Visual determinants of postural control and perception during physical and visual motion

by

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Author's Declaration

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

I understand that my thesis may be made electronically available to the public.

Abstract

The control of balance and posture is a critical task of daily life to limit the risk of falls and potential injury. In order to be successful in the control of balance the central nervous system utilizes sensory feedback from the visual, proprioceptive/somtatosensory and vestibular systems. It is through the detection, processing and perception of these sensory cues that allow us to form an accurate representation of postural events and respond accordingly. In this dissertation I investigate how we perceive postural events, how this perception can change with altered visual cues introduced through virtual reality and how virtual visual motion with differing context can alter postural responses. This dissertation aims to determine the following: (1) to determine if methodological changes effect an individuals perception of postural instability onset, (2) to investigate if visual information can alter our perception of instability onset, (3) to investigate if visual motion with differing visual characteristics can alter postural responses. Results indicate that the methodology utilized during a temporal order judgement task has an effect on the perception of postural instability onset. Additionally, it was observed that virtual visual height impacts the precision of perceptual responses to postural instability onset. Finally, virtual visual motion with differing visual context appeared to only be affected by visual motion duration. However, there were also strong individual differences in postural responses to visual motion, which has not been broadly addressed in the literature. As a whole this thesis can exemplify the importance of visual information on both perceptual and behavioural responses related to posture and balance.

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Dedication

I want to dedicate my dissertation to my grandfather, Bob “Grump” McIlroy.

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Chapter 1

Introduction

Humans are bipedal organisms with a narrow base of support and a high centre of mass. We live in a gravitational environment where falling down is highly likely, and if not rapidly counteracted will threaten our survival. In order to limit instability and falls in daily life, it is critical to detect and perceive instability to control balance. This is a complex task that requires individuals to process sensory inputs from visual, proprioceptive/somatosensory and vestibular systems to allow for an accurate representation of both internal and external environments [15, 16, 118, 145, 146]. These internal and external representations affect how postural events are perceived as well as the subsequent motor actions that are produced. The control of balance and posture relies on each of these modalities to provide unique information about self-motion, which together can be integrated to provide the most accurate representation of a postural event.

This dissertation will be exploring the perception of postural instability onset and the postural responses evoked by visual motion cues. Perception and action can be associated and dissociated from each other which has been outlined in our theoretical framework 1.1.

