CHARACTERIZING VISUALLY EVOKED POSTURAL RESPONSES WITH A VIRTUAL REALITY HEAD-MOUNTED DISPLAY IN YOUNG AND OLDER ADULTS

by

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Abstract

Balance control requires the continuous integration of sensory information to maintain postural stability. Widely accessible virtual reality (VR) head-mounted display (HMD) technology can be used to directly manipulate stimuli presented to the visual system, and subsequent postural responses can then be characterized. This manipulation is of particular importance for older adults, who tend to have greater reliance on vision for balance control. However, at present visual cues in VR are substantially different to those in the real world. As such, previous real-world research investigating vision and postural stability cannot be assumed as directly transferrable to applications in VR using HMDs. Therefore, the purpose of this thesis was to characterize visually evoked postural responses (VEPRs) in VR using an HMD and examine how they varied across environmental conditions and populations of interest.

In the first study of this thesis, a pseudorandom visual stimulus was presented to young adults in VR, with and without the postural threat of a virtually elevated surface height. Findings of evoked sway across experimental conditions demonstrated that young adults were visually sensitive to the stimulus. Despite pronounced psychological effects of the elevated surface height, postural threat did not influence VEPRs. The second study compared the presentation of real and virtual visual perturbations on VEPRs in young and older adults. Results indicated that within a given age group, comparable levels of sway were evoked in the two environments. In both real and virtual paradigms, older adults were more sensitive to visual stimuli than young adults. Evidence of sensory reweighting was observed as both groups were able to proportionally integrate balance-relevant visual cues based on the amplitude of the stimulus.

Overall, this thesis provides an evidentiary basis for the utility of VR HMDs in future investigations of vision and balance, in young and older adults.

Lay Summary

Information from the visual system plays an important role in maintaining one's balance and avoiding a fall, which is a major concern for older adults. The influence of vision on balance control can be examined by presenting an individual with a visual stimulus and evaluating subsequent balance responses. Virtual reality (VR) head-mounted displays (HMDs) are a promising tool for creating unique visual stimuli; however, there are several ways in which virtual environments differ from the real world. This thesis first demonstrated that balance responses could be produced from visual stimuli presented in VR using an HMD. Subsequently, this thesis used identical experimental set-ups in the real world and in VR to establish that similar balance responses could be produced across these two environments. Importantly, this finding was observed in both young and older adults. Therefore, future research should use VR to study vision and assess balance, to help prevent falls.

Preface

The studies presented in this thesis were conducted at the Neural Control of Posture and Movement Laboratory within the School of Kinesiology at the Vancouver-Point Grey of The University of British Columbia (UBC), Canada. At the time of thesis completion, the studies in this thesis have not been submitted for publication. All data presented in this thesis was collected by Emma Nielsen (Nielsen EI). All text and figures in this thesis were created by Nielsen EI under the supervision of Carpenter MG, with guidance from Chua R and Inglis JT.

Study 1, presented in Chapter 2, was reviewed and approved by the UBC Clinical Research Ethics Board (ID: H06-70316, Title: Central and peripheral mechanisms contributing to human balance control). Nielsen EI was the lead investigator for the project and was responsible for conceptualizing the study, designing the experimental procedures, data collection and analysis, interpretation of results, and drafting and revising the study document, figures, and tables. Cleworth TW contributed to project conception and design, data collection and analysis, interpretation of results, and critical review of the study document, figures, and tables. Carpenter MG was the supervisory author and contributed to the project conception and design, interpretation of the results, and critical review of the study document, figures, and tables.

Study 2, presented in Chapter 3 was reviewed and approved by the UBC Behavioural Research Ethics Board (ID: H19-02436, Title: Characterizing the Role of Vision in Older Adults' Balance Control using Virtual Reality). Nielsen EI was the lead investigator for the project and was responsible for conceptualizing the study, designing the experimental procedures, data collection and analysis, interpretation of results, and drafting and revising the study document, figures, and tables. Luu MJ and Assländer L contributed to project conception and design, and data analysis. Chua R and Inglis JT contributed to project conception and design, interpretation of results, and critical review of the study document, figures, and tables. Carpenter MG was the supervisory author and contributed to the project conception and design, interpretation of the results, and critical review of the study document, figures, and tables.

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List of Abbreviations

A-P: Anteroposterior

CNS: Central nervous system

COM: Centre of mass

COP: Centre of pressure

DTF: Discrete Fourier transform

EC: Eyes closed

EDA: Electrodermal activity

EO: Eyes open

FOV: Field of view

HMD: Head-mounted display

MPF: Mean power frequency

MPOS: Mean position

OA: Older adult

P2P: Peak-to-peak

PRTS: Pseudorandom ternary sequence

RMS: Root mean square

SMMSE: Standardized Mini-Mental State Examination

SSQ: Simulator Sickness Questionnaire

SUS-Q: Slater, Usoh, Steed Questionnaire

VEPR: Visually evoked postural response

VR: Virtual reality

YA: Young adult

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For my parents, Kimberley and David, my brother, Matthew, and my roommate, Doug.

Chapter 1: Introduction

1.1 Neurophysiology of vision

Every sensory system requires two critical elements for sensation: a physical stimulus and a receptor. In the case of vision (the sensation related to sight), light is the physical stimulus and the receptors are photoreceptors. Vision enables the simultaneous detection of object colour, form, and motion, which is referred to as parallel processing. At a given instance in time, the visual system is processing the light reflected from the environment in a densely structured optic array (Gibson, 1966). The changes in the structure of an optic array over consecutive time frames, due to relative motion between the eye and the scene, create what is known as optic flow (Gibson, 1966). Optic flow captures the changes across consecutive optic arrays with a vector field, which in turn is interpreted as motion (Gibson, 1966).

When light enters the eye, it travels through the cornea, past the lens, and hits the retina, a membrane that covers the posterior curvature of the eye. A specific type of neuronal cells known as photoreceptors are located in the retina, and there are two types of photoreceptors: rods and cones. Rods are located in periphery and are responsible for vision in lower light conditions, whereas cones are concentrated in the fovea, in an area of the retina known as the macula and are responsible for colour vision. When light hits the rods and cones it causes a state of hyperpolarization that triggers a phototransduction cascade. This results in an action potential propagating along the axons of retinal ganglions cells that form the optic nerve. Information from the visual field travels along the optic nerve in tracts that lead to various regions of the brain, but mainly to the lateral geniculate nuclei. Optic radiations lead from this structure to the visual cortex for processing. Located in the occipital lobe, the visual cortex is divided into five unique regions based on characteristics of structure and function.

Visual processing of motion is completed in three cortical regions, organized hierarchically. The first level, in the primary visual cortex, encodes the direction of motion for local features of an object such as individual edges or boundaries (Hubel & Wiesel, 1968). This leads to ambiguity in the signals as it does not necessarily characterize the overall motion of the object (Wallach, 1976). The second level of motion processing occurs in the middle temporal area in which local motion cues are integrated by cells in this region to characterize patterns of two-dimensional motion (Adelson & Movshon, 1982). The final level of motion processing occurs in the medial superior temporal area, which receives projections from middle temporal cells (Tanaka & Saito, 1989; Orban et al., 1995). This region has been demonstrated to selectively respond to higher-level optic flow such as in translations and rotations (Morrone et al., 2000).

A great deal of research has been dedicated to the estimation of optic flow both using biological and computational models (Brox et al., 2004; Otte & Nagel, 1994). Although optic flow was initially studied in passive vision, Gibson (1966) introduced the concept of ecological optics, proposing that the observer, the environment, and the task impose constraints on the continuous transformation of the visual field. As such, each of these elements are critical for understanding and estimating optic flow (Gibson, 1966).

1.2 Balance, vection, and vision

In order to investigate balance control, it is crucial to examine sensory contributions, as postural stability relies on continuous feedback from the visual, vestibular, and somatosensory systems (Horak & MacPherson, 1996; Maurer et al., 2000). The visual system is perhaps the most obvious contributor to postural control; one can simply close their eyes and observe an increase in body sway (Edwards, 1946; Paulus et al., 1984). Investigation of the visual control of balance has become increasingly feasible, due to technological innovations, and is a research priority given the increased falls risk of a globally aging population.

To gain insight regarding sensory contributions to postural control, a classic method of investigation is to present the system with some sort of input stimulus and evaluate the output balance response (van der Kooij et al., 2005). This is frequently accomplished through vection, a broad class of illusory self-motion phenomena (Hettinger, 2002). It is important to note that stimulation of auditory, haptic, and vestibular systems can also contribute to sensations of vection (Hettinger, 2002; Rieke et al., 2005); however, for the purposes of this thesis, the term vection will specifically refer to the visual system.

A frequently reported sensation of vection occurs while sitting in a stationary vehicle and viewing another move past. This motion may be interpreted as one's own and evokes a subsequent reaction, leading to discomfort and temporary disorientation from incongruent sensory information. This exemplifies the dominance of the visual system, and while this example typically occurs in a seated posture, it is widely known that vection can be utilized during standing balance to evoke compensatory sway (Dichgans & Brandt, 1978; Dichgans et al., 1972; Lee & Lishman, 1975). In 1986, Adolfo Bronstein defined this phenomenon as a visually evoked postural response (VEPR).

1.3 Historical perspectives on vection

Vection is far from a novel concept; systematic study dates back to 1875 (Mach). The term was first cited and used to define self-motion in 1931 by Tschermark (Dichgans & Brandt, 1978). A historically famous (and accurate) instance of vection occurred at the Haunted Swing attraction of the San Francisco Mid-Winter Fair (Hettinger, 2002; Wood, 1895). In the attraction, users reported a swing moving back and forth with increasing amplitude until a 360° pitch rotation was achieved. Of course, this did not actually happen, the surface of the room moved while the patrons remained still. The attraction provided users with the sensation of "goneness within" (p.277) and even led to reports of fainting and nausea (Wood, 1895).

A great deal of credit for the implementation of vection is owed to the psychologist James J. Gibson, who studied the perception of visual space. Gibson observed the visual control of orientation and locomotion in animals (1958) and researched optical ecology, to provide an understanding as to how the ocular system registers its external environment (1966). In Gibson's 1979 publication, "Ecological Approach to Visual Perception", the author considers visual perception from a philosophical framework, as to how the eyes work in their most basic and natural setting, termed "ecological psychology."

Seminal work in understanding vection and balance control took place in the 1970's by three major research groups. In 1972, Dichgans and colleagues first reported that the rotational motion of a large visual surround produced a lateral tilt displacement of the subject, in the direction opposite of the rotation. What is now referred to as circular vection was initially understood as a change in gravity along the subject's line of motion and was suggested to be an internal shift in one's representation of gravity (Dichgans et al., 1972). In a series of circular vection experiments, rotation of the same visual surround induced the perception of self-motion that began a few seconds after the onset of the stimulus and remained temporarily after the stimulus was removed (Brandt et al., 1973). Interestingly, self-reports of perceived motion were maintained as equivalent to the velocity of the visual surround, until a saturation response was observed (Brandt et al., 1973). Occlusion and differential stimuli presentations to the central and peripheral visual fields led to observations that the types of motion perception are dependent on the area of stimulation. Specifically, peripheral vision dominates reports of exocentric motion, the illusion of self-motion in a stationary environment, whereas central vision is most important in egocentric motion perception, in which one observes themselves to be stationary in a moving environment (Brandt et al., 1973). Further research led to foundational evidence identifying the role of stimulus density contrast, onset time, rotational velocity, size, and retinal location on the degree of visual tilt and/or magnitude of perceived circular vection (Brandt et al., 1975; Dichgans & Brandt, 1978; Held et al., 1975; Wist et al., 1975).

Perhaps the most well-known studies regarding vection are the swinging room experiments, published by Lee and Lishman between 1973 and 1977. In 1973, Lee and Lishman first argued that vision itself was an autonomous kinesthetic sense, rather than being solely exteroceptive. The researchers completed a series of 13 experiments in a swinging room where the participants stood on a trolley or the ground, while the systems could be driven in conjunction or separately, thereby manipulating the optic field (Lee & Lishman, 1973). The presentation of conflicting visual and mechanical kinesthetic information resulted in a dominance of sensations congruent with visual manipulations, even when participants were informed in advance of said manipulations (Lee & Lishman, 1973). The authors further explored the potential influences of visual dominance including room motion, illumination, and posture (Lee & Lishman, 1973). The notion of visual dominance in balance control was supported by the work of Lee and Aronson (1974), in which infants, who are suggested to be most reliant on vision for balance, would fall over during motion of the swinging room, whereas adults were less affected. The authors referred to this phenomenon as visual proprioceptive control, and later proposed that vision was the most important source of proprioceptive information by demonstrating that decreasing the quality of ankle-foot proprioception, through unfamiliar and unstable stance positions, increased one's reliance on vision (Lee & Aronson, 1974; Lee & Lishman, 1975). Finally, based off of the work of Gibson (1966), Lee (1980) proposed that future neurophysiological research attempting to better understand vision should be pursued with manipulations of the optic field.

The third body of vection literature from the 1970's provided tremendous insight regarding the parameters of linear vection. In 1975, Berthoz and colleagues published a study demonstrating the importance of peripheral vision for linear vection and provided thresholds for self-motion perception based on both the luminance and velocity of stimuli. The authors also reported that perception of linear vection could slowly adapt or habituate over a time course of approximately 30-50 seconds (Berthoz et al., 1975). The relationship between stimulus velocity and the amplitude of postural adjustments was identified as logarithmic, with a saturation to linear vection occurring at approximately 1m/s (Berthoz et al., 1975; Lestienne et al., 1977). Further, postural responses to linear vection were established as directionally asymmetric, such that forwards moving stimuli produced a 25% greater postural response, likely due to biomechanical asymmetries around the ankle joint, as well as increases in the information provided in the optic field (Berthoz et al., 1975; Eklund & Lofstedt, 1970; Lestienne et al., 1977). The group also documented the interaction between vestibular and visual systems in linear vection, in that vestibular signals dominated during short term accelerations, whereas vision was more important for extended presentations (Berthoz et al., 1975; Pavard & Berthoz, 1977). Although vision was recognized as essential for linear vection, it was proposed to be operating in conjunction with the vestibular system, rather than independently, as previously suggested (Berthoz et al., 1975; Lee & Lishman, 1973; 1975; Pavard & Berthoz, 1977). Finally, while evoked postural sway responses were reported at a latency of 1s, Nashner and Berthoz (1978) demonstrated that the initial muscular responses to linear vection occurred much earlier at around 100ms.

1.4 Visual sensory integration and reweighting

A common finding across balance control research is that there is a time dependant response to the presentation of a perturbing stimulus. The new sensory information is integrated with other stimuli by the central nervous system (CNS) to guide postural control (Horak & MacPherson, 1996; Maurer et al., 2000). A response saturation has been consistently demonstrated across visual perturbation studies, such that increasing velocity or amplitude of the visual stimulus beyond a particular level has no additional effect on postural responses (Lestienne et al., 1977; van Asten et al., 1988b). Below the threshold, however, there appears to be a logarithmic relationship between the linear velocity of the visual stimulus and amplitude of the postural response (Lestienne et al., 1977). The finding that the contribution of the visual system to balance control was dependent upon the magnitude of the visual perturbations is some of the first direct evidence of sensory reweighting (Lestienne et al., 1977).

Sensory reweighting describes the process in which the CNS integrates information from different sensory systems for balance control (Assländer & Peterka, 2014; Peterka, 2002). Specifically, the degree to which a sensory system contributes to the control of balance is dependent upon both the perturbation stimulus and the environmental conditions (Assländer & Peterka, 2014; Peterka, 2002). The postural response to a given stimulus can often be influenced by the presentation of additional sensory cues from other systems (Maurer et al., 2006). Researchers have used a combination of sensory cues and unique means of introducing, manipulating, and removing stimuli to evaluate how the CNS responds to changing sensory information (Assländer & Peterka, 2014; 2016; Jeka et al., 2000; Peterka, 2002). One pertinent method of examining potential sensory reweighting effects is with the presentation of the same stimulus at a number of varying amplitudes (Peterka, 2002). It is also known that patients with various pathologies respond differentially to sensory cues based on the etiology of impairment (Greffou et al., 2012; Peterka & Benolken, 1995; Redfern et al., 2001; 2007).

Experimental modelling has provided enormous insight as to how sensory cues are integrated by the CNS to guide balance control. Peterka (2002) suggests that each sensory system detects error from some point of reference and sends a corrective signal to the CNS. Signals are then summed, and a corrective torque can be applied in combination with neural transformations to maintain balance (Peterka, 2002). Numerous models suggest that this process occurs as a linear response function (Fitzpatrick et al., 1996; Jeka et al., 2000; Maki et al., 1987; Peterka, 2002; van Asten et al., 1988b). Peterka (2002) demonstrated that sensory integration is a linear process for a given steady state stimulus. Irregularities and non-linearities of the system have been identified, specifically when there is a shift in the dominance of sensory inputs (Nashner & Berthoz, 1978; Peterka, 2002). Interestingly, non-linearities have not been observed for individuals with vestibular loss, as they are unable to shift between sensory modalities (Peterka, 2002).

Indirect evidence for visual sensory reweighting comes from adaptation studies evaluating the repeated presentation of visual stimuli. Bronstein (1986) demonstrated that postural responses to linear vection can be suppressed during the second presentation of the stimuli, suggesting that habituation to visual stimuli does not always occur over a large timescale as previously reported (Lestienne et al., 1977). In more recent work, the presentation of a series of rapid visual perturbations demonstrated increasing attenuation of postural responses with each successive perturbation (Mahboobhin et al., 2005). Additionally, the presentation of oscillating visual stimuli prior to the perturbations decreased postural sway responses even further (Mahboobhin et al., 2005). These examples suggest that the CNS is becoming less reliant on, or down-weighting, visual sensory information. This phenomenon may be best explained with the maximum-likelihood estimation theory in that there is an inverse relationship between the variability of the stimuli and the degree to which it is weighted in feedback control systems (Battaglia et al., 2003; Harville, 1977). Thus, if decreased weight is placed on unreliable or unpredictable sensory information, it is important to also examine the changes in sensory function that are known to occur with age-related sensory decline.

1.5 Changes with aging

Preliminary evidence for differences in the visual control of balance due to aging originated from research with children. Compared to adults, children have been found to be much more responsive to visual perturbations and are sensitive to a wider frequency range of visual stimuli (Lishman & Aronson, 1974; Schmuckler, 2017). This increased reliance on vision for balance control may be attributed to the relative development of sensory systems and capacity to utilize information (Lishman & Aronson, 1974; Schmuckler, 2017).

Aging is associated with decreases in the quantity of neurons and receptors related to vestibular function (Rosenhall & Rubin, 1975), as well as impairments to somatosensation in lower limbs and joints relevant for postural stability (Calne et al., 1991; Skinner et al., 1984). Despite decreased visual perceptual skills, it is widely accepted that older adults (OAs) tend to be more visually dependent than young adults (YAs) (Faubert, 2002; Simoneau et al., 1999;

Sundermeyer et al., 1996; Wade et al., 1995). Specifically, OAs are known to have increased sensitivity to visual cues related to balance (Hayes et al., 1985). Peterka and Loughlin (2004) have suggested that instability related to falls may be due to inadequate regulation of these visual cues. Sundermeyer et al. (1996) evaluated visual dependency and postural control strategies following a rapid visual perturbation in healthy YAs and OAs, as well as OAs who had experienced falls. Compared to YAs, fall-prone OAs had significantly increased visual sensitivity and much more frequently employed a hip strategy for postural control (Sundermeyer et al., 1996). The increased visual sensitivity was characterized by extended periods of destabilization following the perturbations which suggests that there may be a decreased capacity to effectively dampen, or modulate, one's response to adverse stimuli over time (Sundermeyer et al., 1996). Most studies have reported that OAs, including fallers and non-fallers, have larger responses to visual stimuli than YAs; however, it is unclear whether these responses are specific to the stimuli or are the product of a more global destabilization (Slaboda et al., 2011; Toledo & Barela, 2014; Wade et al., 1995). OAs have even further susceptibility to visual stimuli when other sensory information is impacted (Borger et al., 1998.)

Given the observed differences in visual dependency between YAs and OAs, (Faubert, 2002; Simoneau et al., 1999; Sundermeyer et al., 1996; Wade et al., 1995) it would be expected that models could demonstrate the consequences of aging on sensory reweighting. Initial modelling by Jeka's group suggested that when there is significant intact peripheral sensory information, there are no differences in sensory reweighting due to age, when using small amplitude visual and haptic stimuli (Allison et al., 2006; Jeka et al., 2006). It was noted however, that observations based on sensory reweighting models are context-specific to the experimental methodologies, such that OAs could adapt and appropriately reweight sensory information because of the extended trial lengths (Jeka et al., 2006). Future sensory reweighting research must consider the external validity of paradigms with long transition times, as these are not always available to OAs when presented with conflicting sensory information in the real world. This project was followed up with another study investigating dynamic sensory reweighting between large and small amplitude translational visual stimuli (Jeka et al., 2010). In this study, both healthy OAs and fall-prone OAs had increased sensory reweighting times when presented with the larger amplitude stimulus, compared to YAs. Additionally, the fall-prone OAs had larger visual gains than the other two groups (Jeka et al., 2010). This suggests that sensory reweighting of visual information may be dependent upon not only age, but other defining characteristics of fall prone OAs, such as the fear of falling (Davis et al., 2009; Hadjistavropoulos et al., 2011).

1.6 Postural threat and sensory systems

Fear of falling has been demonstrated to modify standing balance control in both young and older adults (Davis et al., 2009; Maki et al., 1991). The relationship between emotional states related to fear of falling and balance control can be evaluated with a perceived or real risk to stability, known as a postural threat (Adkin et al., 2000; Adkin & Carpenter, 2018; Brown & Frank, 1997; Carpenter et al., 2001; Cleworth et al., 2012; 2016; Davis et al., 2011; Horslen et al., 2013; 2014; Naranjo et al., 2015; 2016; Hauck et al., 2008; Huffman et al., 2009; Zaback et al., 2019). Postural threats can be achieved through a variety of means including the use of an elevated surface height or the knowledge of impending perturbations in both real and virtual environments (Brown & Frank, 1997; Cleworth et al., 2012; Horslen et al., 2013; Johnson et al., 2017). Postural threats elicit robust psychological and physiological responses including increases in reported fear, anxiety, and electrodermal activity, and decreases in balance-related confidence and perceived stability (Adkin et al., 2008; Cleworth et al., 2012; Zaback et al., 2015). There are also characteristic behavioural changes that occur during postural threat which collectively may be considered as a stiffening strategy in which the amplitude of centre of pressure (COP) movements decrease and frequency content increases, in conjunction with co-contraction of the tibialis anterior and soleus muscles (Adkin & Carpenter 2018; Zaback et al., 2017).

Postural threat is also known to influence a variety of sensory processes. For example, when probed with a tendon tap during postural threat, stretch reflexes are reported to have larger amplitudes due to increased sensitivity of the muscle spindle (Horslen et al., 2013). Research has also demonstrated that vestibular evoked myogenic potentials and vestibular ocular reflexes have an increased gain under postural threat (Naranjo et al., 2015; 2016). This evidence suggests that postural threat evokes a state of sensory gain, in which sensory systems are more sensitive, or “fine-tuned”, to balance relevant stimuli, given the increased necessity of maintaining stability and avoiding a fall (Cleworth et al., 2016; Horslen et al., 2013; Naranjo et al., 2015; 2016). At present it is unclear as to whether the visual system functions in a similar manner under postural threat. However, it is known that the visual system is critical for processing cues relevant to postural threats (Lelard et al., 2014) and during sympathetic activation, the visual system has a defined arousal response that includes pupillary dilation and reduced peripheral vision (McDougal & Gamlin, 2011).

1.7 Methodological considerations for vection

The capacity to draw generalizable conclusions from vection and balance control research is often limited by the highly variable nature across methodologies. The following section will provide a comprehensive yet not exhaustive review of some of the parameters that should be considered when studying VEPRs.

1.7.1 Types of vection

Vection can be produced from linear and rotational motion, both separately and in combination, across all six degrees of freedom. Experimental protocols have historically favoured circular vection (rotation about the roll, pitch, and yaw axes) as it produces strong postural responses, although, linear vection stimuli may have greater real-world application.

