see Fig 4.7). All but one participant showed a significant (see Section 4.3.2) average peak correlation in the FB direction at a lag of zero seconds. All but two participants showed a significant ($p < .000$) average peak correlation in the RL direction at a lag of zero seconds.

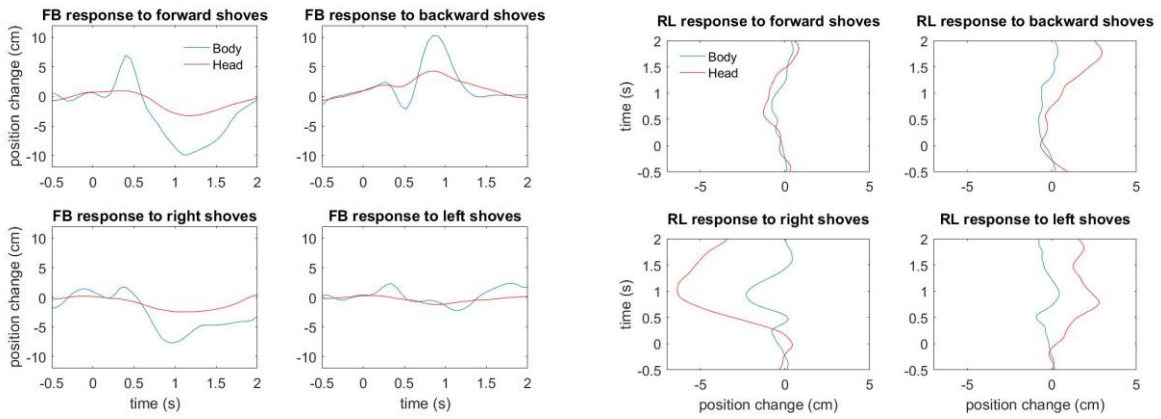

Fig 4.6. Raw trial-averaged data from the head (red) and body (blue) from a representative participant. Data from the head are in units of cm and data from the body are in units of kg. The left set of plots show data in the FB direction and the right set of plots show data in the RL direction.

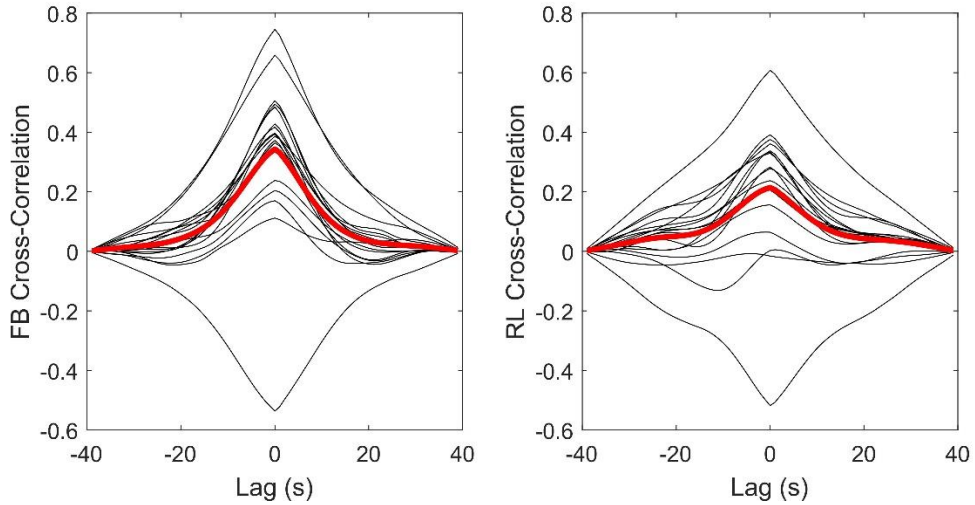

Fig 4.7. Cross correlations between the head and body for the FB (left) and RL (right) directions for lags of -39 to 39 seconds. Each line represents data from a single participant and the average across participants is shown in red.