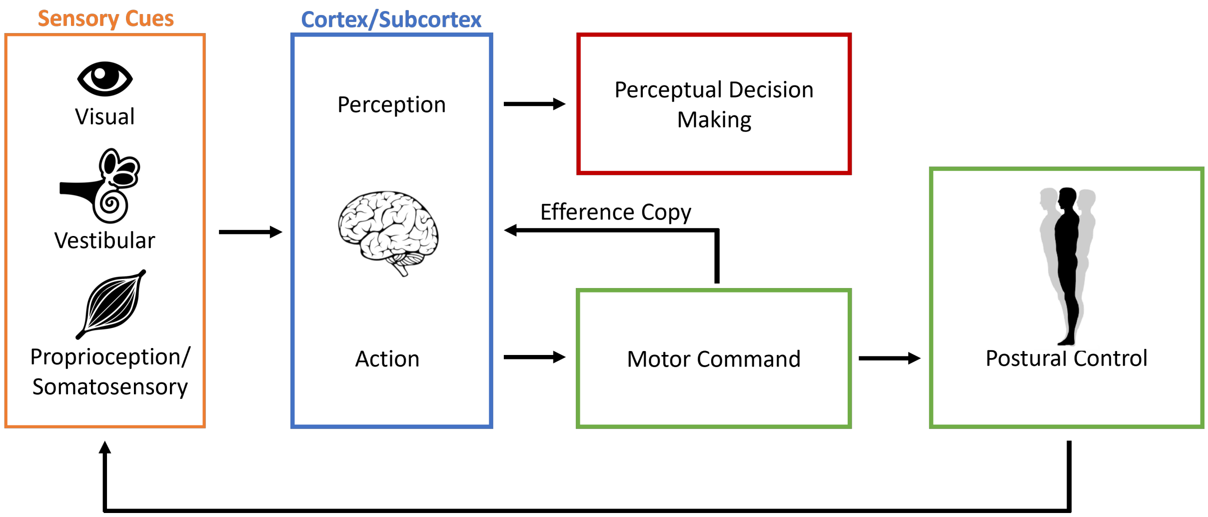

Figure 1.1: The outlined framework visualizes how sensory information provides the initial input needed to drive both perception and action. Subsequently, perception and action utilize similar pathways but can deviate at sub-cortical and cortical structures. Study #1 and #2 focus on the perceptual framework wherein the focus was to explore how individuals perceive the onset of postural instability and how altering visual context can impact these perceptual decisions. These responses are driven by cortical processing of the sensory information retrieved by the various senses. Study #3 is focusing on the behavioural or motor action responses related to visual motion cues. This action pathway runs in parallel to the perceptual pathway wherein the same sensory cues are utilized but the involvement of sub-cortical and cortical structures can play a role in the production of the motor commands to control posture. These motor commands also send an efference copy of the motor command back to cortical and sub-cortical structures. The subsequent postural responses results in the sensory systems receiving updated information about body motion, resulting in a feedback loop to the sub-cortical and cortical structures. Together this thesis is attempting to understand how each of these pathways can be affected by alteration of visual information and the potential link between perception and action related to postural control.

Visual information is an important sensory modality due to the role this sensory system plays in providing cues about the external environment and an individual's body schema in their environment. Visual cues can provide context about self-motion, environmental motion and the location of objects and how their body position relates to these objects. Each piece of this visual feedback can alter perception of postural events and the resultant behavioral responses. This has been observed when individuals are exposed to situations of perceived threat, resulting in both psychological [48, 260] and postural changes [38, 44].

While much is known about the relative perceived timings of various sensory events compared to each other [222, 263, 89, 241, 32], the relative perceived timing of events such as postural perturbation, arguably a very meaningful and potentially life threatening event, has only recently been investigated [148, 149]. Here it has been shown that the onset of a postural perturbation has to occur approximately 45 ms prior to a reference auditory stimulus in order to be perceived as simultaneous [148, 149]. However, this work has not considered the possible role that vision may play on the perceived onset of postural instability. Additionally, exploring how visual information of differing context, such as a perceived threat has not been explored to determine how this may alter an individual's perception of postural instability onset. Understanding postural instability perception and the relative role of different sources of sensory information on postural instability perception could be used to understand how the CNS utilizes sensory feedback to form an individual's perception of postural events and perhaps lead to better fall prevention strategies.

Behavioral responses related to visual feedback have also been broadly explored over the years, from isolating visual motion and its effect on balance [137, 136, 37, 125] to how visual context impacts responses during quiet stance [43, 50] or during physical motion [42, 49]. Though limited research has explored the effect of visual motion with differing visual context (such as perceived threat) and movement characteristics. It is known that visual motion can give the sense of self-motion resulting in postural responses, however how this visual motion is presented to an individual can directly affect the observed behaviour [37]. Therefore, further exploring the effect that visual characteristics have on self-motion perception and the resultant behavioral responses could assist in understanding what factors of vision can dictate posture and balance.

1.1 Control of Standing Balance and Posture

Postural control is a complex sensorimotor task that encompasses two major components: postural orientation and postural stability/equilibrium which can also be referred to as balance [164, 96, 101, 111]. Postural orientation is when the body and the associated limbs are aligned with a reference frame such as gravitational vertical or visual vertical. Postural equilibrium/balance is a state which is achieved through maintaining the centre of mass (COM) within the base of support (BOS) [96, 255, 164, 67, 101, 111]. The COM is maintained within the confines of the BOS through altering the position of the centre of pressure (COP) [176, 192]. The COM represents the mean position of the cumulative mass of the individual, while the BOS represents the area encompassed between the limbs that are in contact with a support surface [255, 192]. The COP is the sum of pressure applied through the body through muscles forces on a focal point to maintain the COM within the BOS. To monitor postural control, the CNS needs to receive a constant influx of information which is then utilized to update an individual's body schema. Body schema is the representation of one's body and limbs in space, which is continually updated during the control of posture and balance. To continually maintain posture, the CNS receives both feedback and feed forward information about the body [165, 164, 252, 66]. Feedback information is typically referred to as the sensory information that is transmitted to the CNS, which includes: somatosensory, vestibular and visual inputs. Feed forward information is utilized to produce predictive type motor commands based on internal body representations, this information then produces a generalized motor command in attempt to limit the loss of balance. Together, this information allows for the precise control of posture and balance through error detection and correction to ensure that postural orientation and stability are maintained.