Although circular vection describes rotation around any of the three axes, Dichgans and Brandt (1978) specify that its definition relates to rotation about the yaw, or z-axis, while roll vection and pitch vection occur about the x and y axes, respectively. During circular vection (about the z-axis) the initial rotation of a stimulus will be interpreted by the user as motion of the surrounding environment. However, with a varying latency, the individual will begin to report that it is themselves who are rotating, and eventually that the motion produced is entirely their own, this point is referred to as saturated vection (Hettinger, 2002). Circular vection has been classically produced in a “vection drum” apparatus (Brandt et al., 1973; Dichgans & Brandt, 1978). Roll vection on the other hand, occurring about the y-axis or frontal plane, can be produced with a series of rotating circles or dots presented directly in front of the individual. When presented with roll vection, individuals typically respond with a postural adjustment in the opposite direction of the rotation, suggesting an internal shift of the gravitational vector (Dichgans et al., 1972). Others suggest that it feels as though their body is rotating continuously, although it remains at a relatively consistent angle. Through repeated exposure to roll vection, individuals can be observed to decrease their degree of body tilt. Pitch vection uses similar stimuli as roll vection, although users tend to report weaker stimulus reactions and decreased perceptions of disturbance (Young et al., 1975). The axial response to pitch vection is asymmetric; larger estimates of postural disturbance are produced from pitch-down versus pitch-up stimuli (Young et al., 1975). The characterization of postural responses to circular vection involve descriptions of both the timing, or latency, and magnitude of the response. These components are influenced by optical parameters of the visual stimuli, that also apply to linear vection, and are described in greater detail below.

The other principal form of vection is linear vection, which occurs in response to translational stimuli. Linear vection can be produced along any axis. In standing balance, the largest evoked responses are along the anteroposterior (A-P) axis, while mediolateral perturbations produce greater responses during walking (Connor & Kuo, 2013). Linear vection can be investigated by a variety of means including swinging or moving rooms, projected images, and virtual reality (VR) paradigms. When presented with a linear perturbation, for example with the front wall moving away, individuals typically perceive themselves to be falling backwards. As a result, they will apply a corrective compensatory torque in the forward direction to adjust to this visually identified loss of balance. As previously stated, there is a directional bias in linear vection such that greater responses have been reported to stimuli moving away from (or in the anterior direction) rather than towards (in the posterior direction) the observer (Lestienne et al., 1977). Again, the latency and amplitude of postural responses to linear vection are dependent upon the optical parameters of the stimuli.

1.7.2 Types of visual perturbations

Although there are a number of ways in which visual perturbations can be created, for the purposes of this thesis, perturbation methods specific to linear vection will be discussed. Perturbation methods for linear vection can be classified based on the number of stimuli and the duration of presentation. Transient stimuli are typically rapid, isolated stimuli that evoke a single compensatory postural response. Presentation of successive transient stimuli can lead to rapid adaptation, or down-weighting, of the visual system (Mahboobin et al., 2005). It can be extremely challenging to evoke compensatory postural responses to single transient visual perturbations in young adults who may be able to employ conscious control strategies (Lee & Aronson, 1974) and are thought to be less visually dominant (Faubert, 2002; Simoneau et al., 1999; Sundermeyer et al., 1996; Wade et al., 1995)

The second type of visual perturbation is a continuous stimulus that occurs over an extended duration. These visual perturbations are frequently used in sensory integration modelling, as they allow for the investigation of a steady-state response and examination of the subtle intricacies of the visual system (Assländer & Peterka, 2014; Peterka, 2002). Continuous stimuli that are highly predictable, such as basic sinusoids, can be easily habituated to over time, whereas the use of stochastic or pseudorandom stimuli may minimize habituation and learning effects due to increased complexity (Peterka, 2002; Toledo & Barela, 2014).

1.7.3 Optical parameters

The following section describes the four major parameters of optics that influence vection and subsequent postural responses, as defined by Dichgans and Brandt (1978). These parameters are essential for the study of vision with linear vection, as it is the change in reflected light across consecutive visual samples of the optic array that ultimately produces the interpretations of motion (Lee, 1980).

1.7.3.1 Size of visual field

Although vection can be produced with a visual field of view (FOV) as small as 10°, the general consensus is that larger FOVs produce more intense visual stimuli (Andersen & Braunstein, 1985; Dichgans & Brandt, 1978). In fact, it has been demonstrated that postural responses are scaled linearly to the size of the FOV during linear vection, and logarithmically during circular vection (Held et al., 1975; Lestienne et al., 1977). Although the size of the FOV is important, it is also critical to have information present in the periphery of the visual field, which is most responsible for postural control and exocentric motion perception (Piponnier et al., 2009; Raffi & Piras, 2019; Warren & Kurtz, 1992). Stimulation to different regions of the visual field activates specific geniculo-cortical pathways and therefore leads to differential processing of visual information (Raffi & Piras, 2019).

1.7.3.2 Temporal frequency

While larger amplitude stimuli can increase postural destabilization, it does not necessarily mean that the responses have stronger coherence; rather, these large stimuli are likely leading to greater internal noise (Assländer & Peterka, 2014; Kiemal et al., 2006; Peterka, 2002). In linear vection, as the velocity of the stimulus increases, so does the postural response, in a logarithmic manner, until postural saturation is reached at 1m/s. (Lestienne et al., 1977).

Several previous studies have utilized optical stimuli with frequencies around 0.2Hz which evoke a robust postural response (Greffou et al., 2008; Musolino et al., 2006; Toledo & Barela, 2014). Some evidence suggests that frequencies of visual stimuli above this value saturate the visual system and limit further postural reactivity (Hanssens et al., 2013; van Asten et al., 1988b). Schmuckler (2017) reported that adults were more sensitive to visual stimuli of a lower frequency, which may relate to the relevance of these stimuli for ecological postural sway. However, the presentation of visual stimuli with a pseudorandom or stochastic frequency pattern may limit saturation effects to higher frequency stimuli (Peterka, 2002). When controlling for frequency, a visual stimulus with a greater velocity will produce a balance response with greater sway variability but weaker coherence to the input signal (Barela et al., 2009; Dokka et al., 2009).

1.7.3.3 Spatial frequency

Researchers often use visual stimuli with a wide range of spatial frequencies to effectively perturb balance (Assländer & Perterka 2014; 2016; Peterka, 2002, van Asten et al., 1988a). The additional texture in the stimulus pattern is known to increase postural responses to visual stimuli (van Asten et al., 1988a). Increasing the spatial frequency of a stimulus improves the density of the optic array in the visual field and can facilitate perception of the temporal velocity of the stimuli (Diener et al., 1976; Masson et al., 1995). Further, the intensity of postural responses has been demonstrated to linearly increase as a function of the stimulus' spatial frequency (Pavard & Berthoz, 1977). Evidence has also reinforced the importance of edges and strong contrast luminance within the visual scene to facilitate perceptions of self-motion (Owen et al., 1983; Warren et al., 1982).

1.7.3.4 Presence of background and foreground information

Additional visual foreground, but not background, information can suppress vection (Howard & Howard, 1994). When multiple frames of motion are presented at once, it is the furthest that informs vection (Brandt et al., 1975). Supplementary background and foreground information can help an individual determine their relative distance to the visual stimulus, which in turn can influence balance control (Dijkstra et al., 1992).

1.8 Inter-individual differences

One of the most important and confounding methodological considerations for vection is the inter-individual variability in visual sensitivity that exists when presenting a given visual stimulus. Although OAs as a population can be characterized as having higher visual sensitivity, variation in sensitivity exists regardless of age, and may be dependent on psychological state, medical condition, and natural disposition (Redfern et al., 2007; Sundermeyer et al., 1996). Capacity to tolerate visual stimuli can also be related to one's ability to integrate visual and vestibular cues; those prone to motion sickness may have a very adverse response to a stimulus that is perfectly tolerable for others (Berthoz et al., 1975; Dichgans & Brandt, 1977). Further, certain populations are known to frequently employ sensory down-weighting, such as trained dancers (Osterhammel et al., 1968). These observations are not to discourage the evaluation of visual sensitivity at a population level, but rather suggest caution when making generalizations and recommend a thorough consideration of other factors that may influence visual sensitivity and subsequent balance control.

1.9 Vection research with virtual reality

The implementation of VR technology in research has become increasingly prevalent in the field of neuromechanics. Systems have made vast advances in their designs; head mounted displays (HMDs) are lighter, more ergonomic, and more accessible than ever before. Importantly, VR provides a safe way to explore responses to novel phenomena. It can also be used to reproduce physiological behaviours typically observed in threatening environments, such as with virtual elevated surface heights (Cleworth et al., 2012). Utilization of VR technology enables exposure of specific populations, such as fall-prone OAs, to otherwise high-risk environments. The scientific community is greatly benefitting from the developments in VR technology by the gaming industry; options for potential experimental paradigms are limitless. When considering visual perturbations, VR presents as an excellent method to specifically probe the visual system and evaluate subsequent postural responses in a manner that maximizes ecological validity. That is to say that experimental paradigms in VR can increasingly approximate the typical behaviours observed in real-world settings.

Despite the promise and enthusiasm surrounding the use of VR in research, several concerns must be addressed prior to implementation. First and foremost, there is an insufficient understanding of the visual contribution to balance control in virtual environments. It cannot be assumed that previous research in the real world using rotating drums or moving rooms can be directly transferrable to VR. This is a fundamental question of the ecological validity across experimental methodologies that must be examined.

In the past, virtual environments have been notorious for inducing motion sickness and surveys have been used to try to quantify the effects of motion sickness in VR (Hettinger & Riccio, 1992; Kennedy et al., 1993). It is possible that trying to induce vection with VR technology may exacerbate symptoms of motion sickness. The use of HMDs can also lead to sensations of claustrophobia and anxiety in some individuals, which may in turn influence one's visual sensitivity (Redfern et al., 2007). Further, virtual environments are inherently unstable; there are no studies to date in which participants are as (or more) stable in VR than in the real world (Kelly et al., 2008; Peterson et al., 2018). Perturbation training may temporarily improve stability but may confound sensory reweighting if used prior to investigations of vision and balance (Peterson et al., 2018). Another important consideration when using VR is one's sense of presence and the extent to which they “buy-in” to the virtual environment. Sensations of vection, and subsequent postural responses may actually vary depending on level of presence or immersion in the environment (Hettinger, 2002; Slater et al., 1994).

The final challenge to consider for the use of VR in research, particularly with HMDs, are the structural constraints of the devices. While humans have a 220° FOV, most modern HMD systems are still considerably limited at between 90 and 110° FOV. With reduction in the peripheral visual field, it is likely that perceptual thresholds of self-motion differ between real and virtual environments, although this has not yet been quantified. Depth perception, which is critical for balance and spatial navigation, has been reported to be compressed in VR HMDs, which leads to underestimations of the environment size in the visual field (Knapp & Loomis, 2004; Mahrun et al., 2019; Wann et al., 1995).

1.10 Aims of thesis

The overall aim of this thesis was to characterize VEPRs in VR environments with the use of visual perturbations. The first study in this thesis aimed to elicit VEPRs in an ecologically valid experimental environment and explore the influence of virtual postural threat on the visual control of balance. The second study aimed to establish the degree to which VEPRs differ when presented in identical real and virtual environments, and further compare the balance responses between young and older adults related to sensory reweighting.

1.11 Research questions

1. What are the temporal frequency characteristics of visual perturbations that evoke postural responses in VR?
2. How does postural threat influence the visual control of balance in VR?

3. Is postural stability differentially influenced by the presentation of visual perturbations in real and virtual environments?
4. What are the effects of aging on the integration of visual information for balance control?

1.12 Research hypotheses

Study 1

- Perturbations that elicit robust postural responses in virtual reality would be primarily comprised of lower frequency visual stimuli (Greffou et al., 2008; Musolino et al., 2006; Toledo & Barela, 2014).
- When under postural threat, the visual system would have greater influence on balance control (Cleworth et al., 2016; Horslen et al., 2013; Naranjo et al., 2015; 2016).

Study 2

- Real and virtual visual perturbations would both evoke compensatory postural sway responses; however, responses in the real-world environment would have stronger coherence with the visual stimuli (Berthoz et al., 1975; Dichgans & Brandt 1978; Hanssens et al., 2013; Keshnar & Kenyon, 2009; Lestienne et al., 1977).
- OAs would be more visually sensitive than YAs to the visual perturbations in both real and virtual environments, such that they would produce larger destabilizing responses and have stronger coherence and greater gains with the visual stimuli than YAs (Faubert 2002; Simoneau et al., 1999; Sundermeyer et al., 1996; Wade et al., 1995)
- When presenting continuous visual perturbations of two different amplitudes, postural responses would have stronger coherence and greater gains to stimuli of smaller amplitude, independent of age or environment (Peterka, 2002).

Chapter 2: Study 1 - Postural sway evoked with pseudorandom visual perturbations at low and high virtual surface elevations

2.1 Methods

2.1.1 Participants

Forty-three healthy YAs volunteered to participate in the study. The experimental procedures were explained to each participant and written informed consent was obtained. Seven participants were excluded from data analysis, three were due to violations of inclusion criteria, and four were due to technical difficulties during data collection. The sample for analysis consisted of thirty-six healthy YAs (mean age (±SD): 22.7 (±4.49) years, 17 female). None of the participants had a self-reported history of musculoskeletal injuries and/or neurological disorders that are known to affect balance, and all self-reported their vision as normal, or corrected to normal. On the experiment intake form, ten participants indicated having a fear of heights. Research procedures were approved by the University of British Columbia Clinical Research Ethics Board, in accordance with the Declaration of Helsinki.

2.1.2 Experimental set-up

Participants were equipped with a VR HMD system (Rift, Oculus, USA). Optic flow was manipulated with the presentation of a novel visual stimulus in the virtual environment (Vizard, WorldViz, USA). Visual stimuli were digitally uploaded and sampled at 1000Hz prior to data collection (Power 1401 with Spike2 software, Cambridge Electronic Designs, UK); the analog visual stimuli were then outputted to Vizard through a digital lab interface (LabJack, Colorado, USA). The virtual environment used, Pit.py, was predeveloped and publicly available in Vizard (Fig. 2-1). It featured a central platform that could be raised to an elevation of 7 virtual meters in an enclosed room (length: 25.02m, height: 19.16m, width: 25.04m). A column of cement blocks, extending from the floor to the ceiling of the room, allowed for a consistent and centrally located visual target with good contrast of vertical and horizontal edges.

2.1.3 Visual stimulus

The visual stimulus was presented as a continuous anteroposterior translation of the virtual environment. Specifically, the perturbation was a pseudorandom, stochastic signal with a frequency range of approximately 0-1Hz and a maximum peak-to-peak (P2P) range of 10cm (Fig. 2-1). Stimulus parameters were specifically selected in order to make comparisons to previous paradigms (Hanssens et al., 2013; Jeka et al., 2006; Mahboobin et al., 2005; Schmuckler, 2017). Each participant was randomly assigned a unique visual stimulus, which was repeated in every trial. The visual stimuli were produced with a custom script in MATLAB, in which two sets of data were each uniquely filtered: 0.25Hz with 1st order Butterworth, and 1.5Hz with a 4th order Butterworth, respectively, and combined with a 2:1 relative weighting. All stimuli were visually confirmed by the researcher to have exponentially decreasing power spectra (Fig. 2-2).

2.1.4 Procedures

Participants stood barefoot on the edge of a force plate (40cm x 60cm; AMTI, USA), with their stance width normalized to their foot length. Foot placement was marked to ensure consistency across trials. Participants were instructed to stand normally with their arms by their sides. Following instrumentation with the HMD, participants were directed to maintain their visual focus on a concrete block at eye-level on the front wall located approximately 12.5m away in the virtual environment. In order to maximize sense of presence in the virtual environment, a familiarization protocol was completed prior to data collection (Cleworth et al., 2012). First, participants were asked with an open-ended question to describe their present surroundings. This was followed by a series of questions requiring participants to complete visual search and identification tasks in the VR environment. The familiarization period was concluded with a one-minute quiet standing trial.

The experimental procedure consisted of four quiet standing trials in the VR environment, each approximately three and a half minutes in duration. The first trial (QUIET) occurred at the ground level with a stable visual scene. The first trial with the visual stimulus was completed at ground level as a practice trial, its purpose being to mitigate potential first trial effects from exposure to the novel experimental paradigm (Adkin & Carpenter, 2019). This practice trial was followed by either another visual perturbation trial at ground level (LOW) or at the virtual elevated surface height (HIGH). The presentation order of the final two trials were randomized between participants to account for known height order effects (Adkin et al., 2000). Participants remained seated while being virtually raised to height. The experience and sensation of being raised to a virtual height was enhanced by audio sounds of a rising hydraulic lift (Cleworth et al., 2012), presented through headphones. Prior to initiation of the HIGH trial, participants were encouraged to look at their elevated visual surroundings and feel the edge of the force plate, which corresponded to the edge of the lift platform in VR.

2.1.5 Measures

Questions assessing participants' emotional state were administered throughout the experiment; (see Appendix A) the text for each question was displayed on the front wall of the virtual environment, before and after each standing trial, and verbal responses were recorded by the experimenter. Ensuring that participants could read the questions in VR served as a means to confirm satisfactory visual acuity. Prior to the start of each trial, participants were prompted to rate their confidence in completing the upcoming trial on a visual analog scale, from 0 to 100, with a larger number indicating greater confidence. After each trial, participants reported perceived fear and stability on a visual analog scale, from 0 to 100, with a larger number indicating greater fear or and stability, respectively. State anxiety was assessed upon the completion of each trial, with a 16-item modified Sport Anxiety Scale, presented on a 9-point Likert scale (Hauck et al., 2008). State questions related to somatic (6 questions) and worry (4 questions) anxiety were summed and averaged to produce the state anxiety score (Johnson et al., 2019). The absence of motion sickness was confirmed throughout the experiment; participants verbally responded to a single "yes/no" question regarding any sensations of motion sickness upon entering the virtual environment and following the completion of each trial. Electrodermal activity (EDA) was recorded as a proxy measure for autonomic arousal (Venables, 1991). Two Ag/AgCl electrodes were placed on the thenar and hypothenar eminences of the left hand to record skin conductance (2502SA, CED, UK), sampled at 1000Hz. EDA was converted into microsiemens, and low pass filtered at 1Hz. Mean EDA was calculated for each participant in every trial.

Postural sway behaviour was obtained with two primary measurements: force plate data and kinematics. Ground reaction forces and moments were recorded from the force plate, sampled at 1000Hz. Centre of pressure (COP) was calculated along the A-P axis and processed with a 2^{nd} order dual-pass Butterworth filter at 3Hz, down-sampled to 100Hz, and DC bias was removed by subtracting the mean position from the entire trial. Full body 3D kinematics were collected from participant's right side, with a single sensor (Optotrak Certus, Northern Digital Inc.) sampled at 100Hz. Kinematic data from a single marker located at the acromion (hereby referred to as KIN), was selected for analysis along the anteroposterior axis. KIN data was also filtered with a 2nd order dual-pass Butterworth filter at 3Hz. Five participants had intermittently missing trunk kinematic data. Two participants were excluded from kinematic analysis due to the volume of absent samples. The remaining three participants' data was spine interpolated; missing data for each participant totalled less than one second and was consecutively missing for no greater than 270ms.

2.1.6 Analysis

In the time domain, VEPRs along the A-P axis were evaluated for COP and KIN data with root mean squared (RMS) and mean power frequency (MPF) calculations. Mean position (MPOS) was also calculated for COP data as the mean position in a given trial, prior to bias removal, and specifies the stance position with respect to the front edge of force platform. RMS and MPF, calculated from the unbiased COP and KIN data, characterize changes in amplitude movement and average frequency content of the power spectra, respectively.

In the frequency domain, the relationship between the visual stimulus and subsequent postural responses was analyzed in terms of the degree of correspondence between the COP and KIN position and the visual stimulus (moving room) position (Fig. 2-2), using signal coherence and frequency response functions (FRFs). Coherence refers to the strength of the signal to noise ratio between an input stimulus and an output response, bound in the frequency domain. It is a unitless measure, ranging from 0, entirely independent, to 1, representing a perfect linear relationship (Halliday et al., 1995; Rosenberg et al., 1989). FRFs, also referred to as transfer functions, describe system dynamics at a given frequency, with regards to response sensitivity (gain) and timing (phase) (Peterka, 2002).

Coherence and FRFs were computed in MATLAB with the freely accessible NeuroSpec 2.0 code, designed for signal processing and statistical evaluation, based on methods from Halliday and colleagues (1995). Estimates of coherence, gain, and phase were evaluated between the visual stimulus position and COP and KIN position, as group means. In accordance with the Neurospec requirement of a power of 2 segment length, each segment was 20.48 seconds long which provided a frequency resolution of 0.048828 Hz. Although 204.80s of data was collected for each trial, representing 10 segments, the first segment (20.48s) of each trial was discarded to ensure that the analysis evaluated the steady state response to the visual stimulus and avoided any initial transient responses (Assländer & Peterka, 2016). Therefore, each participant had 184.32s of data for analysis per trial. COP data was concatenated across participants for a given trial, resulting in 324 joint segments, and approximately 110 minutes of concatenated data. Due to participant exclusion from missing kinematic data (see Measures), 306 joint segments were used for analysis of KIN data; all other parameters remained the same.

Coherence was calculated between the LOW and HIGH conditions. Confidence thresholds for coherent frequencies within each condition were set at 95% and calculated based on the number of non-overlapping segments in the analysis, as described by Halliday and colleagues (1995). Comparison of coherence tests were performed on the LOW and HIGH concatenated coherence data at frequencies with significant coherence in at least one of the conditions.

Gain and phase of the FRFs were estimated for coherent frequencies above the 95% confidence interval (Dakin et al., 2007; Halliday et al., 1995). Pointwise confidence intervals were calculated from the concatenated data in both LOW and HIGH conditions (Halliday et al., 1995). A regression analysis was applied to the phase data to calculate the slope of selected frequencies with significant coherence in both conditions (Dakin et al., 2007; Halliday et al., 1995). The slope was multiplied by $1000/2\pi$ to determine the relative lag, in milliseconds, between the visual stimulus and the evoked sway response (Dakin et al., 2007).

2.1.7 Statistical analysis

Planned comparisons between QUIET and LOW, and LOW and HIGH conditions were performed in SPSS (IBM Corp., N.Y., USA) for behavioural measures: MPOS, RMS, and MPF, and psychological and physiological measures: confidence, anxiety, fear, perceived stability, and EDA. Assumptions of normality were validated with Shapiro-Wilk tests, Q-Q plots, and histograms. Wilcoxon sign-rank tests were completed as necessary. With a Bonferroni correction applied to account for the two comparisons made within each dependent variable, statistical significance was set at an α-level of 0.025.

2.2 Results

2.2.1 Psychological and physiological measures

All psychological and physiological indicators of emotional state were significantly different between LOW and HIGH conditions (Fig. 2-3). Upon completing the trial at virtual height, participants reported significantly increased fear, $Z = -3.438$ $p < 0.001$, and anxiety $Z = -4.537$ $p < 0.001$, while also reporting significantly decreased confidence $Z = -4.848$ $p < 0.001$, and perceived stability $Z = -4.234$ $p < 0.001$ (Table 2-1). Additionally, participants had significantly greater EDA during HIGH (*Mdn* = 22.745) compared to LOW (*Mdn* = 16.465), Z = -4.478 $p < 0.001$ (Table 2-1). In comparison, between QUIET and LOW, balance-related confidence was the only measure that approached a significant difference (QUIET: *Mdn* = 90.0, LOW *Mdn* = 92.5), Z = -2.236 $p = 0.0253$ (Table 2-1; Fig. 2-3).

2.2.2 Behavioural measures

The only statistically significant difference across the behavioural measures was a significant increase in COP MPF during LOW (*Mdn* = 0.209), with the presentation of the visual stimulus, compared to QUIET (*Mdn* = 0.150), Z = -3.503 $p< 0.001$ (Table 2-1; Fig. 2-4).