4.4.3.3 ***Postural response to visual perturbations***

The FB and RL postural responses evoked by visual perturbations in the forward, backward, right, and left directions were compared across time and experiment condition for all participants. Fig 4.8 shows the evoked FB postural response and Fig 4.9 shows the evoked RL postural response to visual perturbations. Note that the weight change scales differ for the FB

responses in Fig 4.8 and the RL responses in Fig 4.9. When pushed in the forward direction, participants swayed backward 500 ms after shove onset and then returned to resting position (0 kg) after another 1.5 seconds (Fig 4.8, top left panel). The magnitude of this response was larger in the HMD-Push condition (shown in red in Figs 4.8, 4.9) than in the Monitor-Push condition (shown in black in Figs 4.8, 4.9). When pushed in the backward direction, participants swayed backward from 250 ms to 500 ms and then forward (Fig 4.8, top right panel) and to the right (Fig 4.9, top right panel) from 500 ms to 2000 ms after shove onset. This response was greatest in the HMD-Push condition. When pushed to the right, participants swayed slightly backward and to the left from 500 ms to 1.5 seconds after perturbation onset. When pushed to the left, participants swayed slightly backwards (Fig 4.8, bottom left panel) and to the right (Fig 4.9, bottom left panel) from 500 ms to 1.5 seconds after perturbation onset. For both the right and left perturbations, the magnitude of evoked postural responses was greater in the HMD-Push condition than the Monitor-Push condition. Note that during shoves to the left, participants also showed a significant sway back to the left at 1.5 seconds. Participants remained relatively still during the HMD-NoPush condition during which perturbations were absent.

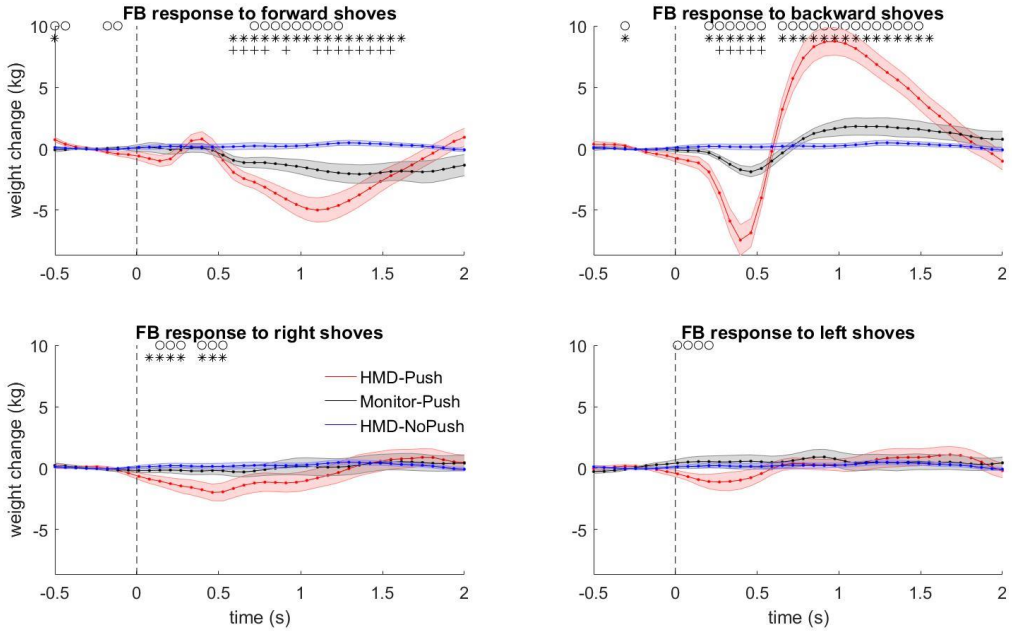

Fig 4.8. Sway in the FB direction for visual perturbations in the forward (upper left panel), backward (upper right panel), rightward (lower left panel), and leftward (lower right panel) directions. Data from the HMD-Push condition are shown in red, data from the Monitor-Push condition are shown in black, and data from the HMD-NoPush are shown in blue. Time in seconds is shown on the horizontal axis and weight change in kg is shown on the vertical axis. The icons at the top of each plot denote a significant difference for: HMD-Push vs Monitor-Push (o), HMD-Push vs HMD-NoPush (*), and Monitor-Push vs HMD-NoPush (+).