1.2 Sensory Involvement in Posture and Balance

The importance of sensory information in the control of balance has been briefly emphasized in the previous sections. The role of sensory information is to provide feedback to the CNS about how our body is moving as well as providing information about our external environment; together this information allows for the formation of motor adjustments to be made to maintain balance. The somatosensory, visual and vestibular systems each have a specific role in the detection of postural instability, which the CNS utilizes to integrate and produce a cohesive representation of posture and balance [16, 118, 145, 146, 102, 15]. Each of these sensory systems are re-weighted depending on the conditions an individual is currently exposed to and the reliability of each of the sensory modalities during the postural task.

1.3 Visual System

1.3.1 Processing Visual Information

The visual sensory system provides an abundance of information with respect to the external environment when controlling balance. The visual system detects motion in the external environment and provides information about self-motion; which is defined as the movement of an individual's body or internal frame of reference. Light enters the eye and is focused on the retina after passing through the cornea, lens, and aqueous humour. There are two different pathways from the retina that project to the lateral geniculate nucleus (LGN) in the thalamus; the magnocellular and parvocellular pathways. The m-cells in the retina project along the magnocellular pathway, while the p-cells project along the paravocellular pathway. The magnocellular pathway is involved in the detection of temporal characteristics of the environment such as motion. The parvocellular pathway is involved in the detection of spatial characteristics and colour of the environment. Both pathways project to the primary visual cortex (V1) where this information is processed and subsequently transmitted to other cortical regions. From V1, the magnocellular pathway feeds into the dorsal stream of visual information which is involved in motion processing, while the parvocellular pathway feeds into the ventral stream of visual information involved in object recognition. This dorsal stream projects to the middle temporal area (MT) which is devoted to motion processing. It has been observed that lesions to the MT cause a decreased ability to detect motion [210, 73]. From the MT, the dorsal stream has projections to the middle superior temporal area (MST) which responds to visual motion and optic flow [77]. The ventral pathway projects to V4 and the inferior temporal area of the temporal lobe, which is involved in object/face recognition as well as colour and shapes [77].

1.3.2 Visual Motion and the Sense of Self-motion

Optic flow is the detection of movement of the body with respect to the external environment through the retina, the retina detects the focus of expansion which allows for the determination of directional movement. Optic flow is in turn known to be important in the sense of self-motion implying an importance of the dorsal stream in the perception of self-motion [134, 77].

The role of visual information, which includes visual motion in the control of balance, has been classically explored with the use of sensory re-weighting or isolation studies. The effect of visual motion on balance control was prominently first explored with the use of moving room paradigms [137, 136, 182]. This paradigm has the participant stand in a room that has walls which can independently move from the floor. The independent movement of the walls introduces a visual perturbation to the individual, while the walls create a sense of self-motion through focal expansion and contraction. This sense of self-motion can then evoke postural responses. Children and older adults are strongly influenced by this sense of visually evoked self-motion or vection, resulting in responses that counter act the perceived self-motion. [137, 136, 138, 92, 18]. These findings indicate the importance of perceived self-motion on overall balance control and how this visual stimulus can drive postural responses, especially in younger and older populations. Characteristics of visual motion can also alter the amplitude of postural sway responses, this includes speed, direction, and type of visual flow [92]. It should also be noted that when the participants know when a visual perturbation is going to occur, there is not a resultant postural response [84]. This indicates that anticipatory responses can negate the effect of visual flow on postural control.