2.2.3 Evoked postural sway

Significant coherence between the visual stimulus and sway response was observed over a wide range of frequencies, as depicted in Figure 2-5. All significant frequencies evaluated in subsequent results are reported in Table 2-2. When evaluating the COP response across frequencies, consistent significant coherence was not achieved in LOW and HIGH conditions until 0.195Hz and 0.244Hz, respectively. However, beyond these values, significant coherence was observed up to the maximum frequency of interest, 0.977Hz (Fig. 2-5). The strongest coherence between the visual stimulus and COP VEPRs occurred at 0.781Hz for both LOW (r^2=0.090) and HIGH (r^2=0.061) conditions. Despite an overall trend of greater coherence in the LOW condition compared to HIGH, the comparison of coherence test did not demonstrate significant differences between the two conditions (Fig 2-5). Evaluation of KIN data demonstrated greater variability in regions of coherence; significance occurred at LOW between 0.195Hz - 0.39Hz and 0.488Hz - 0.83Hz and at HIGH from 0.342Hz - 0.977Hz. Strongest coherence was achieved in the LOW condition at 0.391Hz (r^2=0.061) and at 0.781Hz (r^2=0.038) for the HIGH condition. Up to approximately 0.6Hz, the LOW condition had visibly stronger coherence than HIGH (Fig. 2-5). This difference was observed with the comparison of coherence test (Fig. 2-5); coherence at 0.195Hz was significantly different between the two conditions, and coherence at 0.244Hz and 0.293Hz were just below the confidence limit.

FRFs were analyzed at the specified frequency points with significant coherence (Table 2-2; Fig. 2-6). There were no significant differences between the gain in LOW and HIGH conditions for either COP or KIN measures (Fig. 2-6). For COP, gains ranged at LOW from 0.042-0.084mm/mm and HIGH from 0.037-0.074mm/mm. For KIN, gains ranged at LOW from 0.018-0.097mm/mm and HIGH from 0.018-0.051mm/mm. A linear regression of the phase was applied at frequencies with significant coherence in both LOW and HIGH conditions. The response time lag between the visual stimulus and COP were approximated to be 365ms at LOW and 348ms at HIGH. Response lags for KIN were estimated as 336ms at LOW and 239ms at HIGH (Fig. 2-6).

Table 2-1 Summary of behavioural, psychological, and physiological measures

N = sample size, * denotes statistically significant comparisons.

	Psychological & Physiological Measures														
	Confidence			Fear			Anxiety			Stability			EDA		
	QUIET	LOW	HIGH	QUIET	LOW	HIGH	QUIET	LOW	HIGH	QUIET	LOW	HIGH	QUIET	LOW	HIGH
N	36.000	36.000	36.000	36.000	36.000	36.000	36.000	36.000	36.000	36.000	36.000	36.000	36.000	36.000	36.000
Mean	87.583	91.389	68.194	7.778	8.611	20.694	1.646	1.578	2.283	88.194	87.861	74.861	17.982	18.101	22.898
Std. Error of Mean	2.524	1.988	3.945	2.036	2.453	4.273	0.122	0.118	0.223	2.072	2.256	3.638	1.563	1.440	1.536
Median	90.000	92.500	72.500	0.000	0.000	10.000	1.350	1.200	1.850	90.000	90.000	80.000	16.141	16.465	22.745
Std. Deviation	15.144	11.929	23.669	12.215	14.717	25.639	0.733	0.709	1.336	12.430	13.538	21.827	9.375	8.640	9.218

	COP								
	RMS			MPF			MPOS		
	QUIET	LOW	HIGH	QUIET	LOW	HIGH	QUIET	LOW	HIGH
N	36.000	36.000	36.000	36.000	36.000	36.000	36.000	36.000	36.000
Mean	5.398	5.707	5.398	0.166	0.213	0.234	38.261	38.096	35.674
Std. Error of Mean	0.290	0.312	0.279	0.009	0.013	0.016	3.091	3.008	2.925
Median	5.055	5.219	5.331	0.159	0.203	0.223	39.530	36.130	36.036
Std. Deviation	1.741	1.872	1.672	0.056	0.078	0.096	18.545	18.050	17.551

	KIN					
	RMS			MPF		
	QUIET	LOW	HIGH	QUIET	LOW	HIGH
N	34.000	34.000	34.000	34.000	34.000	34.000
Mean	7.782	7.789	7.554	0.090	0.101	0.097
Std. Error of Mean	0.484	0.539	0.530	0.004	0.005	0.005
Median	7.191	7.455	6.924	0.090	0.095	0.092
Std. Deviation	2.821	3.144	3.088	0.024	0.031	0.032

	Psychological & Physiological Measures									
	Confidence		Fear		Anxiety		Stability		EDA	
	QUIET-LOW	LOW-HIGH	QUIET-LOW	LOW-HIGH	QUIET-LOW	LOW-HIGH	QUIET-LOW	LOW-HIGH	QUIET-LOW	LOW-HIGH
Z score	-2.236	-4.848	-0.258	-3.438	-1.513	-4.537	-0.072	-4.234	-0.236	-4.478
P value	0.025*	< 0.001*	0.797	0.001*	0.130	< 0.001*	0.943	< 0.001*	0.814	< 0.001*

	COP					
	RMS		MPF		MPOS	
	QUIET-LOW	LOW-HIGH	QUIET-LOW	LOW-HIGH	QUIET-LOW	LOW-HIGH
Z score	-1.288	-0.817	-3.331	-0.691	-0.189	-1.634
P value	0.198	0.414	0.001*	0.489	0.850	0.102

	KIN			
	RMS		MPF	
	QUIET-LOW	LOW-HIGH	QUIET-LOW	LOW-HIGH
Z score	-0.248	-0.402	-1.923	-1.034
P value	0.804	0.688	0.054	0.301

Table 2-2 Summary of frequency analysis

Frequencies with significant coherence are presented in LOW and HIGH conditions for COP and KIN data. Gain and phase values are presented at every frequency with significant coherence.

COP							
LOW				HIGH			
Frequency (Hz)	Coherence	Gain (mm/mm)	Phase (rad)	Frequency (Hz)	Coherence	Gain (mm/mm)	Phase (rad)
0.049	0.013	0.047	0.457	0.049	0.018	0.046	2.475
0.195	0.034	0.055	-0.078	0.244	0.026	0.050	-0.828
0.244	0.049	0.071	-0.699	0.293	0.012	0.030	-0.912
0.293	0.035	0.060	-0.576	0.342	0.019	0.041	-1.092
0.342	0.028	0.053	-1.014	0.391	0.030	0.050	-1.525
0.391	0.052	0.078	-1.523	0.439	0.037	0.049	-1.530
0.439	0.019	0.042	-1.409	0.488	0.045	0.054	-1.766
0.488	0.071	0.078	-1.883	0.537	0.024	0.037	-1.772
0.537	0.040	0.053	-2.277	0.586	0.035	0.046	-2.016
0.586	0.045	0.053	-2.037	0.635	0.030	0.042	-2.109
0.635	0.033	0.047	-2.031	0.684	0.037	0.046	-1.908
0.684	0.036	0.046	-1.930	0.732	0.042	0.050	-2.273
0.732	0.060	0.061	-2.255	0.781	0.061	0.063	-2.023
0.781	0.090	0.084	-2.192	0.830	0.040	0.062	-2.165
0.830	0.049	0.070	-2.317	0.879	0.040	0.071	-2.152
0.879	0.044	0.076	-2.223	0.928	0.040	0.069	-2.580
0.928	0.038	0.078	-2.114	0.977	0.031	0.074	3.057
0.977	0.028	0.075	-2.926				

KIN							
LOW				HIGH			
Frequency (Hz)	Coherence	Gain (mm/mm)	Phase (rad)	Frequency (Hz)	Coherence	Gain (mm/mm)	Phase (rad)
0.195	0.033	0.070	-0.048	0.049	0.022	0.084	2.552
0.244	0.055	0.097	-0.669	0.244	0.018	0.051	-0.663
0.293	0.032	0.067	-0.304	0.342	0.025	0.050	-0.773
0.342	0.019	0.045	-0.621	0.391	0.024	0.043	-1.359
0.391	0.061	0.085	-1.408	0.439	0.032	0.039	-1.434
0.488	0.052	0.055	-1.660	0.488	0.030	0.035	-1.703
0.537	0.027	0.033	-1.765	0.537	0.017	0.023	-1.607
0.586	0.030	0.032	-1.716	0.586	0.026	0.027	-1.622
0.635	0.010	0.018	-1.761	0.635	0.013	0.018	-2.032
0.684	0.021	0.023	-1.812	0.684	0.015	0.019	-1.588
0.732	0.023	0.023	-1.689	0.732	0.027	0.023	-2.018
0.781	0.039	0.033	-1.578	0.781	0.039	0.028	-1.556
0.830	0.011	0.019	-2.188	0.830	0.013	0.019	-1.297
				0.879	0.033	0.034	-1.745
				0.928	0.024	0.028	-1.449
				0.977	0.016	0.030	-2.303

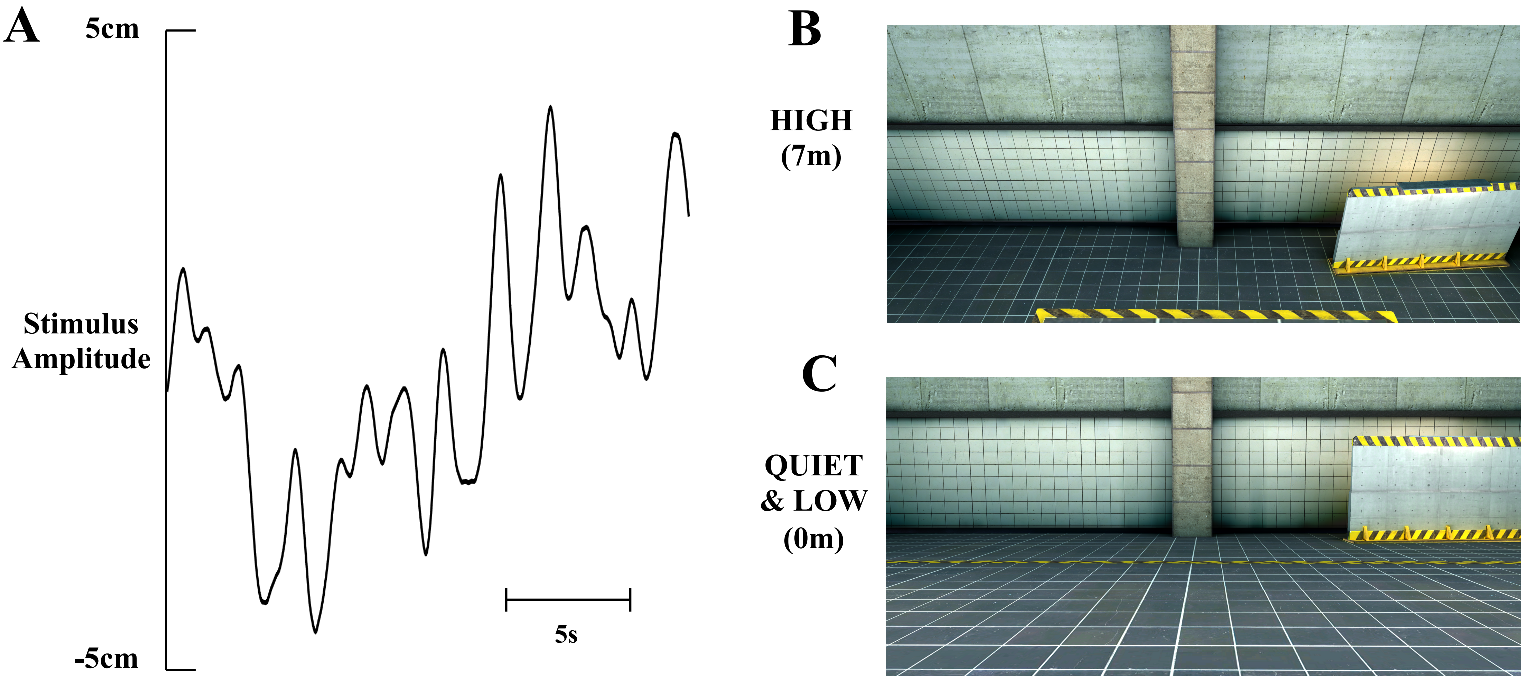

Figure 2-1 Experimental design

(A) 20 second segment of the visual stimulus. Participant view in VR when **(B)** elevated at height and **(C)** at ground level.

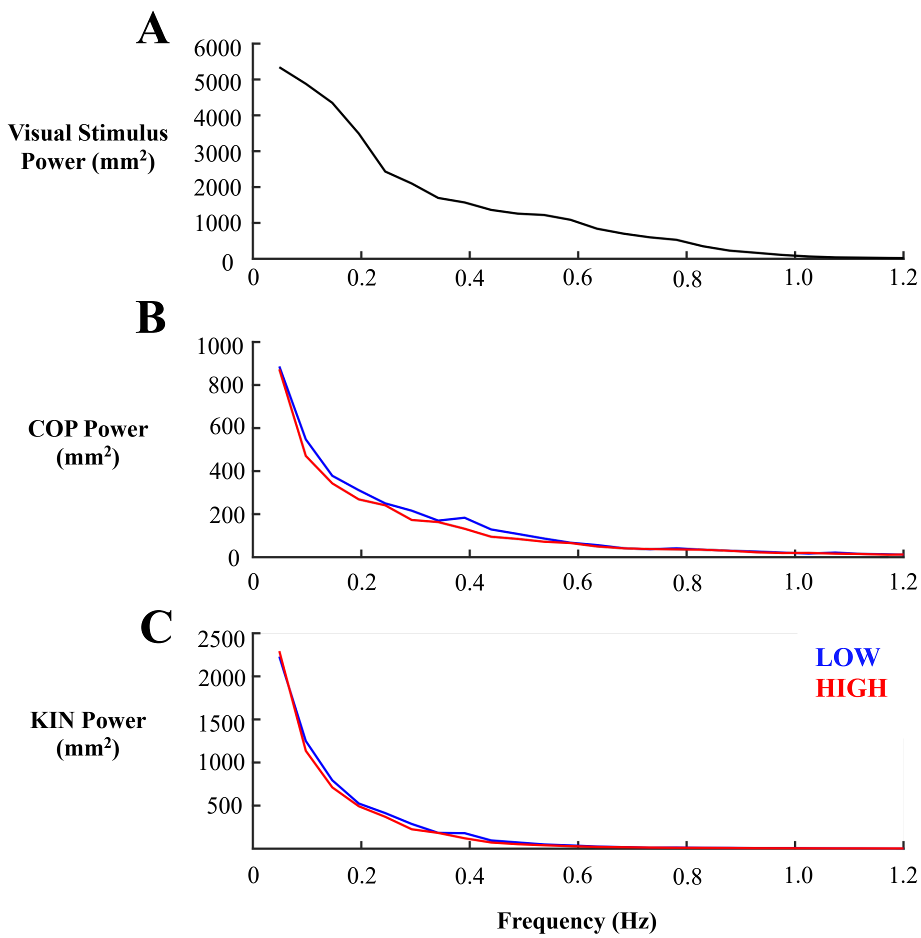

Figure 2-2 Power spectra of (A) visual stimulus (B) COP and (C) KIN

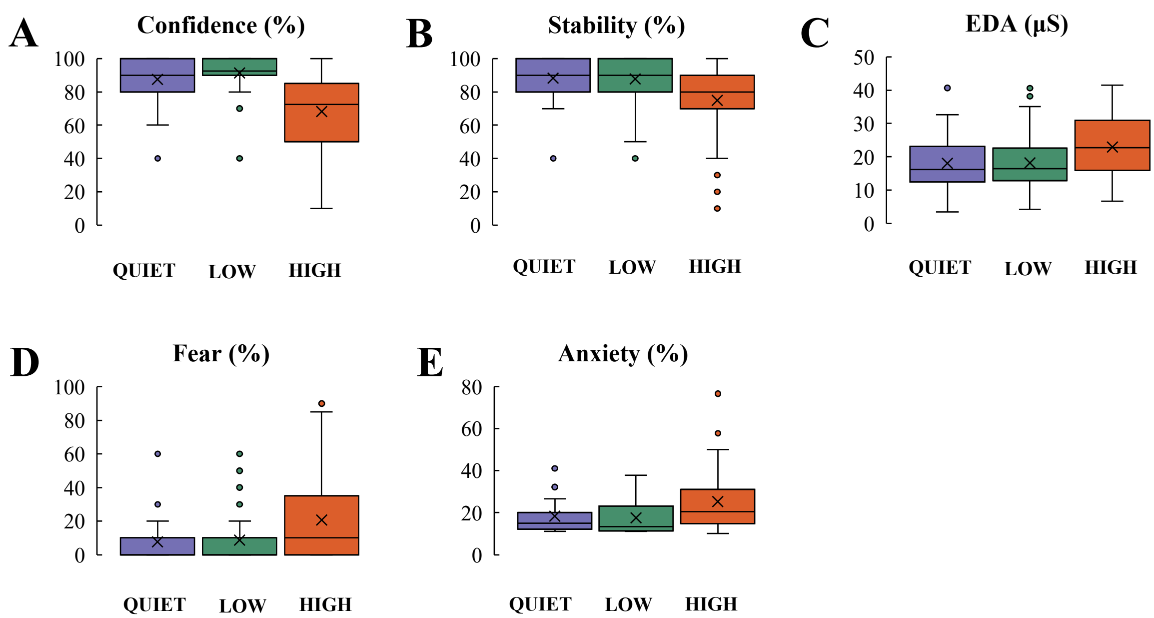

Figure 2-3 Psychological and physiological measures

Boxplots presented across the experimental conditions. Measurements are expressed as a percentage of the maximum potential score, except for EDA. Within a given boxplot, the X represents the mean and the central line indicates median. Markers located beyond the boxplot whiskers represent data outliers.

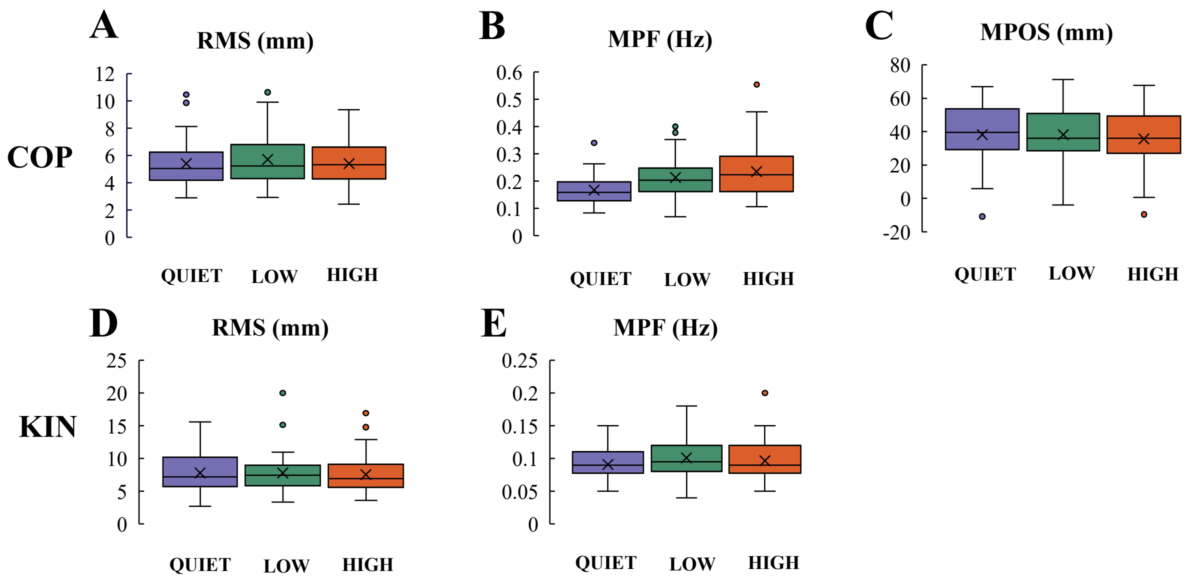

Figure 2-4 Behavioural measures of sway

Sway behaviour plotted for COP and KIN data across experimental conditions with boxplots. Within a given boxplot, the X represents the mean and the central line indicates median. Markers located beyond the boxplot whiskers represent data outliers. For reference, a more positive MPOS value indicates that stance position is closer to the front edge of the force platform.

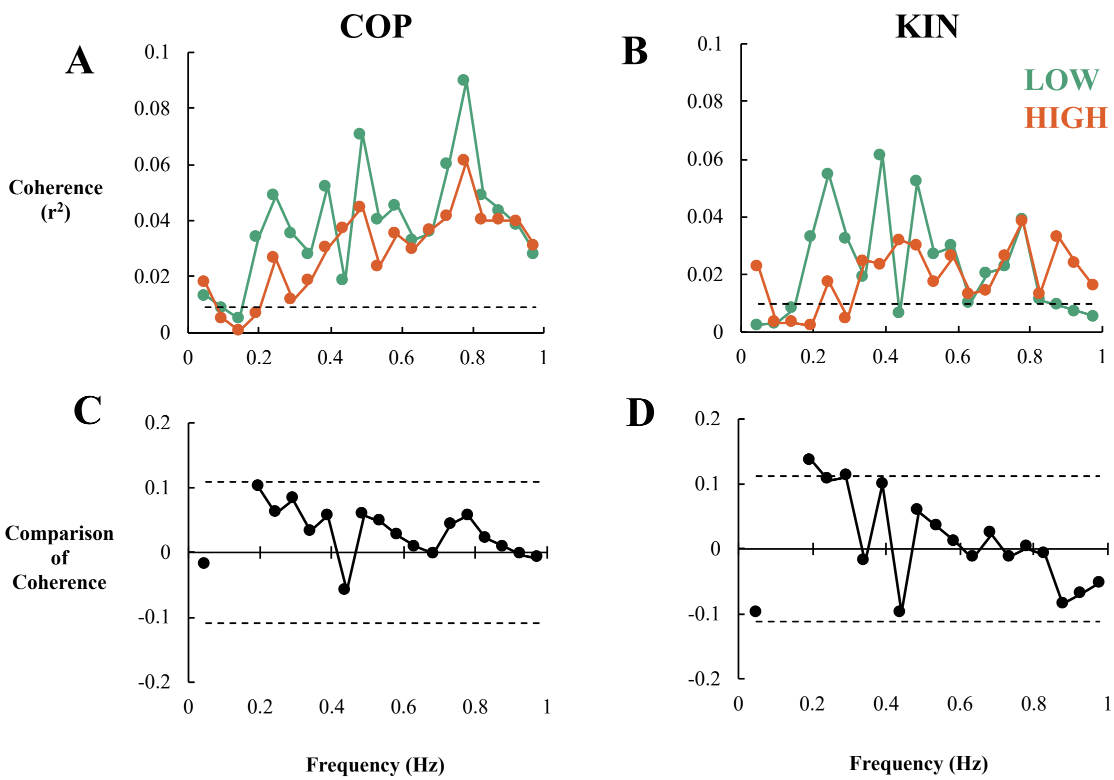

Figure 2-5 Coherence estimates and comparisons

Coherence estimates for **(A)** COP and **(B)** KIN data are presented, as well as comparison of coherence tests for **(C)** COP and **(D)** KIN. Comparisons were completed at frequencies in which at least one condition had significant coherence. Dotted lines indicate boundaries of 95% confidence intervals.