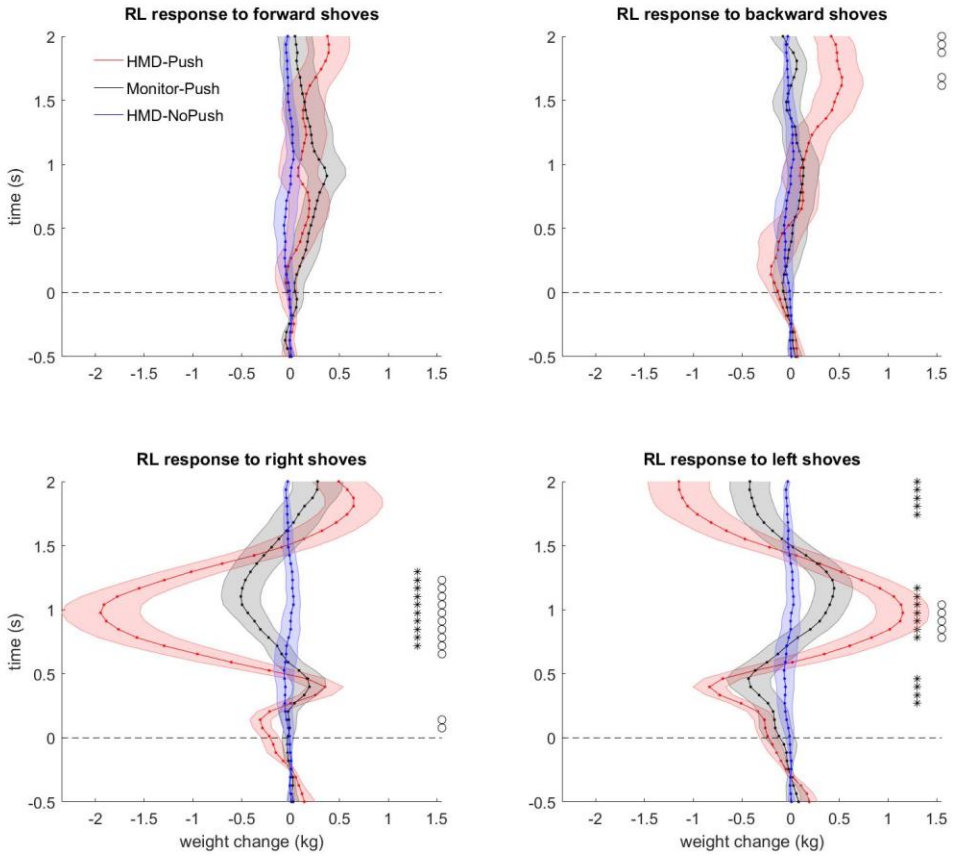

Fig 4.9. Sway in the RL direction for visual perturbations in the forward (upper left panel), backward (upper right panel), rightward (lower left panel), and leftward (lower right panel) directions. Data from the HMD-Push condition are shown in red, data from the Monitor-Push condition are shown in black, and data from the HMD-NoPush are shown in blue. Time in seconds is shown on the vertical axis and weight change in kg is shown on the horizontal axis. The icons on the side of each plot denote a significant difference for: HMD-Push vs Monitor-Push (o), HMD-Push vs HMD-NoPush (*), and Monitor-Push vs HMD-NoPush (+).

Splitting the data up by sickness group showed no significant effects of motion sickness on FB or RL postural responses to visual perturbations from any direction in all experiment conditions (see Fig 4.10).