1.3.3 The Effect of Visual Cue Availability on Balance and Posture

Investigation of the role of vision can also be explored in other ways that do not revolve around the introduction of visual motion to the individual. For instance, visual information can be simply removed by closing the eyes or wearing a blindfold. The role of visual information in the control of balance can then be evaluated by comparing how individuals perform in a balance related task with and without visual information. Previous work has shown that removing visual information contributes to a small change in postural sway characteristics [8, 16, 11]. As these are not dramatic effects, it suggests that other sensory cues can effectively compensate for the loss of visual information during early stages of balance control. As such, removing visual information represents a simplistic method to isolate sensory feedback in the control of posture and balance and evaluate how visual cues effect subsequent responses.

1.3.4 Visuospatial Cues Effect on Balance and Posture

The utilization of visuospatial information about the surrounding environment prior to an external perturbation has been shown to be incorporated into change in support strategies [74, 264]. The use of visuospatial information is also used by individuals when they are exposed to a situation that can be perceived as posturally threatening, such as being at an elevated height [43, 50, 104, 261, 48]. It has been observed during quiet stance when individuals are situated at an elevated edge they will lean away from the edge, while also decreasing the amplitude and increasing the frequency of COP and COM sway [43, 44, 50]. Postural threat also effects dynamic postural responses to external perturbations, specifically resulting in decreased postural sway with an increase in muscle activity and a decrease in muscle activation onset, or in other words a stiffening response [38, 217, 42, 49]. Taken together, these studies demonstrate that threatening visual information processed prior to postural instability can have a direct impact on the adopted motor responses in both quiet standing and dynamic balance control. It should be noted that the constant presentation of threatening visuospatial cues are not required to exhibit alterations in postural responses. Research has exhibited that when participants are exposed to a perceived threatening situation that threat induced postural sway parameters are still evident with limited peripheral vision [56] and with no visual information [1]. Indicating that the initial visual presentation of threatening stimuli is enough to evoke these observed postural alterations.

1.4 Proprioceptive & Somatosensory System

1.4.1 Proprioceptive & Somatosensory Processing

The proprioceptive system detects a variety of sensory cues to provide a representation of bodily movement and position. Proprioception is critical in the control of balance because it provides feedback on body and limb position. The proprioceptive system relies on both muscle and skeletal receptors, such as muscle spindles, golgi tendon organs and joint mechanoreceptors, to relay sensory information. Muscle receptors detect various changes regarding properties of muscle mechanics including muscle length, contraction, stretch and speed, while joint receptors can determine joint angle [211, 201]. Afferent information from these various receptors travel to the dorsal root ganglia before entering the spinal cord through the dorsal horn. Afferent information from the lower limbs travels in the gracile funiculus and terminates in the gracile nucleus located in the medulla. Conversely, upper limb afferent information travels in the cuneate funiculus and terminates in the cuneate nucleus. Axons from the in the gracile nuclei and cuneate nuclei form the medial lemniscus which decussate to the contralateral side and ascend to the thalamus. The medial lemniscus terminates at the ventral posterior lateral nucleus in the thalamus, which then projects to the somatosensory cortex where this information is processed somatotopically. This information can then be processed in various association areas such as 5 and 7 and in motor cortices.

1.4.2 Proprioceptive and Somatosensory Involvement in Balance and Posture

Proprioceptive and somatosensory feedback is believed to be the most heavily relied upon sensory modality in the control of posture and balance [100, 57, 108, 196]. The speed of proprioceptive processing is very quick, as reaction times have been seen in the range of 60-155 ms [54, 151, 212, 161]. In addition, using electroencephalogram (EEG) measuring somatosensory evoked potentials (SEP) from a direct stimulation of the radial nerve produced cortical activation in as little as 20 ms [151, 133]. The importance of proprioceptive information has commonly been reinforced with the exploration of sensory re-weighting research methodology as previously discussed.