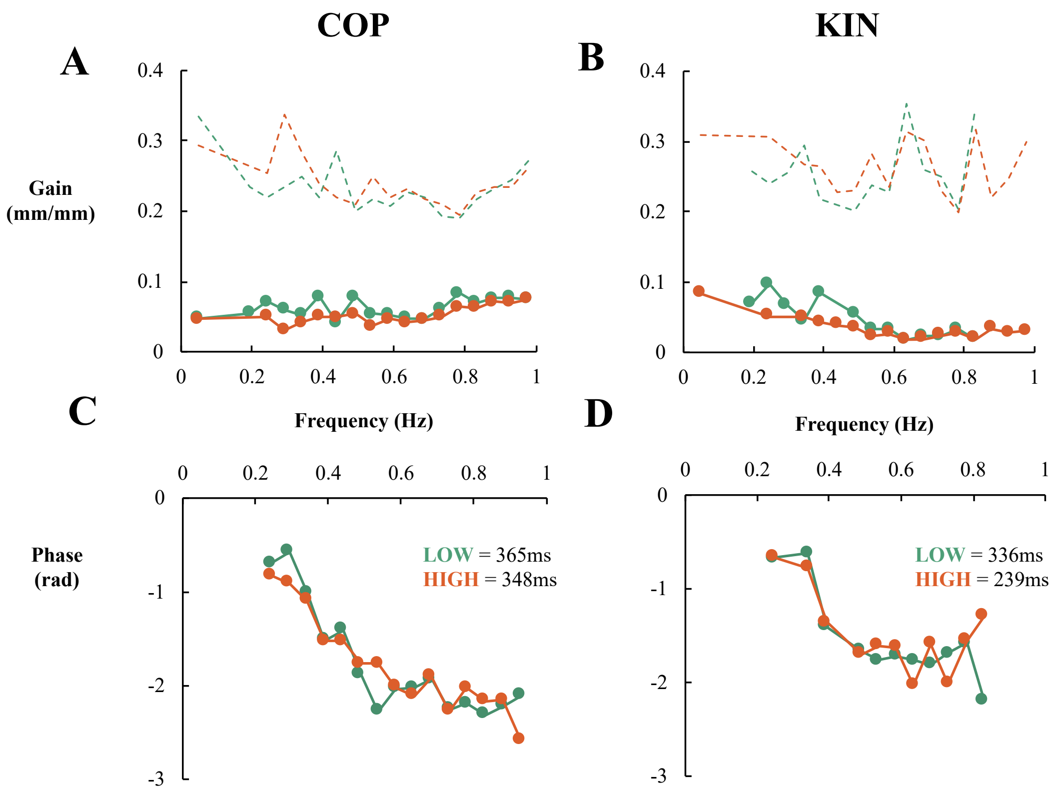

Figure 2-6 Frequency response functions

Gain values are presented for **(A)** COP and **(B)** KIN for frequencies with significant coherence. Upper confidence boundaries are indicated with dotted lines, lower confidence boundaries are not shown as they were less than zero. Phase analysis is presented for **(C)** COP and **(D)** KIN for frequencies with significant coherence in both conditions.

Chapter 3: Study 2 – A methodological comparison of real and virtual visually evoked postural responses and the role of aging

3.1 Preamble

Study 1 provided evidence that a VR HMD could successfully elicit VEPRs in healthy YAs. However, a number of questions arose regarding the nature of these postural responses, namely, the extent to which they were due to the specific context of the HMD and VR environment, how they would differ compare to those produced in the real world, and how they were influenced by age. Therefore, in Study 2 we developed identical experimental paradigms to evaluate VEPRs across real and virtual environments and examine the role of aging. The goal was to ultimately keep as many variables consistent across the two environments including the visual stimuli, the structure of the experimental paradigms, the availability of peripheral vision, and the presence of auditory information. Further, the visual stimulus and analysis techniques selected by the authors in Study 2 were guided by previous research that had successfully evaluated VEPRs in the real world (Assländer & Peterka, 2014; Peterka, 2002). These considerations facilitated a rigorous methodological comparison across environments in order to establish whether the visual control of balance differs between the real world and VR.

3.2 Methods

3.2.1 Participants

Six healthy adults were recruited for participation in this study[1]. Half of the group, three participants, were YAs, between the ages of 18 and 35 (mean age (±SD): 22.33 (±1.53) years, 2

[1] Experiment data collection was terminated shortly after initiation due to restrictions related to the COVID-19 pandemic.

females). The other three participants were OAs, at least 65 years of age or older (mean age (±SD): 71.67 (±4.93) years, 1 female). Participants were recruited from the University of British Columbia (UBC) Vancouver campus. Inclusion criteria for participation specified that all individuals spoke English, were able to provide informed consent, and had normal or corrected to normal vision (with the use of contact lenses or glasses). Individuals were ineligible to participate in the study if they had a self-reported history of neurological or musculoskeletal conditions that are known to affect walking or balance, if they used a hearing aid, or if they were unable to remain standing, unsupported, for three minutes. OA participants had their cognitive function evaluated with the Standardized Mini-Mental State Exam (SMMSE) by a member of the research team and had to receive a score of 24 or greater in order to participate (see Appendix B) (Davey & Jamieson, 2004; Molloy et al., 1991). All individuals provided informed consent prior to study involvement. Experimental procedures were approved by the UBC Behavioural Research Ethics Board.

3.2.2 Experimental set-up

All experimental procedures were conducted inside of an apparatus referred to, hereafter, as the "moving room". The evaluation of visual perturbations on postural control was achieved with physical perturbations of the moving room while participants remained in quiet stance. Postural responses in the real moving room were compared to a second iteration of the experimental protocol completed in an identical, virtual moving room, developed and presented in a VR HMD system (Fig. 3-1).

3.2.2.1 Real moving room

The real moving room was a 4'9"x 8" steel framed room (80/20 Inc, Illinois), enclosed with sheets of corrugated plastic on three of the four sides (Fig. 3-1). Consistent luminance of the room's interior was maintained with ambient lighting provided from LEDs attached to the ceiling of the moving room. The interior of the room had a black, grey, and white plaid pattern of evenly spaced squares (12in x 12in). This particular pattern had two primary advantages. First, including grey in the pattern minimized visual illusions that can otherwise occur in virtual environments with highly contrasting stimuli. In our VR pilot work, the use of a moving room with a black and white interior, with very high contrast luminance, led to reports of various optical illusions and overall visual discomfort. Second, the structured pattern of vertical and horizontal lines provided sufficient cues for perception of both the visual surfaces and visual cues relevant to motion (Diener et al., 1976; Gibson, 1950; Lestienne et al., 1977). Although it is likely that varying the spatial frequency of the room's interior would have provided an even stronger visual stimulus and more information regarding the visual environment (Assländer & Peterka, 2014; Diener et al., 1976), our pilot work suggested that it was not necessary in order to elicit a strong VEPR, and our structured pattern was easier to replicate in both the real and VR environments.

The moving room was mounted on a pair of frictionless rails that allowed it to easily glide forwards and backwards via a uniaxial rotating motor. The selected motor had a 7° P2P amplitude and thus could drive the room approximately 6cm horizontally along a single axis (approximately 1cm/°), with a maximum velocity of 200°/s. Fluctuations of the room's walls due to rapid accelerations of the motor were minimized with horizontal stabilizing bars.

3.2.2.2 Virtual reality environment

The moving room was also presented to participants in VR as an exact replica, entirely to scale. The virtual moving room was developed with Blender (BlenderVR, France) and placed in a virtual laboratory space in Vizard (WorldViz, California) that closely resembled the real laboratory (Fig. 3-1). The virtual environment was displayed in a VIVE PRO HMD system (HTC, Taiwan) which operated via SteamVR (Valve Corporation, Washington). The VIVE provided users with a 110° diagonal FOV with 1440x1600 resolution per eye. The screen, comprised of active matrix organic light emitting diodes, had a refresh rate of 90Hz. Adjustments could be easily made to both the screen distance and the interpupillary distance within the HMD. Most importantly, the ergonomic design of the VIVE accommodated individuals who wore glasses, unlike many other HMDs; an important feature particularly when working with an OA population. The VIVE device had two Lighthouse base stations which were mounted to the top of the real moving room so that the entire experimental protocol could be completed in the same location for real and virtual conditions. Commands to manipulate the movement of the virtual moving room were created externally in MATLAB (Mathworks, USA) and digitally uploaded prior to data collection, sampled at 1000Hz (Power 1401 with Spike2 software, Cambridge Electronic Designs, UK). During an experimental trial, stimuli were outputted to Vizard via a digital interface (Labjack, Colorado, USA).

3.2.3 Control of auditory input

It is well documented that auditory stimuli can be used to enhance visual signaling of self-motion (Rieke et al., 2005). Specifically, they may provide cues that enable discrimination between egocentric and exocentric motion (Väljamäe et al., 2008). Consequentially, when solely examining the influence of visual stimuli, researchers aim to minimize the influence of auditory cues through either the presentation of irrelevant or distracting auditory stimuli (Peterka, 2002). During experimental trials in the present study, participants listened to pink-white noise (20-10000Hz) via SONY WISP600N wireless headphones (Sony Corporation, Japan). The audio stimulus was produced in Noise Generator: a publicly accessible phone application. Participants self-selected the lowest volume of noise with which they were unable to hear external voices. Communication during trials was kept to a minimum in order to maintain sense of presence in the virtual environment and avoid distraction. Participants were not told when a given trial had specifically begun or was completed, rather, they were simply instructed to follow the experimental protocol for the duration of the auditory stimulus.

3.2.4 Visual stimuli

In order to examine how visual perturbations influenced standing balance control, visual stimuli were presented along the A-P axis to induce linear vection. The visual system is much more sensitive to A-P stimuli, compared to mediolateral stimuli, during standing balance control, while the opposite has been observed during gait (O'Connor & Kuo, 2009).

The visual perturbations used in this study were continuous translations: oscillating back and forth along the A-P axis for three minutes, in a given trial (Fig. 3-2). The stimulus used was similar to that of previous research, referred to as a pseudorandom ternary sequence (PRTS) stimulus (Assländer & Peterka, 2014; 2016; Davies, 1970; Peterka, 2002). The stimulus was developed in MATLAB as an 80 step PRTS, with a step duration of 375ms and a cycle length of 30s (Fig. 3-2). The selected stimulus had power between 0.0334 – 2.5Hz at every other harmonic value and was filtered with a 2nd order Butterworth low pass filter at 2.5Hz. The PRTS stimulus was presented at two different P2P amplitudes: 3cm and 6cm. Two amplitudes and two room environments produced a total four experimental conditions: 3cm real, 6cm real, 3cm virtual, and 6cm virtual. Each experimental condition was repeated twice, resulting in a total of eight perturbation trials in the protocol. There was six PRTS cycles in a given trial (3-minute trial, and 30s period), therefore there were 12 PRTS cycles per participant in each experimental condition.

The order of trial amplitude was randomized for each participant, however all trials in a given environment were completed as a block, i.e. all virtual and then all real, or vice versa.

The use of a 3-minute trial length allowed for satisfactory frequency resolution (0.0334Hz) while ensuring that there were enough cycles for signal averaging during data analysis. Additionally, the 3-minute trial length enabled participants to maintain focus on the task without concern for undue fatigue. Previous research suggests that participants do not adapt or habituate to PRTS stimuli, which therefore allows for the examination of visually evoked sway as a steady state response (Assländer & Peterka, 2014; Peterka, 2002), and trials within a block can be concatenated. Breaks were provided in between trials, during which participants once again had reliable visual information; this likely supported the reintegration of vision as a valid source of sensory information (Assländer & Peterka, 2016).

To ensure that the size of participants' peripheral FOV was consistent between the real and virtual environments, participants wore a pair of goggles that limited FOV in the real world to 110° diagonally, the same degree as with the HTC VIVE HMD (Fig. 3-3). Participants wore the goggles for all conditions in the real moving room and only removed them when the VR HMD was required instead.

3.2.5 Procedures

A summary of the experimental protocol is provided in Figure 3-4. During the experiment, participants stood on a force plate mounted equal distance from the lateral walls of the moving room. The force plate was positioned three feet from the front wall of the moving room in order to maximize the density of peripheral visual information and thus facilitate linear vection (Berthoz et al., 1975). Given the spatial constraints of the moving room, it is highly unlikely that differences in stance location relative to the front wall of the moving room would have influenced balance responses (Dijkstra et al., 1992). Stance width was normalized to participants' hip width and kept constant with tape markings on the force plate. Foot placement in the A-P direction was kept constant using a small wooden edge that aligned the force plate with the participants' heels. A chair was positioned behind participants at all times during the experiment and a spotter was present to assist in the event of a major balance disturbance. Note that no participant lost their balance at any time during any of the trials or conditions.

Prior to all experimental conditions, participants completed a 2-minute standing calibration trial on the force plate in order to calculate center of mass (COM) (Assländer & Peterka, 2014; Peterka, 2002). Participants stood with their arms crossed at chest level, looking straight ahead, while the researcher verbally guided them to very slowly explore the boundaries of their standing balance along the A-P axis by creating a variety of angular combinations of the hip and ankle joints (e.g. dorsiflexion at the ankle joint until the participant reached their perceived stable limit, followed by hip flexion) (Assländer & Peterka, 2014; Peterka, 2002).

The presentation order of room environments (i.e. real and virtual) was randomized for each participant. Questionnaires assessing motion sickness and virtual presence were read aloud to the participants by an experimenter, and participants provided a verbal response to each question which was then recorded by the experimenter. Questionnaires are provided in Appendix B.

If a participant began the experiment in the real moving room, they first completed two, 2-minute quiet stance trials, one with their eyes open, and another with their eyes closed. For all standing trials, participants were asked to maintain their visual focus on one of the square blocks located at approximately eye level. They were instructed to stand as "normally as possible" with their arms crossed in front of their chest. After the quiet stance trials, participants completed the

Simulator Sickness Questionnaire (SSQ). Participants then experienced 4, 3-minute continuous perturbation trials, with the order of amplitude conditions randomized (Fig. 3-4). Following each 3-minute trial, participants were seated for a mandatory 2-minute break and completed the SSQ.

Prior to the VR perturbations, participants were fitted to the VR HMD, and completed a familiarization protocol in order to maximize immersion and sense of presence (Cleworth et al., 2012). The familiarization period was no less than two minutes and involved various visual search and identification tasks within the virtual moving room. Participants were asked to provide a description of the interior wall surfaces, the virtual motor, the lab space, and the floor. Additionally, participants were asked to verbally estimate the depth of the room. VR is widely known to compress stereoscopic depth cues in egocentric vision, although technological improvements have reduced some of this underestimation error (Mahrun et al., 2019; Wann et al., 1995).

Once adequately familiarized with the VR environment, participants completed a modified version of the Slater, Usoh, Steed Questionnaire (SUS-Q) to evaluate their sense of presence in the virtual environment (Slater et al., 1994), in addition to the SSQ. Questionnaires were read aloud to the participants while in the virtual moving room, and participants indicated their responses verbally. Participants then stood up, were guided verbally to the appropriate foot position and complete a 2-minute, eyes open, quiet stance trial in the VR environment.

Following a mandatory two-minute break, participants completed the same 4, 3-minute continuous perturbation trials in VR. As in the real moving room, the order of amplitude conditions presented was randomized. Following each trial, participants had a mandatory 2-minute seated break and completed the SSQ. After completing all virtual trials, the study was concluded with another iteration of the SUS-Q in VR. Participants were allowed to take off the

HMD for a break at any time during the VR portion of the experiment, however, the familiarization protocol was then repeated following re-entry into VR.

3.2.6 Measures

3.2.6.1 Sway behaviour

Sway behaviour and its control were measured with kinematic and force plate data. Ground reaction forces and moments were recorded from a single force plate (40cm x 60 cm; AMTI, USA), sampled at 100Hz. COP was calculated along the A-P axis. The signal was debiased by removing the mean and filtered with a second order dual-pass Butterworth filter at 3Hz. Kinematic data was collected from each participant throughout each trial with a single camera bank (Optotrak Certus, Northern Digital Inc.) at 100Hz. Single kinematic markers were placed at C7 (shoulders), and at level of the sacroiliac joint (hips). Another marker was placed on the real moving room to monitor the displacement of actual room motion. Kinematic data was also debiased and filtered with a second order dual-pass Butterworth filter at 3Hz. Any missing kinematic data was inspected on a case-by-case basis for inclusion. If the length of missing data was shorter than 100ms consecutively, it was filled with a spline interpolation function. Parameters for COM calculations were obtained during the calibration trial from a regression analysis between COP displacements and a linear combination of hip and shoulder kinematic displacements (Assländer & Peterka, 2016). This calculation was possible due to the very slow nature of the calibration trial in which A-P COP approximated COM, except during small A-P body accelerations (Brenière. 1996; Peterka, 2002; Winter, 1998). COM was then calculated for each trial with trial-specific shoulder and hip kinematic data and regression coefficients.

Linear position of COM and COP along the A-P axis were the final variables of assessment. These variables were compared to the linear position of the moving room along the A-P axis. The real moving room position was recorded from the kinematic marker on the frame and the virtual moving room position was obtained from the output of the HMD device, as recorded by Vizard with the lab interface (Labjack, Colorado, USA).

3.2.6.2 Motion sickness

Motion sickness was probed throughout the study with the SSQ. Although the questionnaire was initially developed for pilots working in flight simulators, it has high external validity for use in VR research (Kennedy et al., 1993). The 16-item questionnaire assesses user symptoms in the domains of nausea, oculomotion, and disorientation (Kennedy et al., 1993). The presence of each system is reported as none, slight, moderate, or severe, which corresponds to a score between 0 and 3 (none – 0, severe – 3). Scores were then summed for a subtotal in each domain, as well as an overall total. Testing would have been terminated in this study if the SSQ total score had ever reached a score greater than 30 (out of a potential 48 points), which it did not.

3.2.6.3 Sense of presence

Virtual presence was assessed in this study with a modified version of the SUS-Q presence questionnaire, which evaluated one's "sense of being there" with 6 questions presented on a 7-point Likert scale (Slater et al., 1994). The presence score was calculated as the average response to all questions. The questions were been modified such that presence could be assessed while participants were in the virtual environment, rather than completed retrospectively (see Appendix B).

3.2.7 Analysis

3.2.7.1 Body sway

Spontaneous and evoked sway were quantified in terms of measures of mean power frequency (MPF) and root mean squared (RMS) of COP and COM. Mean position (MPOS) of COP, denoting stance position from the front edge of the force plate, was also obtained prior to bias removal from the COP signal. MPF and RMS were both calculated from the unbiased signal, and describe the average frequency of the power spectrum, and changes in amplitude, respectively.

3.2.7.2 Frequency domain analysis

Signal fidelity between the visual stimulus (moving room position) and subsequent VEPRs, from both COP and COM, was evaluated through concurrent analysis of coherence and FRFs.

For the purposes of selecting the frequency range for analysis, the power spectra of each response were plotted across all participants in a given condition. Integration allowed for the definition of the frequency threshold of 95% power in which consideration for analysis was made, with a potential maximum of 2.5Hz, as defined by the frequency limit of the input stimulus.

FRFs, describing the system dynamics between the input stimulus and output response, provide an indication of response sensitivity (gain) and timing (phase), across a given frequency range (Peterka, 2002). Coherence refers to the strength of coupling between two signals, bound in the frequency domain. Values of coherence range from 0, entirely independent, to 1, a perfect linear relationship (Halliday et al., 1995; Rosenberg et al., 1989).

Coherence, gain, and phase were computed with custom scripts in MATLAB (Assländer & Perterka 2014; 2016; Peterka, 2002). The 30s PRTS stimulus was averaged across participants within each age group, amplitude, and room condition. In order to avoid the potential confound of transient system responses to the initial onset of the visual stimulus, the first 30s PRTS cycle was dropped from each trial (Assländer & Peterka, 2016). Analysis in the frequency domain was completed with a discrete Fourier transform (DFT) appropriate for stimuli of a periodic function (Assländer & Peterka, 2014; Pintelon & Schoukens, 2001). Coherence was calculated from the ratio of the cross-spectra, normalized by the square root of the power spectra of the two signals (Halliday et al., 1995).

FRFs were then calculated as the ratio of complex DFT components between COM (and COP) responses and the PRTS stimulus at every frequency with energy (Assländer & Peterka, 2014). Gain and phase values at each frequency were obtained from the FRFs as the absolute value and the angle of the mean complex vector, respectively (Assländer & Peterka, 2014). Assuming a linear system, the slope of the phase (in radians) was multiplied by $1000/2\pi$ to estimate the response lag between a particular range of significant coherent frequencies (Dakin et al., 2009). Phase estimates describe the angle of the complex frequency responses, therefore gains of small magnitudes can result in large variability in the phase (Halliday et al., 1995). To ensure that the linear regression analysis accurately estimated the time lag, standardized criteria were developed for frequency omission, such that, a phase value was omitted from the regression analysis if it caused a major inflection from the previous phase value, and if the gain at that particular frequency was less than 0.10mm/mm.

Due to the small sample size, confidence bounds, set at 95%, were obtained with bootstrapping methods (Zoubir & Boashash, 1998). Using the "bootstrp" function in MATLAB, existing coherence and gain datasets was separately re-sampled 400 times to obtain a more accurate estimate of population variance (Zoubir & Boashash, 1998). Therefore, significant differences in coherence and gain between conditions were identified by the non-overlapping regions between sets of bootstrapped confidence bounds.

3.3 Results

Due to the exceptional circumstances regarding the participant sample[1], results were primarily based off of descriptive statistics, particularly mean and standard deviation (SD), for the purposes of this thesis.

Participants tolerated the real and virtual moving room environments well, with and without the visual stimuli. No experiments were terminated due to motion sickness; the greatest score on the SSQ for any given trial was 11.

3.3.1 Sway during quiet stance

A summary of all data pertaining to sway behaviour across the quiet stance conditions is provided in Table 3-1. Across all experimental conditions, YA group average MPF was lower than OA group average MPF for COP and COM measures (Fig. 3-5). The eyes closed condition produced the largest group average MPF for all OAs, compared to the other two eyes open conditions. This finding was not observed in YAs (Table 3-1). Group average RMS was the largest in the eyes closed condition for the YAs, but not for the OAs (Table 3-1). There were no observable differences in RMS across the eyes open conditions between the two age groups (Fig. 3-5). MPOS data indicated that on average, OAs' A-P COP tended to be closer to the front of the force platforms than that of the YAs (Table 3-1, Fig. 3-5).

3.3.2 Sense of virtual presence

Assessments of virtual presence at the beginning of the VR portion of the experiment demonstrated that on average YAs reported lower virtual presence than OAs (YAs: 4.028 (±0.268), OAs: 5.833 (±0.927)) (Fig. 3-6). For each age group, average presence was not substantially different at the end of the VR component of the experiment. Additionally, at this time point, the level of reported virtual presence did not differ between the two age groups ((YAs: 4.306 (±1.088), OAs: 5.556 (±1.084)) (Fig. 3-6).

3.3.3 Visually evoked sway

Due to a technical production error, the stimuli presented in the virtual moving room were 10% larger in amplitude than those presented in the real moving room. This discrepancy may be partially reconciled by the fact that the difference was consistent across all participants and all experimental conditions, such that the 3cm and 6cm P2P stimuli in VR were always 3.3cm and 6.6cm P2P, respectively. Depending on the stimulus amplitude, this equated to a 1.5mm or 3mm increase of room movement in a single direction; likely an imperceptible difference. That said, this discrepancy has been taken into consideration when interpreting results, particularly for environment comparisons in the time domain.

Upon averaging across cycles, evoked sway for COM was demonstrated to varying degrees for all experimental conditions (Fig. 3-7). Response traces most visibly aligned with the stimulus in the 3cm real condition in YAs. Although averaged YA evoked sway for COM did not appear to closely follow the general position of the visual stimulus, corresponding changes in the directionality of the response were observed (Fig. 3-7). The evoked sway COM traces were more challenging to discern in OAs, who demonstrated greater sway variability, however general trends of correspondence were still observed (Fig. 3-7). Evoked sway patterns were generally less clear for averaged COP traces (Fig. 3-8), again particularly for OAs.

A summary of sway behaviour, in terms of MPF and RMS for both COM and COP, is presented in Table 3-2. MPF, for both evoked COM and COP sway, was larger for OAs than YAs, across experimental conditions (Fig. 3-9). There were no discernable trends between age groups or experimental conditions for RMS (Table 3-2; Fig. 3-9).

3.3.4 Frequency response analysis

Frequency thresholds for analysis were set at 1Hz for COM and 1.5Hz for COP given that 95% of the power fell below these ranges for all participants (Figs. 3-10, 3-11).