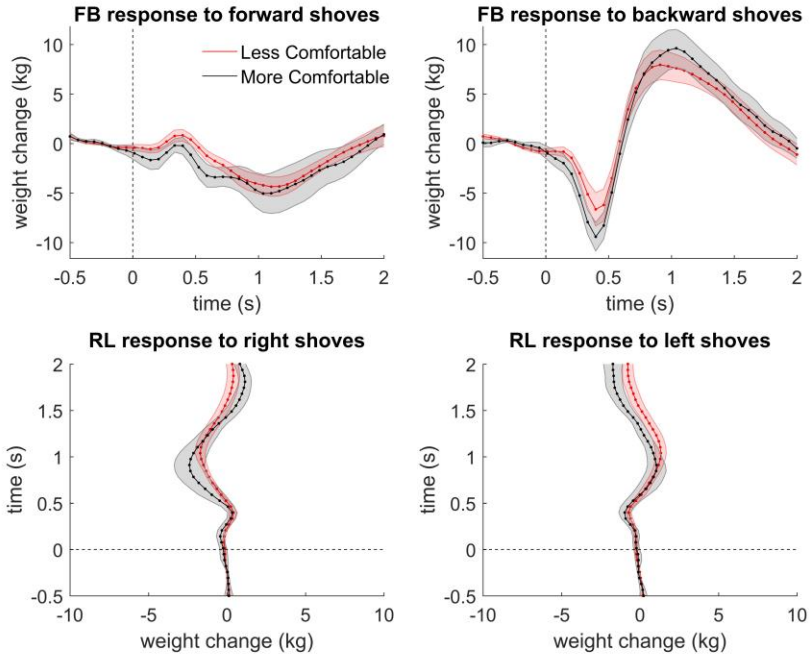

Fig 4.10. Sway in the FB direction for visual perturbations in the forward (upper left panel) and backward (upper right panel) directions and sway in the RL direction for perturbations in the right (lower left panel) and left (lower right panel) directions. Data for less comfortable participants are shown in red and data from more comfortable participants are shown in black. Time in seconds is shown on the horizontal axis and weight change in kg is shown on the vertical axis for FB data. Time in seconds is shown on the vertical axis and weight change in kg is shown on the horizontal axis for RL data.

4.5 Discussion

We found that motion sickness increases are significantly greater when one uses an HMD to view a virtual world through which one navigates than when one uses a display monitor. Others have reported similar findings during stationary use of an HMD to navigate a VE (Dennison et al., 2016; Kim et al., 2005). Because participants moved about a VE in the present experiment, optic flow provided a visual signal consistent with head movement that failed to match signals from vestibular and proprioceptive systems consistent with no head movement. Many other studies have reported a strong relationship between vection caused by optic flow and motion sickness (Bonato et al., 2008; Bubka & Bonato, 2006; Classen et al., 2011; Diels & Howarth,

2011; Flanagan et al., 2004; Golding et al., 2009; Hettinger et al., 1990; Keshavarz et al., 2014; Lee et al., 1997; Smart et al., 2002; Stoffregen & Smart, 1998).

Motion sickness increased with experiment time regardless of the presence or absence of perturbation events in both the HMD-Push and HMD-NoPush conditions (see Fig 4.3). The increases in SSQ scores (see Tables 4.1, 4.2) associated with VE navigation show that participants felt worse after using the HMD than after viewing a display monitor. This result shows clearly that the sensory mismatches produced while trying to navigate the VE without perturbations were enough to produce significant motion sickness in nearly all participants. Results shown in Fig 4.10 demonstrate that the participants who felt more comfortable responded to visual perturbations with postural sway nearly identical to that of those who reported feeling more uncomfortable.

The results of cross-correlation analysis show that the body and head were closely coupled. This suggests that most participants controlled their stability with changes at the feet. Only one participant showed a significant negative correlation between the head and the body, suggesting that when they were exposed to a shove in the forward direction, for example, they leaned backward at the hips and forward with their head (see Fig 4.7). However, for all participants, the peak correlation was at a lag of nearly zero seconds, indicating that any changes in position for the body were transferred to the head.

Postural instability was shown to increase only when visual perturbations were present in the Monitor-Push and HMD-Push conditions, but not in the HMD-NoPush condition. This finding disagrees with others who have reported that postural instability is strongly related to reports of motion sickness by HMD users (Chardonnet, Ali Mirzaei, & Mérienne, 2017; Munafo, Diedrick, & Stoffregen, 2017). It is important to point out that there is currently no gold standard

for defining postural instability in the field and thus measures of postural changes and definitions of instability differ widely across studies.

In exposing subjects to a series of visual perturbations about their direction of travel, we have introduced a new way to produce rapid visually-induced changes in posture. We found that the evoked postural response was larger when participants experienced visual perturbations through an HMD. However, we do not believe that the difference in the magnitude of postural response between the Monitor-Push and HMD-Push conditions is linked to motion sickness. Our data show that more comfortable and less comfortable participants reacted nearly identically for all directions of visual perturbations. What is likely the case is that the VE is realistic enough when viewed through an HMD that participants experience the visual perturbations as if they were being pushed around in the real world. Surprisingly, there was still a significant response to the perturbations when viewed on a desktop monitor, and the evoked sway response to these stimuli matched closely the time course of the same response during HMD use.

In conclusion, we found that navigation of a VE while wearing an HMD produced enough sensory mismatch that nearly all participants experienced motion sickness, even when postural sway did not increase from baseline measures. Although HMD use was linked to greater evoked postural sway responses to unexpected visual motion, the presence of these events was not met with reports of increased motion sickness symptoms.

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