Isolating proprioceptive information is a difficult task due to the large variety and number of various somatosensory receptors throughout the body. However, there are methods to partially limit somatosensory input to the CNS to provide general insight into the effects of somatosensory modification on the control of posture and balance. Some of the methods that have been implemented include tendon vibration, ice baths, compliant surfaces and sway referenced surfaces [118, 253, 103, 167, 165, 181, 16, 233]. This research is important in providing an understanding of how well the other sensory modalities can compensate for this unreliability with proprioceptive feedback. When researchers actively reduce the reliability of proprioceptive cues, the CNS must re-weight sensory feedback to rely more prominently on the unaffected sensory cues during a balance task, usually implying that visual and vestibular cues become critical in the maintenance of balance. Sensory re-weighting designs can provide researchers with insight into how balance responses are altered with the increased reliance on other sensory modalities.

There is one recorded instance of complete proprioceptive loss from the neck down in an individual, referred to as patient IW, caused by an auto-immune reaction following a severe fever [57]. This complete loss of proprioceptive and somatosensory input left IW with the inability to sense touch or determine limb orientation. The only way IW could determine where their limbs were during both passive movement and active movement was to use their eyes to visually confirm what their limbs were doing [57]. This extreme case was able to demonstrate the effect of complete proprioceptive loss on the control of posture and balance. This individual exhibited much greater COP sway than healthy individuals and was incapable of maintaining balance without visual information [57]. IW was also more prone to galvanic vestibular stimulation with the loss of somatosensory feedback when compared to healthy populations. It is important to note that patient IW represents an extreme case and it is known that both healthy young and older populations can maintain balance with the removal of visual input due to information provided by proprioceptive and vestibular systems [165, 100].

1.5 Vestibular System

1.5.1 Vestibular Processing

The vestibular system is involved in the detection of both linear and rotational head accelerations. Information about head accelerations are utilized in the detection of self-motion, voluntary and reflexive movement, oculomotor control and spatial orientation. The vestibular system is composed of two primary types of organs, the otolith organs and the semicircular canals. The otolith organs are composed of the utricle and saccule, which provide information about linear acceleration in both the horizontal and vertical plane, respectively, as well as tilt of the head relative to the constant force of gravity which is equivalent to an upwards acceleration. Within the otolith organs are the otoconia embedded in the otolithic membrane on top of hair cell stereocillia. Movement causes a displacement of the otoconia and otolithic membrane resulting in a deflection of the stereocilia causing the activation of the hair cells. The semicircular canals contain endolymph within the canals, as well as the cupula which also contains stereocilia. Rotation of the head introduces an inertial component to the endolymph resulting in the displacement of the stereocilia causing the activation of the hair cells. The semicircular canals provide information about rotational accelerations from the posterior, anterior and horizontal canals which detect pitch, yaw and roll accelerations collectively. Vestibular cues are transmitted via the vestibular nerve to the vestibular nuclei located in the medulla and pons; the lateral and descending nuclei receive input from the semicircular canals and otolith organs. Descending visual information is also received by the vestibular nucleus. At the cortical level, vestibular information has been observed to be processed in the parieto-vestibular insular cortex (PIVC) and the dorsal middle superior temporal lobe (MSTd). Visual information is also believed to be processed in these regions, highlighting the close relationship between these two modalities [81, 82, 68].

1.5.2 Vestibular Involvement in Posture and Balance

Vestibular information has been shown to be processed at slower speeds compared to somatosensory, visual and auditory information. Specifically, it has been observed through vestibular evoked potentials (VEPs) that they can occur as early as 20 ms [59], or as late as 200 ms after the onset of the vestibular input [25]. Reaction times to vestibular stimuli have also been shown to have longer latencies; Barnett-Cowan and Harris, (2009) [23] exhibited reaction times of 438 ms to galvanic vestibular stimulation (GVS) which is substantially longer than both somatosensory and visual systems. The role of vestibular input has been observed to have a moderate effect on postural control through GVS and natural degradation including unilateral vestibular loss (UVL) and bilateral vestibular loss (BVL) [167, 103, 195, 146]. The use of GVS directly introduces an electrical stimulus to the vestibular nerve which results in the activation of all the vestibular organs, leading to the perception of illusory head movement. Research utilizing GVS revolving around these techniques has found that the vestibular system has an effect on postural sway and balance [30, 57, 84, 76].