As shown in Figure 3-12, coherence between the visual stimulus and COM VEPRs was demonstrated for both YAs and OAs. Both age groups achieved maximum coherence strength at 0.3667 Hz (YAs: $r^2 = 0.223$, OAs: $r^2 = 0.299$) but trends suggest that OAs generally had stronger coherence across the frequency range of interest (Fig. 3-12). Gains ranged between 0.077mm/mm (at 0.833Hz) and 0.586mm/mm (at 0.7667Hz) for YAs and between 0.07mm/mm (at 0.3Hz) and 0.828mm/mm (at 0.7667Hz) for OAs. Similar to coherence, confidence bounds did not indicate significant differences between the two age groups, although on average OAs tended to have larger gains (Fig. 3-12).

Similar values of coherence and gain were observed when the 3cm stimulus was presented in the virtual moving room. OAs generally had stronger coherence and greater gains than YAs, although no significant differences were identified with the confidence bounds (Fig. 3-12).

Frequency analysis of COP VEPRs demonstrated similar coherence for both age groups; general trends suggest that OAs had stronger coherence than YAs in the virtual condition (Fig. 3-

13). Across real and virtual conditions, large gains were demonstrated (Fig. 3-13). OAs tended to have larger gains than YAs at higher frequencies; confidence bounds indicated significant differences at 1.233Hz and 1.3Hz in the virtual environment (Fig. 3-13).

Phase analysis is presented in Figures 3-16, 3-17, 3-18. The time lags between the stimuli and COM VEPRs in the 3cm real condition were approximated at 667ms for YAs and 611ms for OAs. Interestingly, time lags for COP VEPRs were longer for both age groups in the real moving room (Fig. 3-18). For YAs, lag times in the 3cm virtual moving room condition were shorter in both COM (630ms) and COP (611ms), compared to the real moving room. In virtual reality, OAs also had a shorter lag time for COP (577ms) but a slightly increased lag time for COM (639ms).

3.3.5 Young adult amplitude comparisons

When presented with the visual stimulus in the real world, YAs demonstrated trends of stronger coherence to the 3cm amplitude than the 6cm amplitude for COM VEPRs (Fig. 3-14). Larger gains were observed for the 3cm stimulus in the real moving room, with significance indicated by confidence bounds at 0.5Hz and 0.7667Hz (Fig. 3-14). In VR, there was no evidence of any differences in COM VEPRs between the 3cm and 6cm stimuli, for both coherence and gain (Fig. 3-14).

COP results demonstrated similar findings, with no significant differences in coherence between 3cm and 6cm stimulus amplitudes in both environments (Fig. 3-15). Gains for the 3cm stimulus was indicated by confidence bounds to be significantly larger than the 6cm stimulus in the real moving at 0.5Hz, 0.7667Hz, 1.1667Hz, and 1.3667 Hz. In the virtual environment, gain values were larger at 0.7 Hz and 1.233Hz, for the 3cm condition, than the 6cm condition (Fig. 3-15).

Phase analysis for YAs revealed shorter time lags in the 6cm stimulus compared to the 3cm stimulus, in both the real and virtual environments (real 3cm: 667ms, real 6cm: 561; virtual 3cm: 630ms, virtual 6cm: 592ms) (Figs. 3-16, 3-18). This trend was also demonstrated for COP data (real 3cm: 811ms, real 6cm: 576; virtual 3cm: 639, virtual 6cm: 541ms) (Figs. 3-17, 3-18).

3.3.6 Older adult amplitude comparisons

Coherence values were strong in both real and virtual environments, however, there were no discernable trends between the two amplitude conditions, in both COM and COP (Figs. 3-14, 3-15). For COM in the real moving room, comparisons of gain were pronounced between the two stimulus amplitudes; confidence bounds demonstrated significant differences in gain for the 3cm amplitude at 0.3667Hz, 4.337Hz, 0.633Hz, 0.7667Hz, 0.833Hz, and 0.9667Hz (Fig. 3-14). In the virtual moving room, the confidence bounds for the 3cm amplitude demonstrated a significantly greater gain at 0.667Hz and 0.7Hz (Fig. 3-14). Gains for COP VEPRs demonstrated similar trends with increased gain for the 3cm, compared to the 6cm stimulus; confidence bounds indicated significant differences at 0.633Hz in the real environment and at 0.7Hz in the virtual environment (Fig. 3-15). In both environments, OAs demonstrated a decreased time lag with the 6cm stimulus. This was consistent across measures of both COM (real 3cm: 611ms, real 6cm: 576; virtual 3cm: 639ms, virtual 6cm: 500ms) and COP (real 3cm: 863ms, real 6cm: 721ms; virtual 3cm: 577ms, virtual 6cm: 471ms) (Fig. 3-16, 3-17, 3-18).

Table 3-1 Behavioural measures of sway during quiet stance conditions

YA – young adult, OA – older adult, St.Dev – standard deviation.

	COP								
	RMS (mm)			MPF (Hz)			MPOS (mm)		
	Real, Eyes Open	Virtual, Eyes Open	Real, Eyes Closed	Real, Eyes Open	Virtual, Eyes Open	Real, Eyes Closed	Real, Eyes Open	Virtual, Eyes Open	Real, Eyes Closed
YA1	5.352	5.693	8.340	0.093	0.136	0.068	-62.863	-56.566	-62.060
YA2	5.205	5.454	8.794	0.219	0.205	0.167	-58.836	-42.532	-55.101
YA3	2.492	1.764	3.373	0.175	0.151	0.176	-64.833	-58.468	-64.584
YA Mean	**4.350**	**4.304**	**6.836**	**0.162**	**0.164**	**0.137**	**-62.177**	**-52.522**	**-60.582**
YA St.Dev	1.611	2.202	3.007	0.064	0.036	0.060	3.057	8.703	4.911
OA1	4.264	3.419	5.833	0.385	0.410	0.620	-39.177	-40.157	-42.064
OA2	3.910	5.127	4.264	0.542	0.209	0.730	-41.901	-46.950	-41.083
OA3	7.179	4.969	5.984	0.171	0.271	0.411	-53.767	-46.964	-35.348
OA Mean	**5.118**	**4.505**	**5.360**	**0.366**	**0.297**	**0.587**	**-44.948**	**-44.691**	**-39.498**
OA St.Dev	1.794	0.944	0.953	0.186	0.103	0.162	7.758	3.926	3.628

	COM					
	RMS (mm)			MPF (Hz)		
	Real, Eyes Open	Virtual, Eyes Open	Real, Eyes Closed	Real, Eyes Open	Virtual, Eyes Open	Real, Eyes Closed
YA1	5.173	5.266	9.281	0.071	0.084	0.037
YA2	5.989	5.393	8.811	0.069	0.073	0.065
YA3	2.535	1.943	3.373	0.091	0.077	0.096
YA Mean	**4.566**	**4.201**	**7.155**	**0.077**	**0.078**	**0.066**
YA St.Dev	1.805	1.957	3.284	0.012	0.005	0.029
OA1	3.873	2.903	3.835	0.094	0.134	0.224
OA2	3.316	4.757	3.204	0.110	0.096	0.132
OA3	6.529	4.138	6.364	0.091	0.120	0.122
OA Mean	**4.573**	**3.933**	**4.468**	**0.099**	**0.117**	**0.159**
OA St.Dev	1.717	0.944	1.673	0.010	0.019	0.056

Table 3-2 Behavioural measures of sway during visual perturbation conditions

YA – young adult, OA – older adult, St.Dev – standard deviation.

	COP							
	RMS (mm)				MPF (Hz)			
	Real 3	**Real 6**	**Virtual 3**	**Virtual 6**	**Real 3**	**Real 6**	**Virtual 3**	**Virtual 6**
YA1	4.133	5.624	6.894	6.150	0.114	0.081	0.097	0.134
YA2	8.935	7.918	7.518	8.775	0.160	0.228	0.245	0.253
YA3	4.465	4.675	3.088	4.949	0.134	0.153	0.157	0.138
YA Mean	**5.844**	**6.072**	**5.833**	**6.625**	**0.136**	**0.154**	**0.166**	**0.175**
YA St.Dev	2.681	1.667	2.398	1.957	0.023	0.073	0.074	0.067
OA1	4.659	5.478	5.776	6.489	0.533	0.511	0.554	0.601
OA2	6.324	5.414	6.772	6.972	0.202	0.300	0.411	0.214
OA3	8.351	7.076	6.140	5.884	0.159	0.224	0.387	0.325
OA Mean	**6.445**	**5.990**	**6.229**	**6.448**	**0.298**	**0.345**	**0.451**	**0.380**
OA St.Dev	1.849	0.942	0.504	0.545	0.205	0.149	0.091	0.199

	COM							
	RMS (mm)				MPF (Hz)			
	Real 3	**Real 6**	**Virtual 3**	**Virtual 6**	**Real 3**	**Real 6**	**Virtual 3**	**Virtual 6**
YA1	3.943	5.644	6.018	6.082	0.066	0.055	0.053	0.064
YA2	6.362	7.309	7.420	8.575	0.077	0.081	0.094	0.082
YA3	4.027	3.876	3.036	3.894	0.078	0.083	0.072	0.080
YA Mean	**4.778**	**5.610**	**5.491**	**6.184**	**0.074**	**0.073**	**0.073**	**0.075**
YA St.Dev	1.373	1.717	2.239	2.342	0.007	0.016	0.020	0.010
OA1	3.489	3.695	4.290	4.533	0.156	0.167	0.151	0.164
OA2	5.181	4.827	5.815	6.154	0.080	0.074	0.117	0.071
OA3	8.016	5.709	5.184	5.037	0.051	0.095	0.113	0.121
OA Mean	**5.562**	**4.744**	**5.096**	**5.242**	**0.095**	**0.112**	**0.127**	**0.119**
OA St.Dev	2.287	1.009	0.766	0.830	0.054	0.049	0.021	0.047

A B

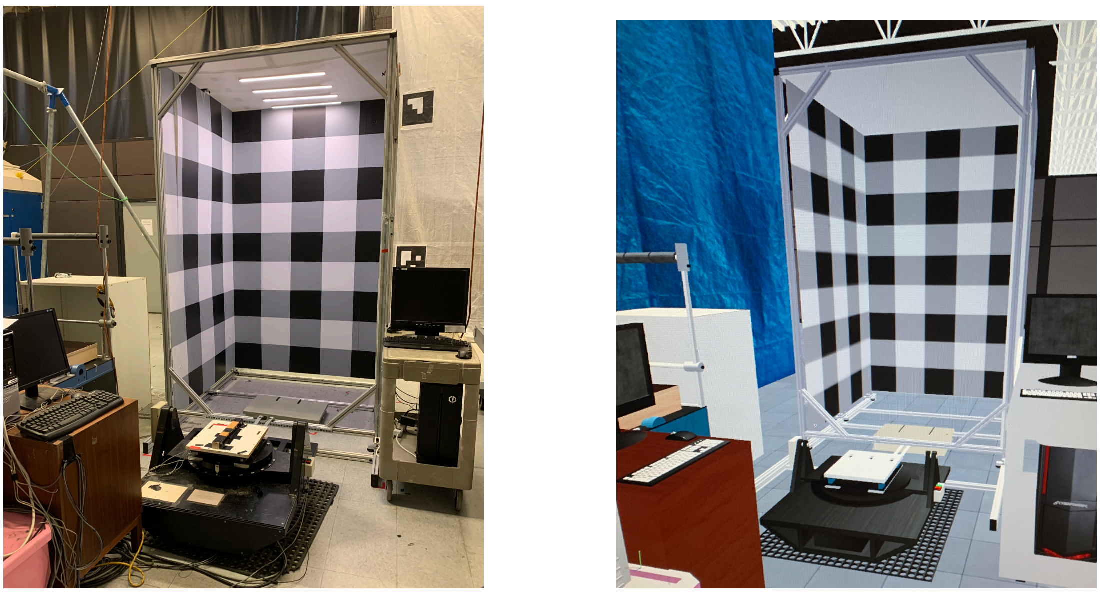

Figure 3-1 Moving room experimental paradigm

(A) Moving room in the real world and **(B)** moving room replicated in the virtual environment.

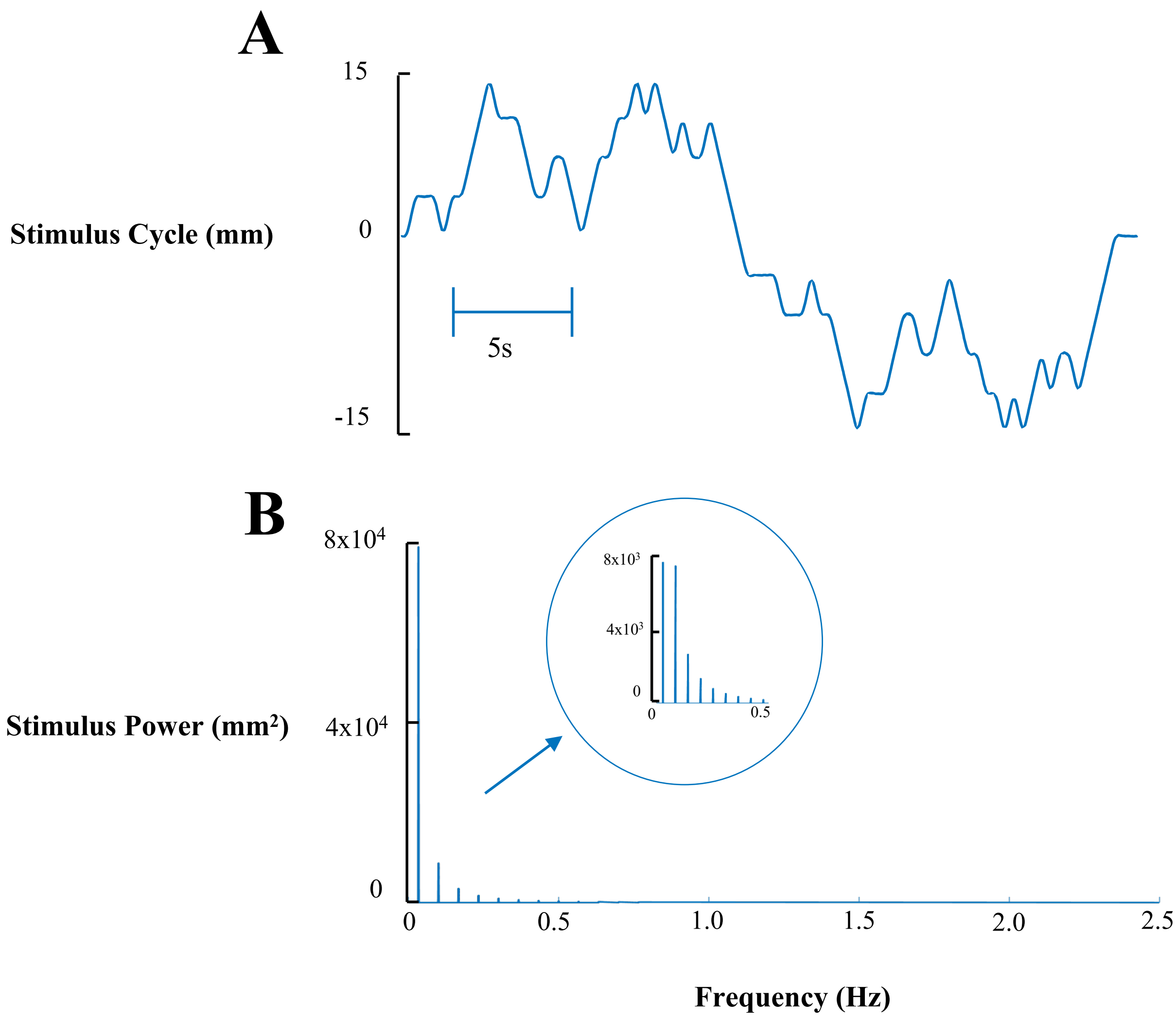

Figure 3-2 Visual stimulus characteristics

(A) 30 second stimulus cycle, P2P 3cm and **(B)** stimulus power spectra.

Figure 3-3 Goggles for peripheral visual field restriction

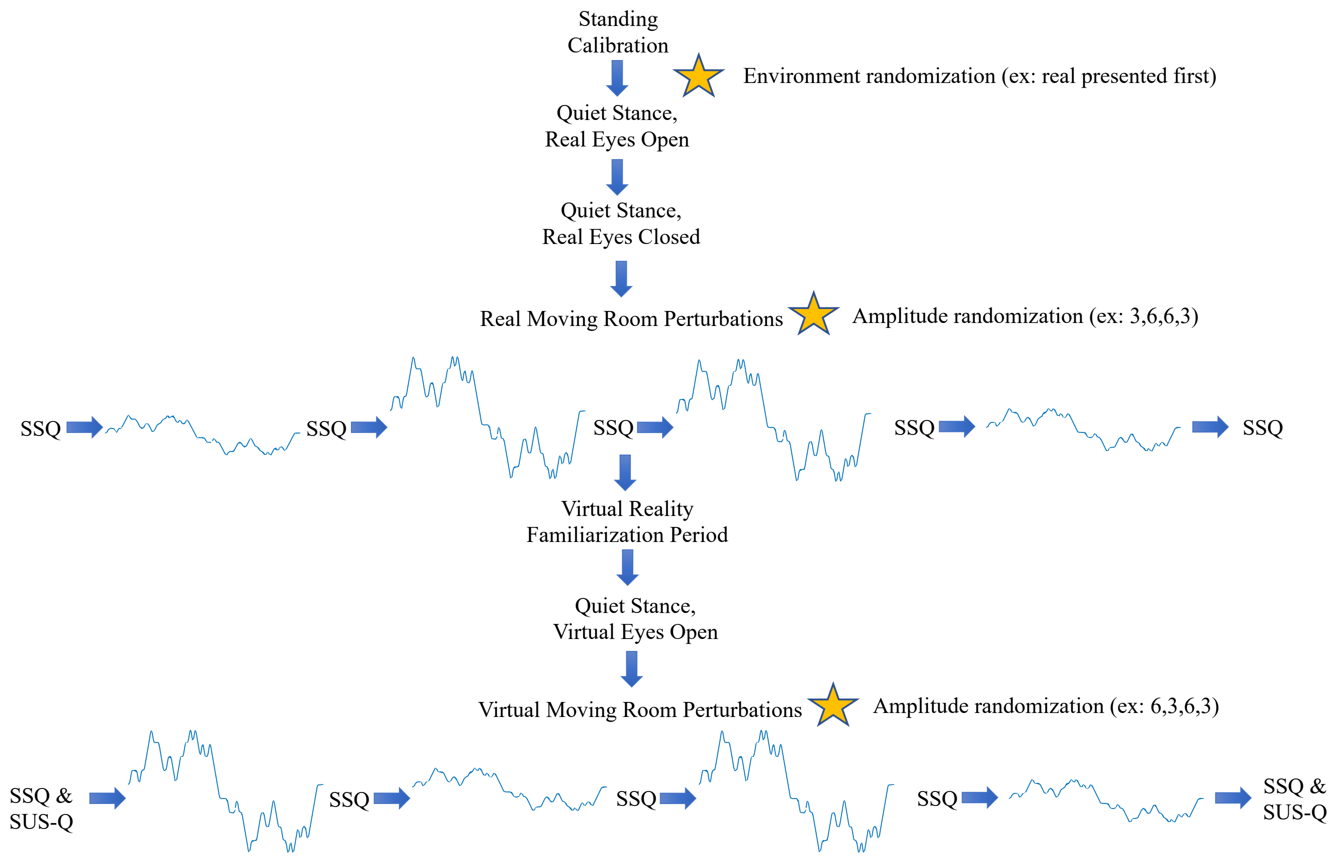

Figure 3-4 Study 2 experimental protocol

SSQ and SUS-Q indicate the administration of the Simulator Sickness Questionnaire and Slater, Usoh, Steed Questionnaire for virtual presence, respectively.

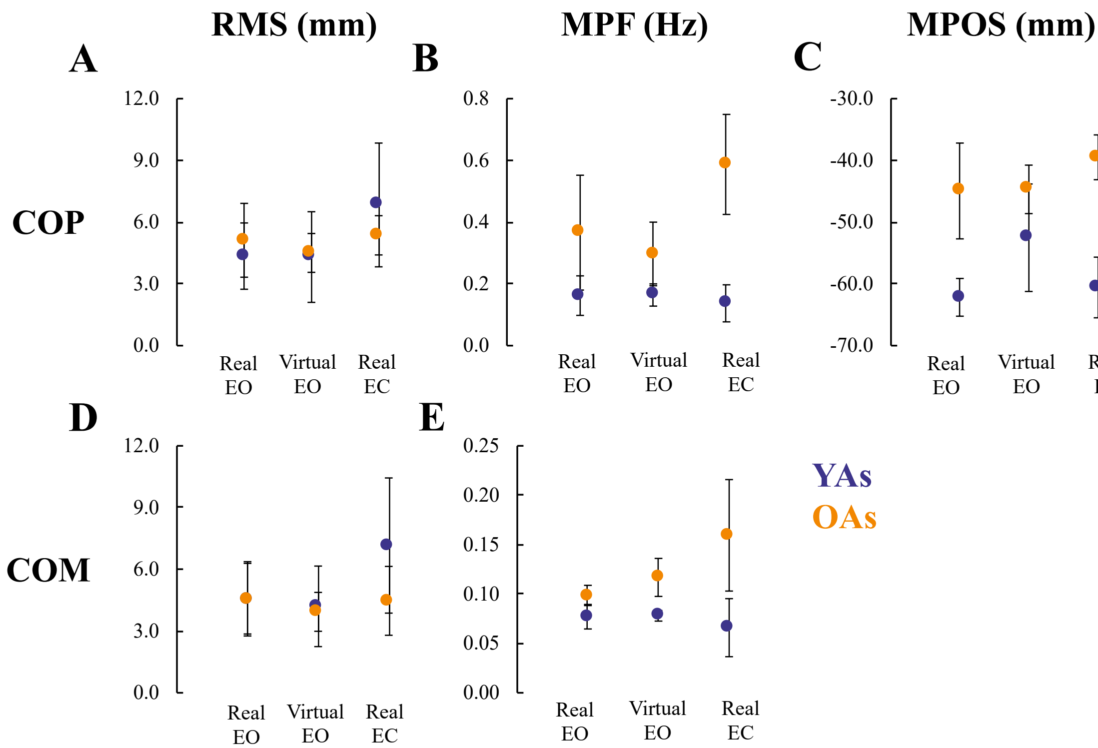

Figure 3-5 Sway characteristics during quiet stance conditions

Group averages and standard deviations are presented. EO = eyes open, EC = eyes closed. For reference, a more positive MPOS value indicates that stance position is closer to the front edge of the force platform.

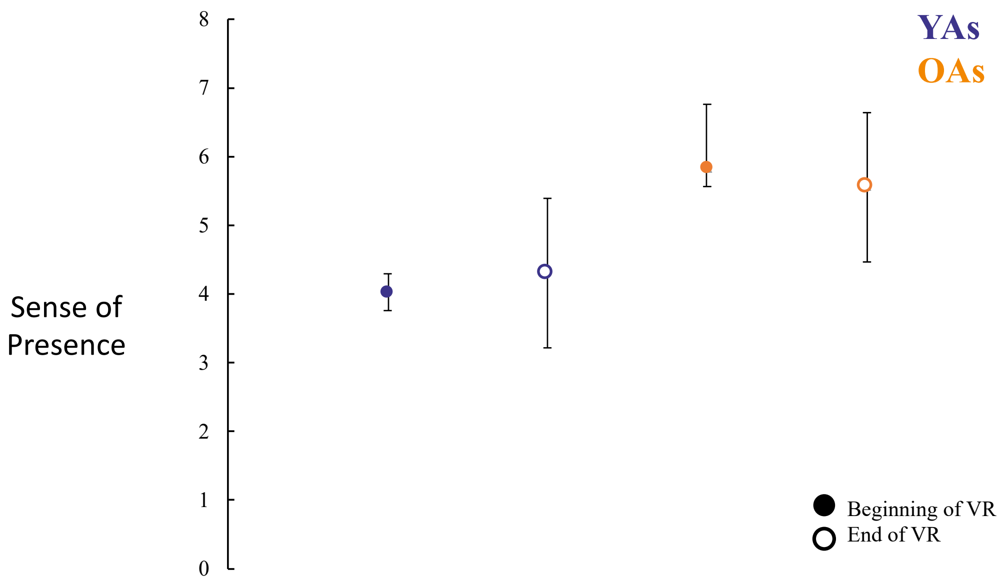

Figure 3-6 Presence questionnaire responses

SUS-Q group averages and standard deviations are presented.

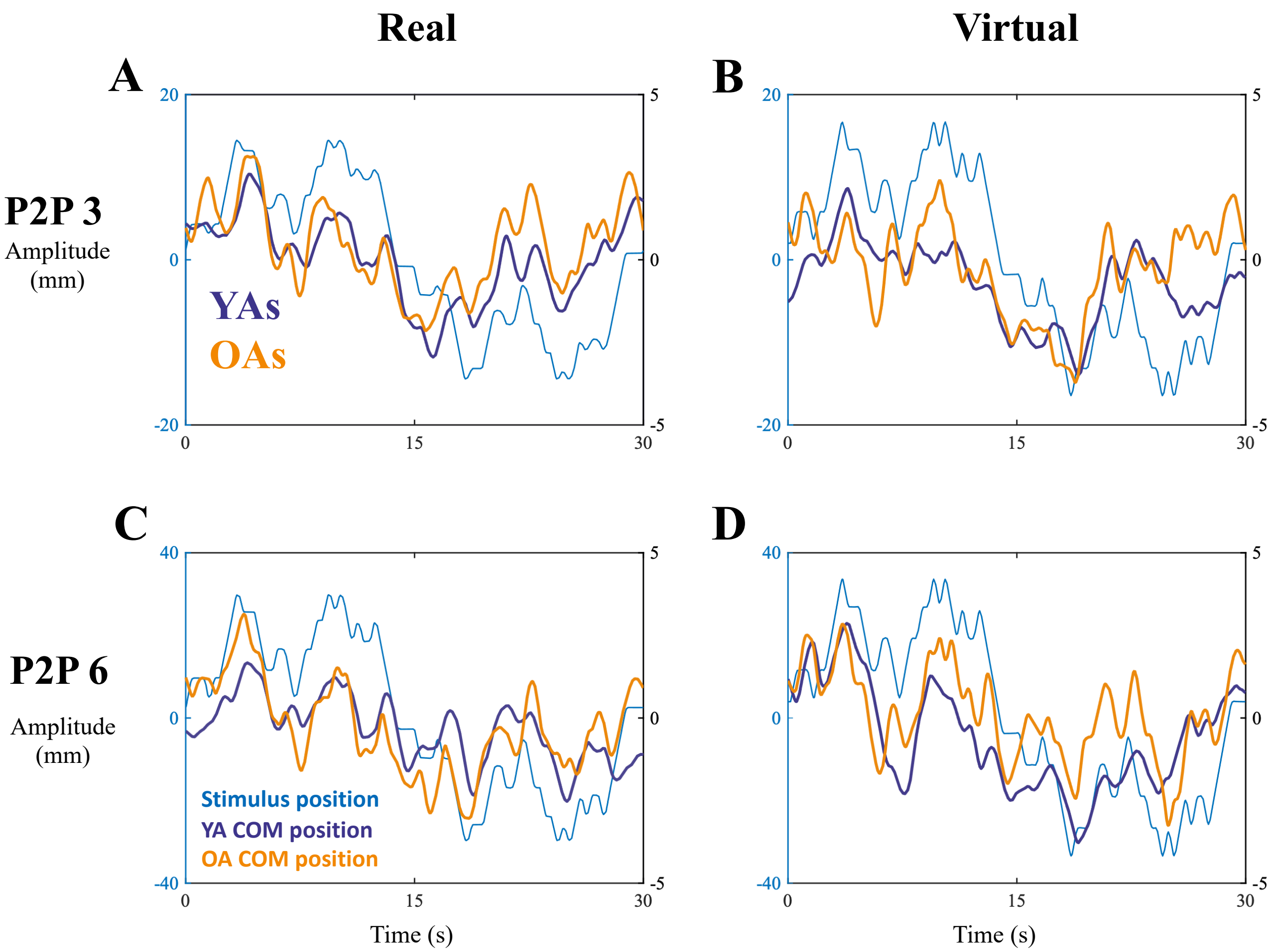

Figure 3-7 Comparison of averaged visual stimuli and COM responses

Left y-axis provides the scale for the visual stimulus, right y-axis provides the scale for the COM responses. Responses are averaged across the 30 second cycles within each experimental condition and age group. P2P 3 = peak-to-peak 3cm stimulus, P2P 6 = peak-to-peak 6cm stimulus.

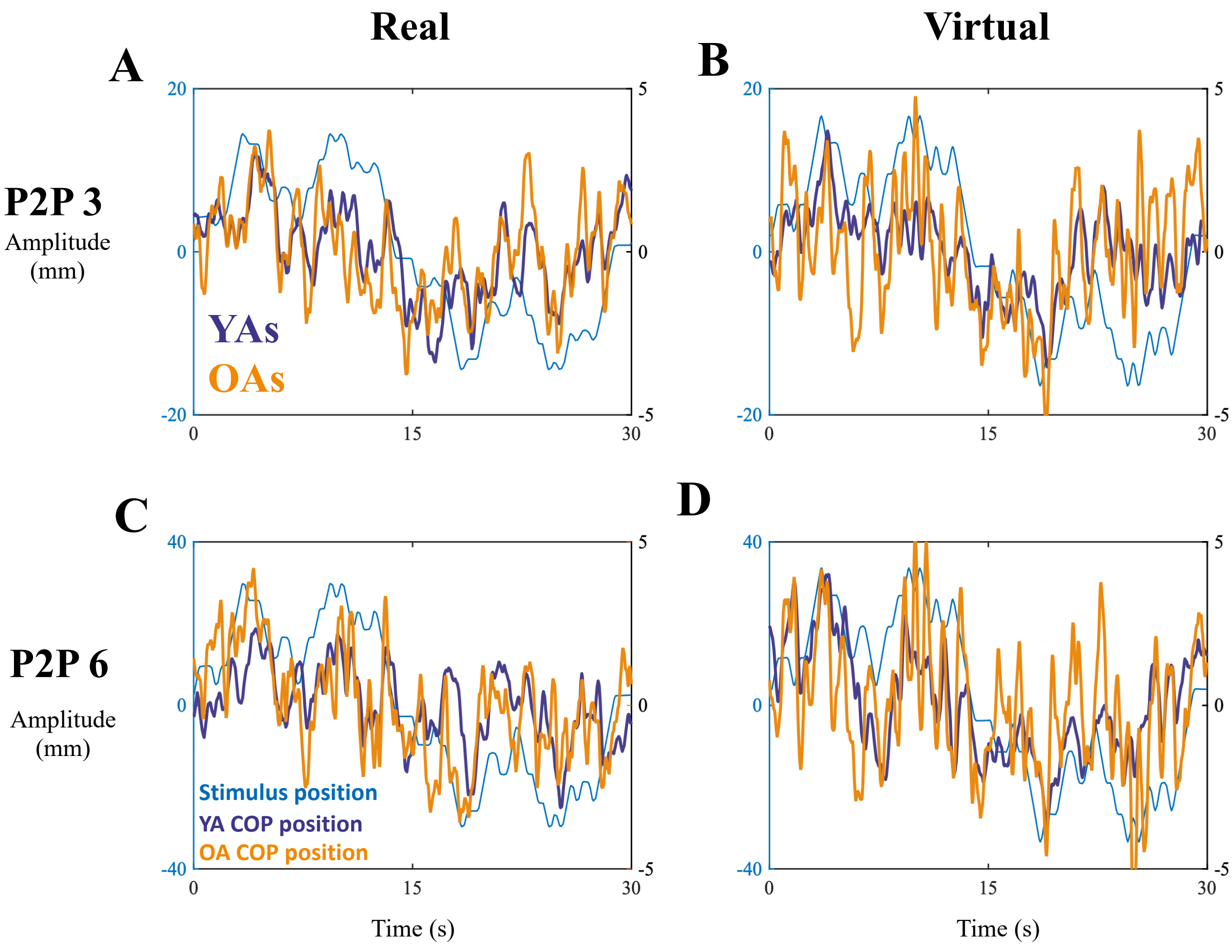

Figure 3-8 Comparison of averaged visual stimuli and COP responses

Left y-axis provides the scale for the visual stimulus, right y-axis provides the scale for the COP responses. Responses are averaged across the 30 second cycles within each experimental condition and age group. P2P 3 = peak-to-peak 3cm stimulus, P2P 6 = peak-to-peak 6cm stimulus.

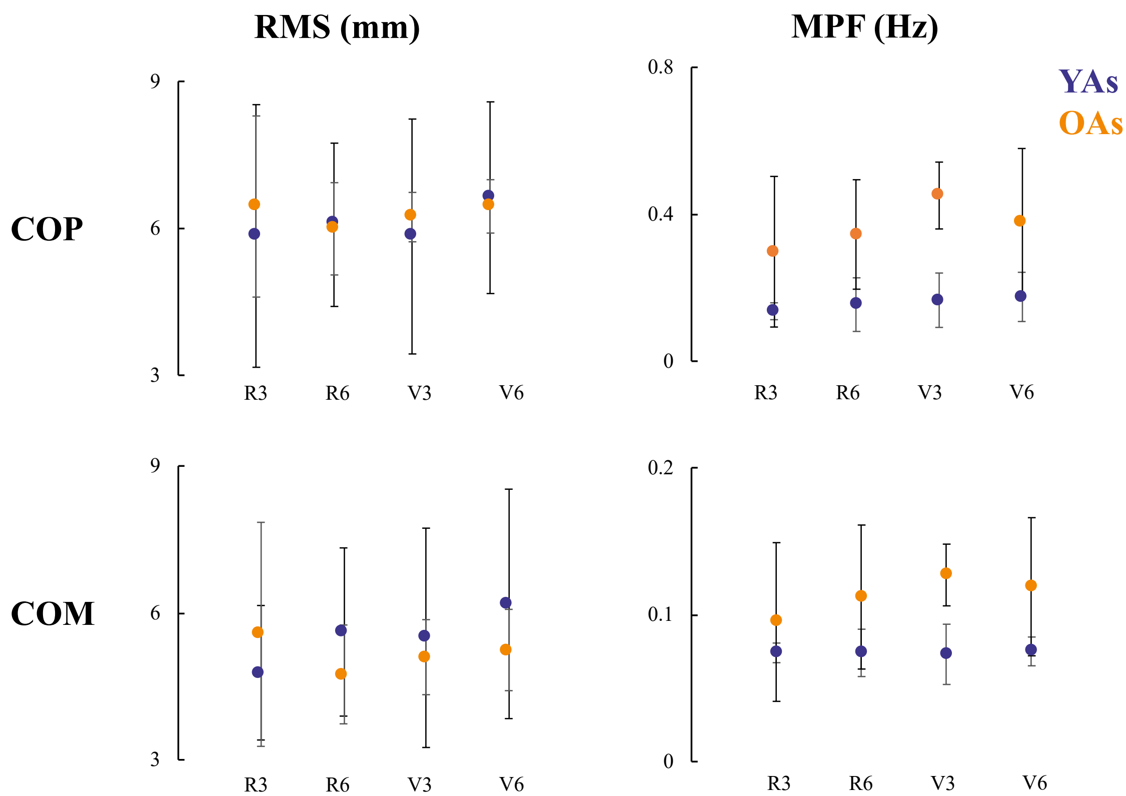

Figure 3-9 Sway behaviour during visual perturbation conditions

Group averages and standard deviations are presented. R3 = real 3cm condition, R6 = real 6cm condition, V3 = virtual 3cm condition, V6 = virtual 6cm condition.

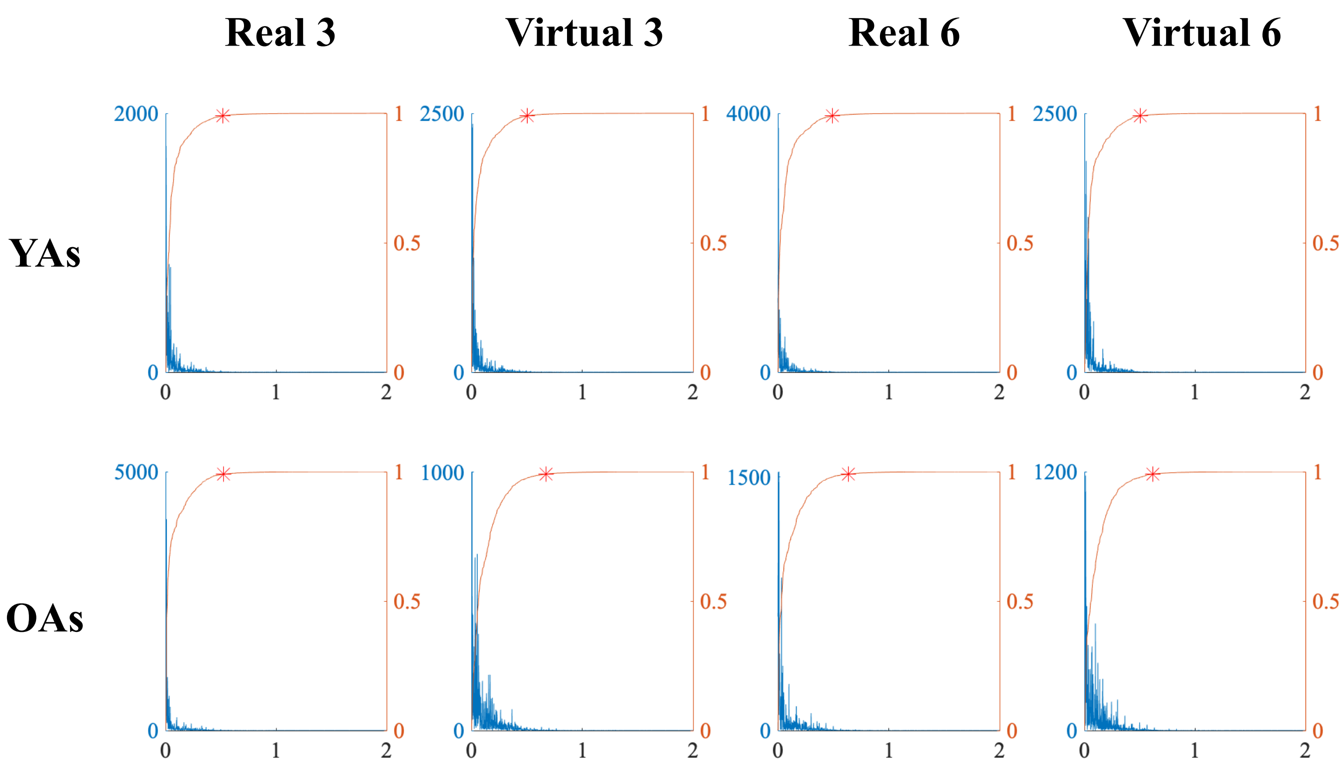

Figure 3-10 COM power analysis

The power spectrum of COM for a given experimental condition is presented on the left y-axis. The integral of cumulative power is presented on the right y-axis. The red marker indicates the frequency at which 95% of COM power exists for a given experimental condition.

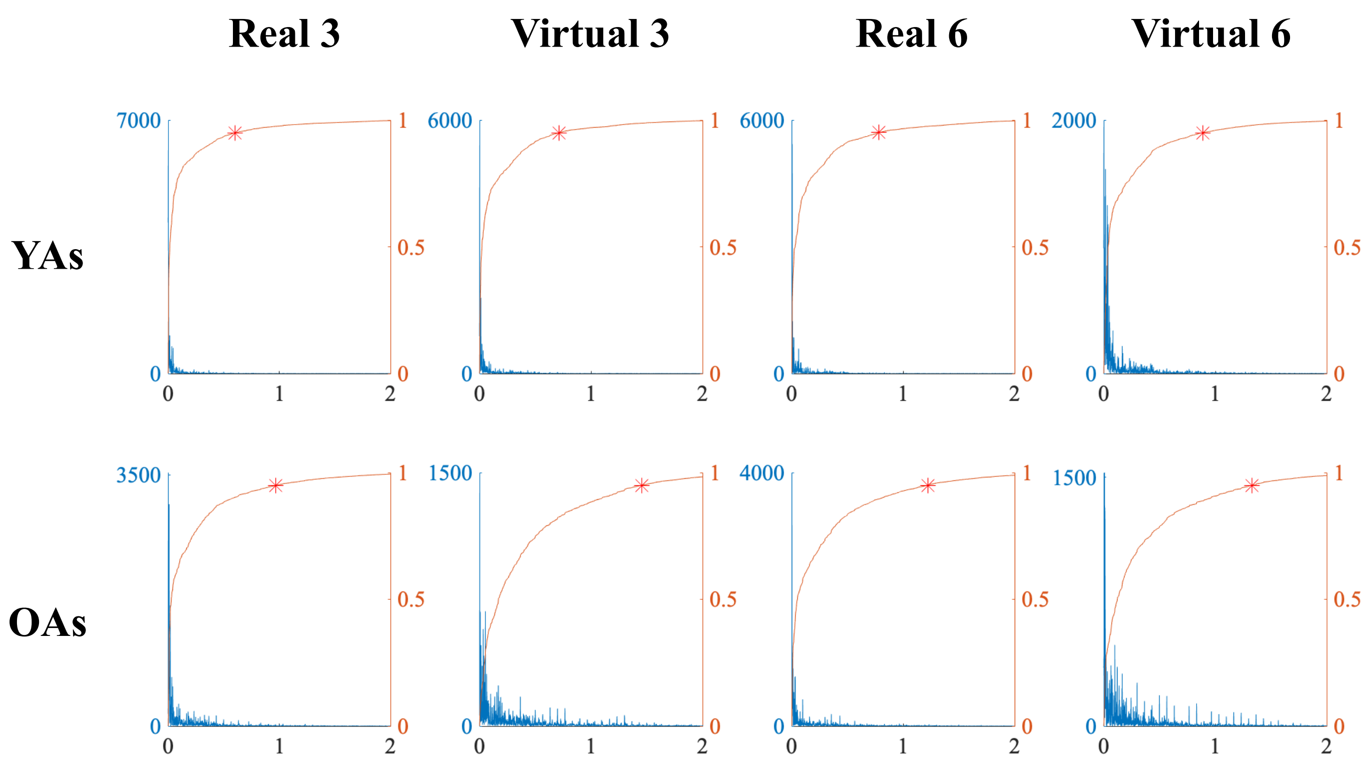

Figure 3-11 COP power analysis

The power spectrum of COP for a given experimental condition is presented on the left y-axis. The integral of cumulative power is presented on the right y-axis. The red marker indicates the frequency at which 95% of COP power exists for a given experimental condition.

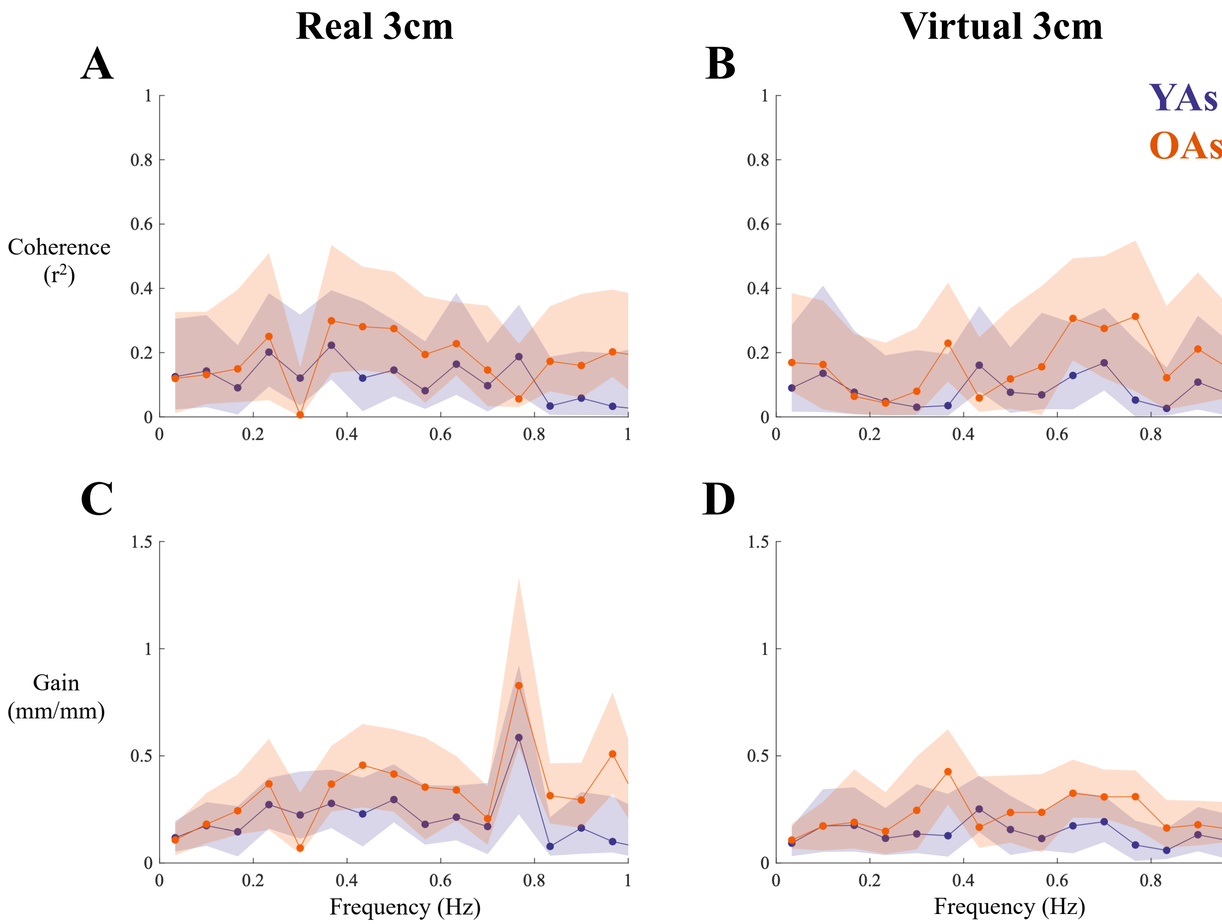

Figure 3-12 COM coherence and gain responses for the 3cm stimulus

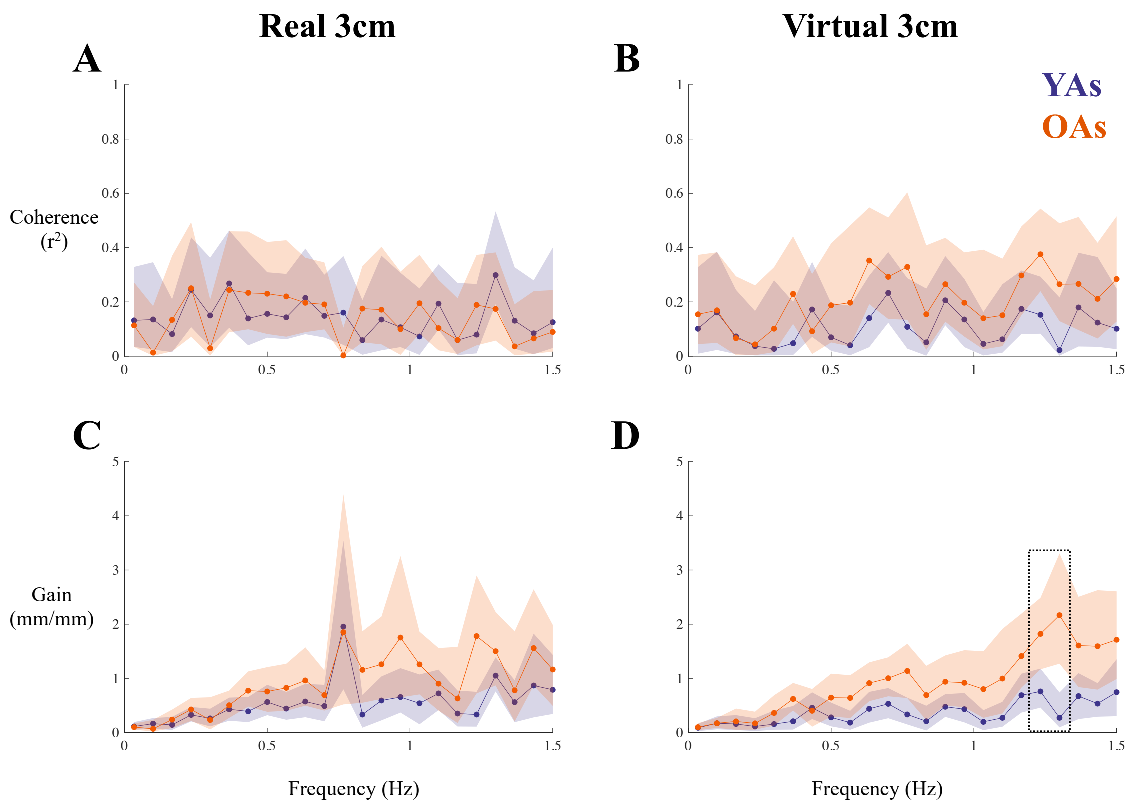

Figure 3-13 COP coherence and gain responses for the 3cm stimulus

Dotted boxes indicate frequencies with non-overlapping confidence bounds.