Additionally, due to the close interaction between vestibular and visual information, as observed through the vestibular ocular reflex, visual information has been found to greatly decrease the effect of vestibular input on the control of balance [84]. In addition, the patient who lost his somatosensory system, patient IW, was exposed to GVS to investigate the effect of vestibular stimulation on the control of balance. Here, patient IW had much more pronounced postural adjustments to GVS compared to controls, but they were able to maintain balance with their eyes open. However, they exhibited a complete inability to maintain balance when their eyes were closed [57]. This has led researchers to believe that vestibular sensory cues can play less of an immediate role in the control of balance when compared to somatosensory and visual systems.

1.6 Multisensory Integration and Sensory Reweighting

The CNS utilizes each of the sensory modalities to produce the most accurate representation of balance and posture. This is proposed to be achieved by giving a weight to each sensory system depending on the reliability and importance of sensory cues which is dependent on the task being performed [118]. The usefulness or reliability can vary dramatically depending on the conditions presented to an individual. Visual information could be down-weighted in situations of low light or up-weighted in conditions where the visual information is providing important environmental cues related to postural threat. Sensory reweighting research has exhibited that postural responses can be directly impacted by these changes in sensory cue reliability, specifically when introducing conflicting sensory cues in regards to balance control [118, 191]. Additionally, sensory re-weighting and optimal multisensory integration affects the perception of events as well. Sensory reweighting ensures an accurate and precise representation of events when more than one sensory modality is involved [10].

1.7 Cortical Activity in the Control of Balance and Posture

The understanding of the role of the cortex in the control of balance is a rapidly growing field of research. For years, it was believed that sub cortical structures were in control of balance responses without the involvement of the cortex [213, 153]. It was previously demonstrated that cats and dogs that suffered spinal lesions were unable to stand, whereas decerebrate animals exhibited tonic muscle activity to maintain an upright posture [213, 153]. When utilizing platform perturbations, it was found that spinalized animals exhibited an inability to maintain upright stance or produce a compensatory postural adjustment (CPA) to the perturbation [152]. Decerebrate cats also exhibited direction specific postural responses to external perturbations, like that of intact cats [95]. However, these decerebrate cats were unable to produce large enough responses to oppose the postural perturbation [95]. These findings indicate a clear role of the sub cortical structures in the control of balance, but research has also exhibited a role of the cortex in balance control. Individual measurement of layer 5 corticofugal neurons in the motor cortex were found to be active during a balance task among rabbits in which they responded to occasional platform tilts and during locomotion [29]. These layer 5 corticofugal neurons are known to be connected with the thalamus, subcortical and the spinal structures involved with motor pathways. Similarly, it was also found that pyramidal tract neurons in the motor cortex representing the forelimb in cats were active in this same platform tilting paradigm [28]. The involvement of the cortex in the control of balance has been observed in animals and humans suffering from motor cortex lesions; they exhibit abnormal compensatory stepping responses to control balance when exposed to perturbations [61, 20]. These findings set the pretense that the cortex and subcortical structures play a role in the control of balance and that these findings can be related to humans as well. It has been theorized that postural responses may occur in different latency loops.

The first latency loop is the short latency (SL), they are believed to represent the role of reflex pathways to the spinal cord; however, SL responses are not enough to control balance alone [112, 179]. The medium latency (ML) responses are believed to represent either poly-synaptic reflex pathways or pathways travelling to subcortical regions resulting in activation of muscle stabilizing activity and various whole-body muscle synergies that are involved in balance control [112, 179]. The long latency (LL) responses correspond with transcortical loops which indicate the role of cortical regions in the control of balance [179]. The role of the cortex may not be involved in the early stages of the postural responses, but rather may be involved later to help shape and modulate postural responses. The involvement of the cortex in later phases of postural control has been observed with the use of transcranial magnetic stimulation (TMS) over the motor cortex, resulting in increased muscle activity in postural muscles (i.e. soleus) [232]. Alteration of the rectus femoris activity has been observed via electromyography (EMG) when stimulating the motor cortex with TMS during the LL response window. TMS stimulation that was timed to SL and ML responses did not have any affect on EMG responses in the rectus femoris during a passive stretch of the muscle, but a modulation of EMG activity was observed in the LL response [179]. These findings suggest that the cortex can play a role in the modulation of postural responses, though the role of this cortical involvement may not be until later in the postural response. Therefore, it is important to consider how the cortex utilizes sensory cues and how perception could provide insight into how the cortex utilizes sensory cues in the production of motor responses to balance.