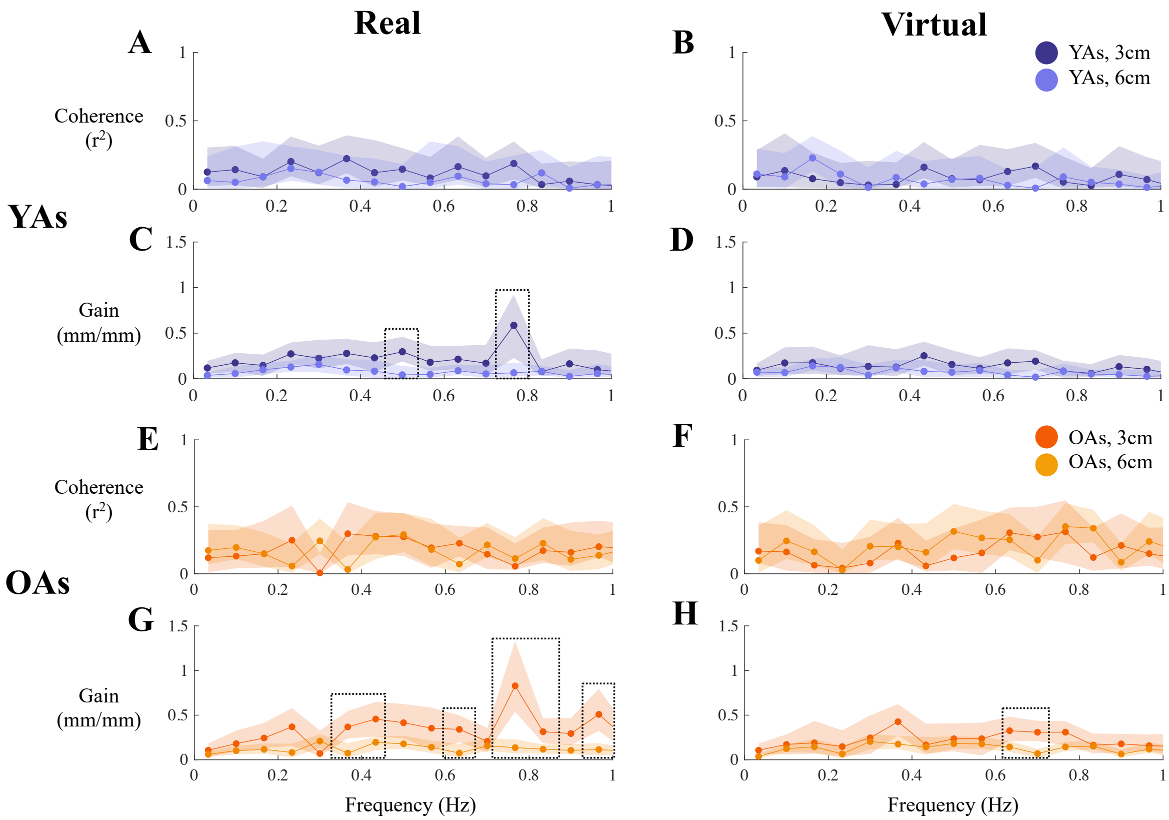

Figure 3-14 Amplitude comparison for COM coherence and gain responses

Dotted boxes indicate frequencies with non-overlapping confidence bounds.

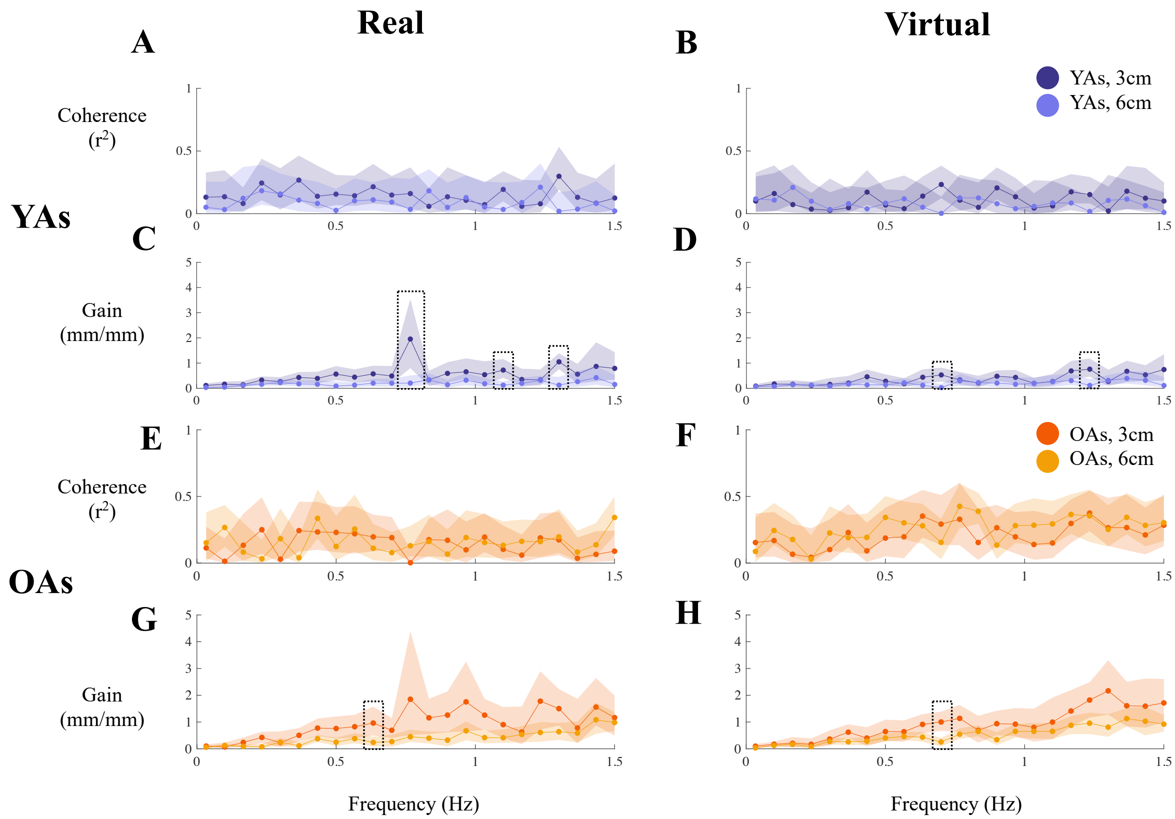

Figure 3-15 Amplitude comparison for COP coherence and gain responses

Dotted boxes indicate frequencies with non-overlapping confidence bounds.

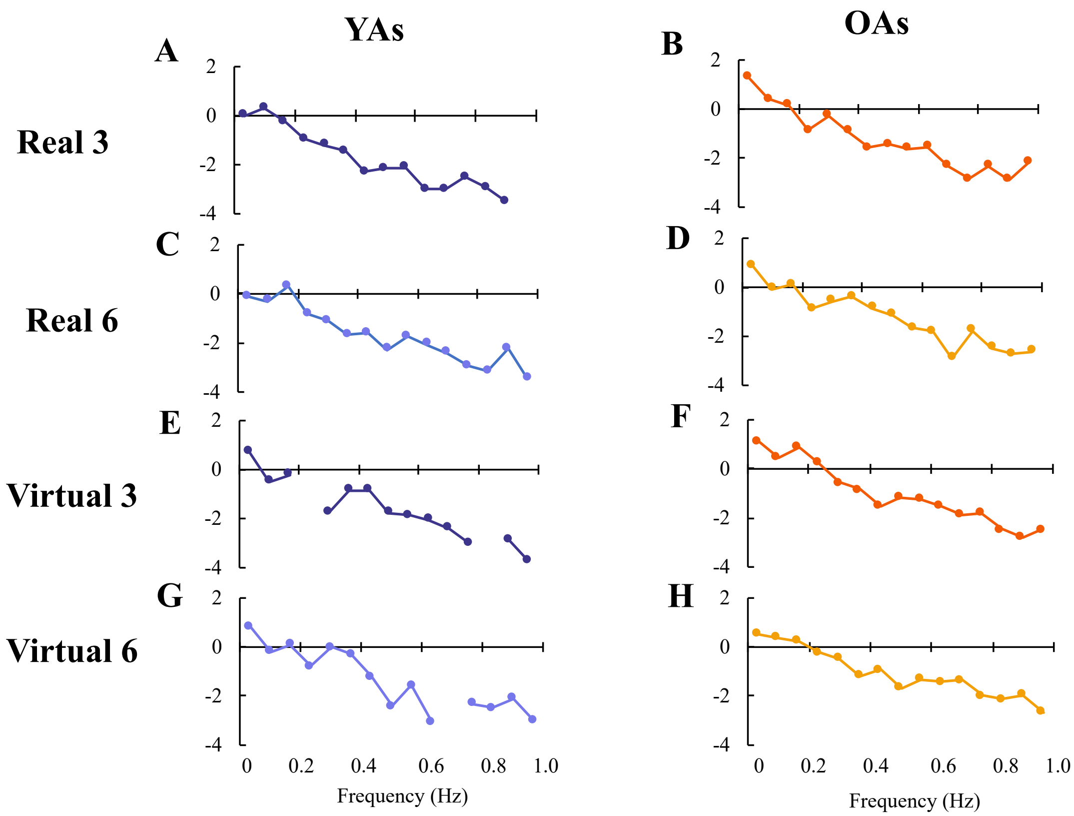

Figure 3-16 COM phase analysis

Phase is presented in radians on the y-axis.

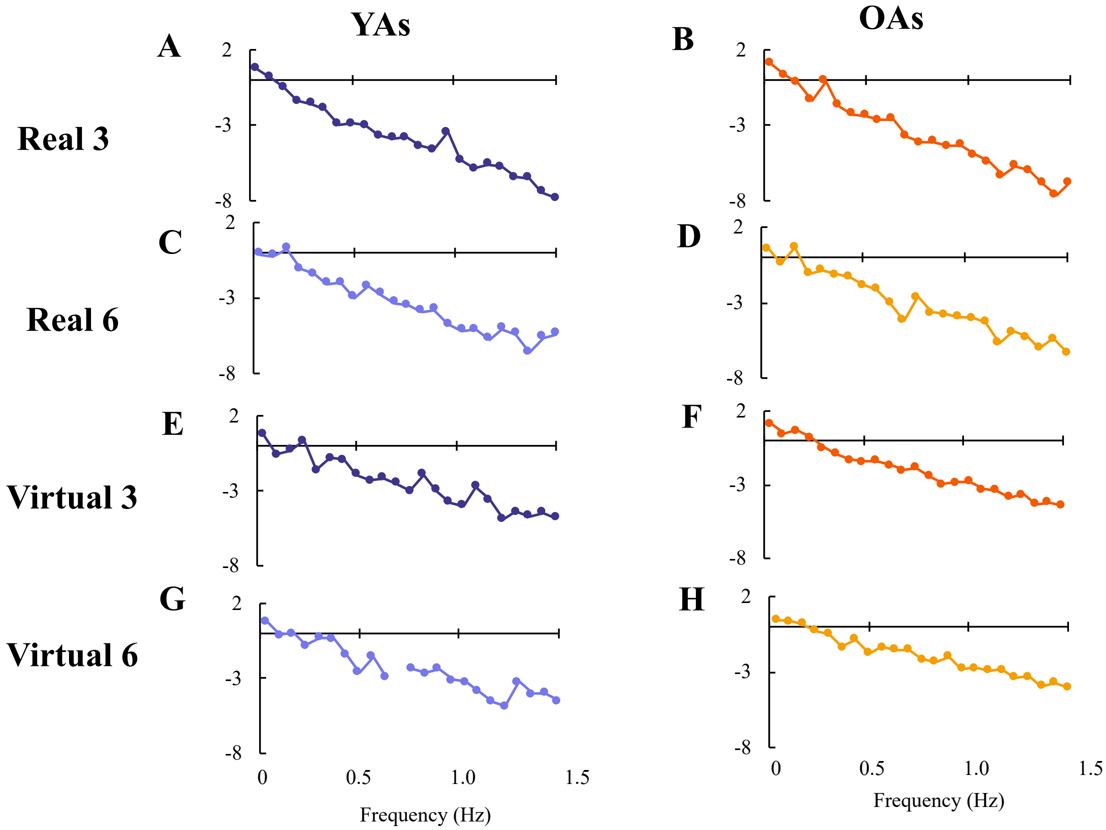

Figure 3-17 COP phase analysis

Phase is presented in radians on the y-axis.

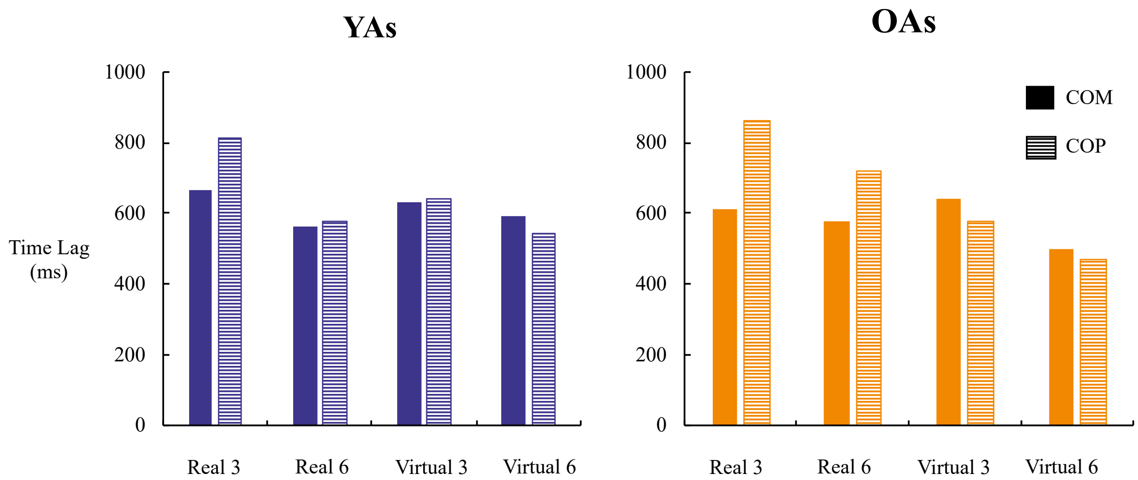

Figure 3-18 Response lag comparisons

Chapter 4: Discussion

4.1 Overview

The overarching aim of this thesis was to elicit and evaluate VEPRs in VR with an HMD. In order to do so, this thesis was divided into two separate studies to examine various experimental paradigms, populations of interest, and perturbation methodologies that are relevant for the visual control of balance. In Study 1, a pseudorandom visual stimulus was presented in an ecologically valid paradigm and the influence of a virtual postural threat on evoked sway was investigated. VEPRs were successfully produced in the virtual environment across a wide range of frequencies in the absence and presence of postural threat; however, threat did not have any significant influence on the evoked responses. From Study 1, a number of fundamental questions regarding the nature of VEPRs in VR arose, which were used to inform the design of the subsequent study. Study 2 completed a methodological comparison between visual perturbations presented in similar real and virtual experimental environments. Young and older adults participated in the study and two amplitude conditions were presented in order to assess the effects of age and sensory reweighting on the visual control of balance. Both real and virtual environments elicited VEPRs of similar magnitudes in young and older adults. Although OAs were more sensitive to the visual stimuli, sensory reweighting of the visual stimuli was demonstrated in both age groups.

4.2 Interpretations and implications of Study 1

4.2.1 Presentation of pseudorandom stimuli in virtual reality

VEPRs were initially identified by the significant increase in MPF of COP displacements from QUIET to LOW conditions. In this study, the average frequency content of postural sway in VR increased with the presentation of visual stimuli, across a frequency range of 0.0488-1Hz. Despite previous reports of instability in VR (Hettinger, 2002; Horlings et al., 2009), this study demonstrated that participants perceived themselves to be equally stable with and without the visual stimulus, when standing at the virtual ground level. Specifically, for both QUIET and LOW conditions, the median score for perceived stability was 90, out of a possible 100 points (0 indicating that they did not feel stable at all and 100 indicating that they felt extremely stable). The absence of differences and overall high scores in perceived stability supports the use of VR HMDs in future balance-relevant paradigms.

Evaluations of VEPRs in the frequency domain demonstrated coherence with the visual stimulus, across the targeted frequency range. Despite the stimulus and response having significantly greater power in lower frequencies (Fig. 2-1), coherence was strongest at approximately 0.0781Hz ($r^2 = 0.09$) for the COP data. This finding is in contrast with the first hypothesis of Study 1, based on previous reports suggesting that lower frequencies, between 0.1-0.3Hz, are typically most relevant for VEPRs (Hanssens et al., 2013; Kiemel et al., 2006; Lestienne et al., 1977; van Asten et al., 1988b). The translational components of rotational stimuli used by Peterka (2002) were calculated in order to estimate an appropriate amplitude for comparison to the present study. Following the appropriate adjustments, the strength of coherence observed in this study was lower than that reported by Peterka (2002) in which coherence ranged from approximately 0.1-0.6Hz. That said, it is difficult to establish meaningful comparisons of coherence across experimental paradigms unless the stimuli parameters and environments are consistent. For instance, Peterka (2002) used a large visual surround to evoke perturbations and the interior was a plaid pattern with a high spatial frequency, thereby maximizing the chance of eliciting a strong postural response (Diener et al., 1976; Masson et al., 1995; van Asten et al., 1988a). Further, weaker coherence in the present study may have also been due to the pseudorandom or stochastic nature of the stimulus; such that the inherent noise and complexity of the stimulus would likely reduce the signal-to-noise ratio, compared to that of a simpler sinusoid. For instance, when Toledo and Barela (2014) compared postural sway to visual perturbations of simple sinusoidal stimuli, complex periodic stimuli, and non-periodic stimuli, coherence was strongest for the simple sinusoids. This supports the hypothesis that the complexity of sway periodicity influences postural responses (Musolino et al., 2006; Toledo & Barela, 2014).

FRFs were further used to characterize the VEPRs at LOW in which maximum gains of 0.084mm/mm were reported at 0.781Hz for COP displacements, and 0.097mm/mm at 0.224Hz for KIN displacements. For context, gains of this magnitude indicate that a 10cm visual perturbation would produce approximately 0.84/0.97cm of sway displacement. Although these gains represent less than 10% of the original stimulus and are unlikely to compromise balance, they still demonstrate the efficacy of the present study to evoke postural sway. Further, they are larger than the typically range of COP RMS (0.53-0.72cm) observed during quiet standing (Carpenter et al., 2001). Comparable gains for similar stimuli have been previously reported; Kiemal and colleagues (2006) demonstrated that the COM gain for a 10cm A-P translating stimulus fluctuated around 10% (maximum of 14% at 0.344Hz). Further, presentation of a 5cm sum-of-sines visual stimulus produced gain values that were 50-100% larger than that of the 10cm stimulus (Kiemal et al., 2006). Stimuli of a smaller amplitude are predicted to have larger gains in accordance with the principles of sensory reweighting (Kiemal et al., 2006; Peterka, 2002).

The second component of the FRF analysis estimated a 201-480ms phase lag between the COP and the visual stimulus, which falls within the wide range of 100-1000ms previously reported (Assländer & Peterka, 2014; Bronstein & Buckwell, 1997; Gabor, 2009; Maurer et al., 2006; Nashner & Berthoz, 1978; Peterka, 2002). Characterizing the phase lag of the visual system in reactive balance control is much more challenging than in other sensory systems (Dakin et al., 2009; Mildren et al., 2017), given the large time delay and potential for conscious control of postural responses to the visual stimuli (Bronstein & Buckwell, 1997; Gabor, 2009; Maurer et al., 2006; Nashner & Berthoz, 1978; Sundermeyer et al., 1996).

Evoked sway responses observed in the present study demonstrate the feasibility of producing and evaluating VEPRs in VR with an HMD. To the best of my knowledge, this is the first study of its kind to present evidence that pseudorandom stimuli in a virtual environment similar to that of the real world can be used to evoke postural sway. Recently, Engel and colleagues (2020) published a study that also evaluated VEPRs with an HMD VR system, with the use of a non-structured and abstract environment. Pilot evidence suggests that abstract VR environments are less stable than those with a realistic structure. Therefore, when seeking to examine the visual system from an ecological perspective, it may be advantageous to utilize environments and paradigms that maximize external validity.

A key finding from Study 1 is that VEPRs can be elicited with intermittent high frequency stimuli, during steady state balance control. Similarly, Engel and colleagues (2020) have reported phase-coupling to visual perturbations of 1.5Hz. It is suggested that these higher frequency responses may be explained in part by new models of standing balance that describe balance control as a multi-segmented pendulum system (Dokka et al., 2009; Engel et al., 2020; Hsu et al., 2007), rather than the inverted pendulum model classically used (Winter et al., 1998).

These more complex models can allow for different standing strategies that are responsive to higher frequency stimuli (Dokka et al., 2009; Engel et al., 2020; Hsu et al., 2007). While previous research suggests that lower frequencies are more relevant for balance control, it is important to note that higher frequencies, albeit low power, could still have a pertinent role, particularly in this novel VR HMD setting (Hanssens et al., 2013; Lestienne et al., 1977; Schmuckler, 2017). As previously described, due to the substantial structural constraints of VR HMDs, it cannot be immediately assumed that visual system functions in a similar way to that of the real world.

Responsivity to stimuli of higher frequencies must also be considered in relation to stimulus complexity. I would like to propose that the intermittent and non-predictable presentation of the high frequency perturbations as a component of the visual stimulus limited habituation or adaptation that has been previously reported (Hanssens et al., 2013). Consequentially, this study suggests that high frequency stimuli, can and should be evaluated using continuous pseudorandom visual stimuli, with a VR HMD system.

4.2.2 Virtual threat and the visual control of balance

Significant differences between LOW and HIGH trials for all psychological and physiological measures of postural threat were demonstrated in Study 1. This observation supports the previous finding that postural threat can be manipulated during stance with a virtual elevated surface height paradigm, to a similar extent as with a real elevated surface height (Cleworth et al. 2012). Despite the aforementioned observations, there were no significant differences in behavioural measures of threat related to evoked sway between LOW and HIGH, across RMS, MPF, and MPOS.

Contrary to the second hypothesis in Study 1, these findings suggest that the virtual postural threat did not strongly influence or alter the visual control of balance. In YAs, it is possible that the visual stimulus dominated any potential behavioural effects of the postural threat, despite clear psychological and physiological indicators. YAs may have also engaged in self-talk strategies to navigate the threatening paradigm. For instance, in this study, anecdotal descriptions were provided from a number of participants who said that they repeatedly reminded themselves that the threat was only virtual and therefore should be ignored. It is possible that this coping strategy may have actually led to a directed effort to disregard, or down-weight the integration of the threatening visual stimuli. This observation is supported by research documenting changes in attentional focus when exposed to the elevated surface height paradigm in the real world (Zaback et al., 2016). When under postural threat, individuals typically redirect their attention from task-irrelevant information to threat-relevant stimuli, movement processes, and self-regulatory strategies (Zaback et al., 2016), similar to that described in the present study. It is important to consider however, that just because a participant may have been more attentive to the threat-relevant visual stimuli, it does not necessarily mean that they were also more responsive. This may in part explain the lack of differences in evoked sway across the height conditions. In future research, assessing changes in attention during exposure to visual perturbations, with and without postural threat, may provide greater insight regarding the conscious control and regulation of VEPRs.

4.3 Interpretations and implications of Study 2

4.3.1 Sway characteristics of quiet stance

Across all quiet stance conditions OAs had greater MPF sway than YAs. This is consistent with other studies that suggest that sway content increases with age due to reductions in postural stability (Carpenter et al., 2006; Maki et al., 1990; Prieto et al., 1996). The understanding of vision as a stabilizer for balance control (Paulus et al., 1984) was supported by the finding that OAs had the greatest average MPF values for the eyes closed quiet stance condition. A lack of differences in COP and COM RMS between young and older adults, as observed in this study, has also been reported across the literature (Carpenter et al., 2006; Maki et al., 1990; Prieto et al., 1996). It was interesting to note that the MPOS of COP for OAs was closer to the front edge of the force platform than YAs. Having a more anterior COP position may indicate a strategy for improved stability when anticipating some form of perturbation (Johnson et al., 2017). It is also possible that the differences in COP MPOS could have been indicative of increased levels of arousal or stimulation (Johnson et al., 2017; Maki & McIllroy, 1996). Previous research has demonstrated that physiologically arousing tasks completed during quiet, unperturbed stance were associated with increased forward leaning (Johnson et al., 2017; Maki & McIllroy et al., 1996). The interpretations of this finding must be reviewed with caution as MPOS measurements were not in reference to the position of the ankle joint or standardized to foot length. Future data collection will include anthropometric measurements of the feet to ensure that valid interpretations can be made.

4.3.2 Sensation of virtual presence

As assessed by the modified SUS-Q, there were no changes in presence within each age group across the time of exposure in the virtual moving room. This observation is critical as a changing sense of immersion over the course of the trial could indicate adaptation or habituation, and limit responsiveness to visual perturbations (Hettinger, 2002).

Consistency of presence in the virtual moving room may have been supported by several factors. First of all, presence in the environment was likely more feasible because of the intentionally replicated design and scaled representation of the space to the actual lab environment (Whitton, 2003). Pilot work was completed to ensure that perceptions of object sizes, such as the tiles on the floor, for example, were consistent between real and virtual environments. Presence and user immersion in the environment are also dependent on the latency of the visual displays (Sanchez-Vives & Slater, 2005). Technological advances in the motion tracking of HMD systems have resulted in very short latencies between movement of the participant's head while wearing the system and the updated view in the virtual environment (Sanchez-Vives & Slater, 2005). Finally, the absence of motion sickness in the virtual environment likely also facilitated consistency in immersion such that participants were not preoccupied with the discomfort of various stimuli (McCauley & Sharkey, 1992).

It is interesting to note that the OAs had stronger reports of presence upon entering VR than the YAs. This observation corresponds with the understanding of YAs as less visually dependent than OAs (Faubert, 2002; Simoneau et al., 1999; Sundermeyer et al., 1996; Wade et al., 1995); however, presence scores for YAs could have increased over the experiment with engagement and exposure to the virtual environment. Presence scores in VR have been reported to increase with anxiety (Bouchard, 2008). Although the current study did not measure anxiety or arousal, it is possible that a lack of previous experience with VR may have influenced initial perceptions of the virtual environment (Huygelier et al., 2019).

4.3.3 Small amplitude visually evoked postural responses

Evoked sway was compared to the visual stimulus by averaging responses across the 30s stimulus cycles. Response functions were concatenated across participants in a given age group for each experimental condition. In the 3cm, real moving room condition, OAs demonstrated general trends of stronger coherence and larger gains, compared to YAs. These results support the second hypothesis of Study 2 that OAs were more visually sensitive to the stimulus than the YAs.

Increased visual sensitivity in OAs has been reported extensively in previous literature across experimental paradigms (Faubert, 2002; Loughlin & Redfern, 2001; Simoneau et al., 1999; Sundermeyer et al., 1996; Toledo & Barela, 2014; Wade et al., 1995). Demonstrations of increased visual sensitivity in OAs have been correlated with physiological declines in proprioceptive feedback due to aging (Lord et al., 1991; Teasdale et al., 1991; Toledo & Barela, 2014). OAs have been reported to be more sensitive to visual perturbations, particularly those of increased amplitude and signal complexity (Prioli et al., 2005; Toledo & Barela, 2014; Wade et al., 1995). It is important to recognize while OAs may have increased sensitivity to visual stimuli, it does not also imply increased response specificity (Slaboda et al., 2011; Toledo & Barela, 2014; Wade et al., 1995). The general results of the present study suggest that OAs had stronger coherence than YAs; that is to say that the evoked sway was more correlated with the visual stimuli. It important to note that coherence to the signal involves both the related (periodic) and random (remnant) components of sway, therefore, just because the OAs had more coherent sway does not mean that it was also more related to the specific frequency characteristics of the stimuli (van der Kooij & Peterka, 2011).

4.3.4 Replication in virtual reality

Both young and older adults demonstrated VEPRs when identical visual stimuli were presented in the real and virtual moving rooms. Similar to the real moving room, OAs had trends of stronger coherence and larger gains than YAs in the virtual moving room. When considering the first hypothesis of Study 2 with regards to the 3cm stimulus, the findings of this study suggest that VEPRs can be successfully produced in young and older adults using a VR HMD, without significant changes in the frequency response of the evoked sway.

4.3.5 Evidence of sensory reweighting

In accordance with the third hypothesis of Study 2, across environments and age groups, there was a general trend of decreases in gain as the stimulus amplitude increased. The observed non-linearities in sway responses, with respect to the two stimulus amplitudes, can be explained by the relative weighting of different sensory channels (Peterka, 2002). Specifically, visual stimuli of larger amplitudes would be more down weighted by the CNS in the sensory integration process (Peterka, 2002). This observation is supported by the maximum-likelihood estimation theory, such that the greater variability a given stimulus has, the less heavily it is weighted in feedback control processes (Battaglia et al., 2003; Harville, 1977).

Although present, the observations of sensory reweighting are less clear for YAs across experimental conditions. As YAs were less sensitive to visual stimuli, regardless of experimental condition, it is less likely that large differences between gains could have been observed.

Throughout the experiment, OAs demonstrated strong evidence of sensory reweighting. Previous research supports this finding, suggesting that when given a sufficient time-course, OAs successfully reweight sensory information (Allison et al., 2006). It is unlikely that the observed age-related differences in sensory reweighting are due to differential integration at the level of the CNS (Allison et al., 2006; Toledo & Barela, 2014). Rather, differences in sensory reweighting are more likely due to age-related thresholds for stimulus detection (Allison et al., 2006; Toledo & Barela, 2014). For example, in lower-limb proprioception OAs typically require greater magnitudes of passive sway in order to detect changes in joint position (Toledo & Barela, 2014). Therefore, the down-weighting of larger amplitude stimuli by OAs may have been achieved because the other sensory systems may have more rapidly identified the larger evoked sway and more easily discriminated between cues of egocentric and exocentric motion (Toledo & Barela, 2014).

4.4 Limitations

There are two general categories that describe the limitations of the research presented in this thesis. Specifically, the limitations are related to the perceptual thresholds of visual stimuli in VR and the inter-individual variability in visual sensitivity.

At present, no studies have established visual perceptual thresholds in VR. Therefore, the first study presented in this thesis utilized a relatively large amplitude stimulus to ensure that the visual stimulus could be perceived by all participants in VR. It is likely that stimuli closer to perceptual threshold would have produced postural responses with stronger coherence and larger gains (Peterka, 2002).

Study 2 was also limited by a lack of understanding related to perceptual thresholds for motion in real and virtual environments. While the experiment was successful in eliciting sensations of self-motion that led to VEPRs, there was no way of establishing which components of visual motion were perceived and subsequently, what elements of sway may have been under conscious control. Further, variations in evoked sway across experimental conditions may have also been related to differential perceptions of self-motion. The goggles that limited the peripheral FOV in the real moving room were an attempt to account for the known influence of the size of peripheral field on the perception of self-motion, that can widely differ between real and virtual environments (Sanchez-Vives & Slater, 2005).

The second overarching limitation of this thesis is the inter-individual variability in visual sensitivity that can confound attempts to characterize the visual control of balance in a specific paradigm or population. It is generally accepted that beyond age, visual sensitivity can vary between individuals based on a number of characteristics such as natural disposition, previous exposure, and psychological state (Brown et al., 1984; Maboobhin et al., 2005; Redfern et al., 2007; Sundermeyer et al., 1996). It can be argued that the experimental paradigms in this thesis provided their own measures of visual sensitivity. However, they still need to be validated against other tests of visual sensitivity such as assessments of just-noticeable differences in visual contrast sensitivity and optic flow. The second study of this thesis slightly improved upon this limitation as both virtual presence and motion sickness were assessed throughout the experiment. It is likely that visual sensitivity is correlated to both increased sensations of presence and symptoms of motion sickness (Hettinger, 2002; Slater et al., 1994).

A fundamental limitation of the second study was its small sample size, due to restrictions on data collection during the experiment collection period[2]. Although this prevented the completion of a majority of the proposed statistical analyses, the use of bootstrapped confidence intervals likely improved the variance estimation of the sample population. This method of statistical analysis was intentionally developed for clinical and experimental settings with extremely low sample sizes and has been previously validated in comparable experimental paradigms (Anson et al., 2014; Engel et al., 2020; Zoubhir & Boushash; 1998). Continuing data collection in the future will enable the consolidation and refinement of present observations.

4.5 Recommendations for future research

This thesis has demonstrated the efficacy of using a VR HMD to study the visual control of balance. Future research must establish the perceptual thresholds for self-motion in VR, in

[2] Scheduled data collection coincided with the onset of the COVID-19 pandemic.

both young and older adults. With this information, visual stimuli can be successfully developed that elicit maximal VEPRs in targeted experimental paradigms.

Further research should apply the experimental paradigms described in this thesis to populations of special interest. For example, OAs are known to be more dependent on vision for balance control (Lishman & Aronson, 1974; Schmuckler, 2017) and also report increased fear and anxiety, and decreased confidence related to maintaining balance and avoiding falls (Adkin & Carpenter, 2018). Therefore, with respect to Study 1, it would be of interest to examine how age influences standing balance control under a virtual elevated surface height and further, if OAs' VEPRs are modulated under virtual postural threat.

The OA population should also be further investigated in relation to specific characteristics of deficits in balance control. In Study 2e, none of the OA participants had experienced a fall in the past six months. Prior research has demonstrated that OAs who have reported previous falls or loss of balance have greater visual sensitivity and rely more heavily on visual cues for balance, than healthy OAs (Sundermeyer et al., 1996). It has been proposed that both characteristics of age and balance function are relevant for VEPRs (Sundermeyer et al., 1996). Therefore, the final suggestion when examining OAs in future research would to be assess both those who are active and those who are sedentary, as physical activity may moderate the observed decreases in sensory integration that occurs with age (Prioli et al., 2005).

The final overarching recommendation for future research would be to further evaluate sensory reweighting in virtual environments with a combination of sensory manipulations. For example, visual perturbations in VR could be applied in conjunction with a sway-referenced platform, or galvanic vestibular stimulation, which probe proprioceptive and vestibular systems, respectively. This would expand upon the current understanding of sensory reweighting as the use of VR could support a variety of novel paradigms to examine the relative integration of conflicting sensory information.

4.6 Clinical applications

This thesis had provided evidence of the utility of VR HMDs in assessing the visual control of balance and the feasibility of doing so in an OA population. The finding of this research that VR can successfully elicit VEPRs with HMDs, supports its use in future clinical balance-related assessments and training programs. The application of VR HMDs would be of particular benefit to clinical interventions that aim to maximize external validity and thus assist OAs with the everyday goal of maintaining balance and avoiding falls.

4.7 Conclusions

In conclusion, the overall findings of this thesis support the use of VR HMDs for research related to the visual control of balance, in young and older adults. First, VEPRs were established with a pseudorandom stimulus in a VR paradigm that had strong external validity. Evoked sway responses were achieved to a comparable degree across experimental conditions with and without the presence of a virtual postural threat. Second, VEPRs were demonstrated to be similar when produced in the real world and in a replicated virtual environment. Across experimental conditions, OAs were more dependent on visual information for balance control. Evidence of sensory reweighting was observed in both young and older adults in the real and virtual environments. Collectively, these results suggested that VEPRs can be successfully produced with a VR HMD system. This technology should be encouraged in future research for a variety of experimental paradigms and populations of interest.

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Appendices

Appendix A Study 1 Questionnaires

A.1 Balance confidence, fear of falling, and perceived stability

Balance Confidence:

Please use the following scale to rate how confident you are that you can maintain your balance and avoid a fall during the balance task:

0……………………………………50……………………………………100

I did not feel confident at all	I felt moderately confident	I felt extremely confident

Fear of Falling:

Using the following scale, please rate how fearful of falling you felt when performing the balance task:

0……………………………………50……………………………………100

I did not feel fearful at all	I felt moderately fearful	I felt extremely fearful

Perceived Stability:

Using the following scale, please rate how stable you felt when performing the balance task:

0……………………………………50……………………………………100

I did not feel stable at all	I felt moderately stable	I felt extremely stable

A.2 State anxiety

Light grey questions were not used.

Please answer the following questions about how you honestly feel just after standing at this height using the following scale:

1	2	3	4	5	6	7	8	9
I don't feel at all				I feel this moderately				I feel this extremely

1. **I felt nervous when standing at this height**
2. **I had lapses of concentration when standing at this height**
3. **I had self doubts when standing at this height**
4. **I felt myself tense and shaking when standing at this height**
5. **I was concerned about being unable to concentrate when standing at this height**
6. **I was concerned about doing the balance task correctly when standing at this height**
7. **My body was tense when standing at this height**
8. **I had difficulty focusing on what I had to do when standing at this height**
9. **I was worried about my personal safety when standing at this height**
10. **I felt my stomach sinking when standing at this height**
11. **While trying to balance at this height, I didn't pay attention to the point on the wall all of the time**
12. **My heart was racing when standing at this height**
13. **Thoughts of falling interfered with my concentration when standing at this height**
14. **I was concerned that others would be disappointed with my balance performance at this height**
15. **I found myself hyperventilating when standing at this height**
16. **I found myself thinking about things not related to doing the balance task when standing at this height.**

Appendix B Study 2 Questionnaires

B.1 SMMSE

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Guidelines & Protocols Advisory Committee

STANDARDIZED MINI-MENTAL STATE EXAMINATION (SMMSE)

NAME OF PATIENT	DATE

Directions for administration of the SSMSE:

1. Before the questionnaire is administered, try to get the person to sit down facing you. Assess the person's ability to hear and understand very simple conversation, e.g. *What is your name?* If the person uses hearing or visual aids, provide these before starting.
2. Introduce yourself and try to get the person's confidence. Before you begin, get the person's permission to ask questions, e.g. *Would it be alright to ask you the same questions about your memory?* This helps to avoid catastrophic reactions.
3. Ask each question a maximum of three times. If the subject does not respond, score 0.
4. If the person answers incorrectly, score 0. Accept that answer and do not ask the question again, hint, or provide any physical clues such as head shaking, etc.
5. The following equipment is required to administer the instrument: A watch, a pencil, Page 3 of this SMMSE with CLOSE YOUR EYES written in large letters and two five-sided figures intersecting to make a four-sided figure, and Page 4, a blank piece of paper.
6. If the person answers: What did you say?, do not explain or engage in conversation. Merely repeat the same directions a maximum of three times.
7. If the person interrupts (e.g. What is this for?), reply: *I will explain in a few minutes, when we are finished. Now if we could proceed please… we are almost finished.*

I am going to ask you some questions and give you some problems to solve. Please try to answer as best as you can.

1. Time: 10 seconds for each reply:

a)	*What year is this?* (accept exact answer only).	/1
b)	*What season is this?* (accept either: last week of the old season or first week of a new season).	/1
c)	*What month is this?* (accept either: the first day of a new month or the last day of the previous month).	/1
d)	*What is today's date?* (accept previous or next date).	/1
e)	*What day of the week is this?* (accept exact answer only).	/1

2. Time: 10 seconds for each reply:

a)	*What country are we in?* (accept exact answer only).	/1
b)	*What province are we in?* (accept exact answer only).	/1
c)	*What city/town are we in?* (accept exact answer only).	/1
d)	(In home) *What is the street address of this house?* (accept street name and house number or equivalent in rural areas). (In facility) *What is the name of this building?* (accept exact name of institution only).	/1
e)	(In home) *What room are we in?* (accept exact answer only). (In facility) *What floor of the building are we on?* (accept exact answer only).	/1

3. Time: 20 seconds

Say: *I am going to name three objects. When I am finished, I want you to repeat them. Remember what they are because I am going to ask you to name them again in a few minutes.* (Say the following words slowly at approximately one-second intervals): *Ball / Car / Man.*

For repeated use: Bell, jar, fan; Bill, tar, can; Bull, bar, pan.

Please repeat the three items for me. (score one point for each correct reply on the first attempt.)

If the person did not repeat all three, repeat until they are learned or up to a maximum of five times (but only score first attempt). /3

Continued Over …

4. **Time: 30 seconds**
Spell the word WORLD. (you may help the person to spell the word correctly) **Say:** *Now spell it backwards please.* If the subject cannot spell world even with assistance, score 0. Refer to Page 3 for scoring instructions. /5

5. **Time: 10 seconds**
Say: *Now what were the three objects I asked you to remember?*
(score one point for each correct answer regardless of order) /3

6. **Time: 10 seconds**
Show wristwatch. Ask: *What is this called?*
(score one point for correct response: accept "wristwatch" or "watch"; do not accept "clock" or "time", etc.). /1

7. **Time: 10 seconds**
Show pencil. Ask: *What is this called?*
(score one point for correct response; accept "pencil" only; score 0 for pen) /1

8. **Time: 10 seconds**
Say: *I would like you to repeat a phrase after me: No ifs, ands or buts*
Score one point for a correct repetition. Must be exact, e.g. no ifs or buts, score 0). /1

9. **Time: 10 seconds**
Say: *Read the words on this page and then do what it says.* Then, hand the person the sheet with CLOSE YOUR EYES on it. If the subject just reads and does not close eyes, you may repeat: *Read the words on this page and then do what it says*, (a maximum of three times. Score one point only if the subject closes eyes. The subject does not have to read aloud. /1

10. **Time: 30 seconds**
Hand the person a pencil and paper (Page 3). **Say:** *Write any complete sentence on that piece of paper.*
Score one point. The sentence must make sense. Ignore spelling errors. /1

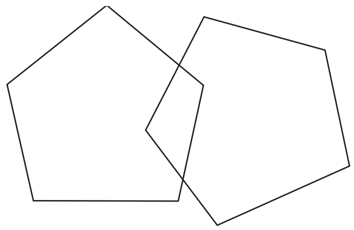
11. **Time: 1 minute maximum**
Place design, eraser and pencil in front of the person. **Say:** *Copy this design please.* Allow multiple tries. Wait until the person is finished and hands it back. Score one point for a correctly copied diagram. The person must have drawn a four-sided figure between two five-sided figures. /1

12. **Time: 30 seconds**
Ask the person if he is right or left handed. Take a piece of paper, hold it up in front of the person and **say:** *Take this paper in your right/left hand* (whichever is non-dominant), *fold the paper in half once with both hands and put the paper down on the floor.* Score one point for each instruction executed correctly.

Takes paper in correct hand	/1
Folds it in half	/1
Puts it on the floor	/1

Total Test Score:	**/30**
Adjusted Score	**/**

 Molloy DW, Alemayehu E, Roberts R. Reliability of a standardized Mini-Mental State Examination compared with the traditional Mini-Mental State Examination. American Journal of Psychiatry, 1991; 148(1): 102-105.



FOLD LINE

Scoring WORLD backwards (instructions for item #4)

Write the person’s response below the correct response.
Draw lines matching the same letters in the correct response and the response given.
These lines MUST NOT cross each other.
The person’s score is the maximum number of lines that can be drawn without crossing any.

Examples:

D	L	R	O	W
D	L	R	O	W

= Score 5

D	L	R	O	W
D	R	W	O	D

= Score 3

D	L	R	O	W
L	O	W	R	O

= Score 3

D	L	R	O	W
L				

= Score 1

D	L	R	O	W
L	R	R	W	O

= Score 3

D	L	R	O	W

= ________

FOLD ALONG THIS LINE AND SHOW INSTRUCTIONS TO PERSON

Close your eyes

Item 10: **Sentence Writing**

Standardized Mini-Mental State Examination (SMMSE) Scoring

Table 1: Stages of Cognitive Impairment as Defined by SMMSE Scores

SCORE	DESCRIPTION	STAGE	DURATION (years)
30-26	could be normal	could be normal	varies
25-20	mild	early	0-23
19-10	moderate	middle	4-7
9-0	severe	late	7-14

Table 2: Areas of Functional Impairment

SCORE	ACTIVITIES OF DAILY LIVING	COMMUNICATION	MEMORY
30-26	could be normal	could be normal	could be normal
25-20	driving, finances, shopping	finding words, repeating, going off topic	three-item recall, orientation to time then place
19-10	dressing, grooming, toileting	sentence fragments, vague terms (e.g., this, that)	spelling WORLD backward, language, and three-step command
9-0	eating, walking	speech disturbances such as stuttering and slurring	obvious deficits in all areas

Adapted from: Vertesi A, Lever JA, Molloy DW, et al. Standardized mini-mental state examination: Use and interpretation. Canadian Family Physician 2001; 47:2018-2023.

The score for WORLD reversal is 17 per cent of SMMSE score (5 of 30 points). Incorrect scoring of WORLD reversal may result in incorrect assumptions of clinical change. One can review the score for WORLD reversal at: www.attentionmmse.com. Self-learning of this task may also be done at this website.

Reference:
Davey RJ, Jamieson S. The validity of using the mini mental state examination in NICE dementia guidelines. J Neurol Neurosurg Psychiatry. 2004; 75:343-44.

B.2 SSQ

No ___________________ Date _________________

Simulator Sickness Questionnaire

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

Please fill in this questionnaire. Circle below if any of the symptoms apply to you now.

1. General discomfort	None	Slight	Moderate	Severe
2. Fatigue	None	Slight	Moderate	Severe
3. Headache	None	Slight	Moderate	Severe
4. Eyestrain	None	Slight	Moderate	Severe
5. Difficulty focusing	None	Slight	Moderate	Severe
6. Salivation increase	None	Slight	Moderate	Severe
7. Sweating	None	Slight	Moderate	Severe
8. Nausea	None	Slight	Moderate	Severe
9. Difficulty concentrating	None	Slight	Moderate	Severe
10. "Fullness of the Head"	None	Slight	Moderate	Severe
11. Blurred vision	None	Slight	Moderate	Severe
12. Dizziness with eyes open	None	Slight	Moderate	Severe
13. Dizziness with eyes closed	None	Slight	Moderate	Severe
14. Vertigo*	None	Slight	Moderate	Severe
15. Stomach awareness**	None	Slight	Moderate	Severe
16. Burping	None	Slight	Moderate	Severe

* Vertigo is experienced as a loss of orientation with respect to vertical upright.

** Stomach awareness is usually used to indicate a feeling of discomfort which is just short of nausea.

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

B.3 Modified SUS-Q

<u>Virtual Reality Presence Questionnaire</u>

1. Please rate your sense of being in the room, on the following scale from 1 to 7, where 7 represents your normal experience of being in a place.

I have a sense of "being here" in the room: 1. Not at all, 7. Very much'

2. To what extent is the room currently the reality for you?

The room is currently the reality for me...1. At no time, 7. Almost all the time'

3. Do you think of the room more as images that you see, or more as somewhere that you are visiting?

The room seems to me to be more like... 1. Images that I see, 7. Somewhere that I am visiting'

4. During this experience, which is strongest on the whole, your sense of being in the room, or of being elsewhere?

I have a stronger sense of... 1. Being elsewhere, 7. Being in the room'

5. During this experience, do you often think to yourself that you are actually in the room?

I think of the room as a place in a way similar to other places that I have been today... 1. Not at all, 7. Very much so'