1.8 Measuring Posture and Balance

1.8.1 Force Plates

A primary method to measure balance and posture is using force plates. Force plates are a tool that measures forces and moments applied at the feet. These forces and moments can subsequently be used to calculate the centre of pressure (COP). As previously mentioned the COP is the sum of pressure applied through body forces on a focal point to maintain the COM within the BOS. In the circumstance of standing balance and posture that is primarily done through forces applied at the feet. The COP is a commonly utilized measurement within the realm of balance and posture as a variety of different measures can be utilized. The COP sway provides context in overall movement of the individual whereas measures such as the root mean square (which is a measure of variability) or pathlength can be calculated to give a sense of the amount of sway over a period of time [125, 193]. Additionally, measures about onset of COP sway, peak amplitude of COP sway or directionality of the COP sway can be derived to gauge balance and posture characteristics [52, 193]. This makes force plates a useful measure in gaining an overarching view of an individual's balance and postural responses.

1.8.2 Accelerometers

Accelerometers are a tool that can measure the acceleration of different body segments. By placing accelerometers on various body segments such as the head, torso, or legs, researchers can gather insight on how a specific body segment responds during a balance and posture task [5]. This is useful because unlike force plates which provide a cumulative measure of balance and postural responses, accelerometers can differentiate movement at different parts of the body and provide more context as opposed to assuming a rigid body [209, 5]. For instance, accelerometers on the limb can provide measures of acceleration variability, peak acceleration and rate of change; while velocities and displacements can also be derived from accelerometers with some limitations in accuracy. Tandem use of accelerometers with force plates may be particularly useful as additional information can be provided about body movement during the control of balance and posture.

1.8.3 Electromyography (EMG)

The use of electromyography (EMG) allows for researchers to explore how muscle activity changes during balance and posture. This is a useful measurement because EMG provides one of the earliest measures of motor responses to balance and posture [67]. EMG serves as method of measuring response speed to balance and posture by examining the onset of EMG for a targeted muscle. This differs from force plate and accelerometer data which typically represents the motor outcome performed by muscles. Further, EMG can be utilized to provide information about the amplitude of a muscular response, allowing one to quantify the magnitude of response needed to control balance and posture.

1.9 Perception

1.9.1 Perception of Sensory Events

The detection of sensory signals and converting these physical stimuli into electrical inputs is the concept of sensation. This sense of sensory information can drive both perception of events and action in response to sensory events. Perception is achieved through the processing and integration of sensory information to form a meaningful and accurate representation of both our internal and external environments. Forming an accurate perception of events of both the internal and external environment requires the CNS to be able to receive, integrate and bind information to produce coherence between stimuli. Coherence is the ability to integrate various sensory cues that are conducted at varying speeds, transmitted to various cortical regions and processed at different rates to be utilized to produce an accurate perceptual representation of our actions and the environment. It is important that sensory information occurring from the same event is bound together when forming perceptual representations of events as this coherence could have a direct effect on action.

Research has explored how individuals perceive sensory information during perceptual tasks in order to gain an understanding of how the CNS accounts for detection, transmission, and processing differences across modalities. Commonly utilized stimuli for comparison are visual, auditory and tactile sensory cues. Here it has been found that visual stimuli typically needs to precede auditory cues to be perceived as synchronous [130, 122, 113], touch must occur prior to visual stimuli to be perceived as synchronous[223, 222, 88, 89], touch needs to be presented prior to sound to be perceived as synchronous [185, 89] and vestibular cues need to precede vision, touch and auditory cues to be perceived as synchronous [23]. This research demonstrates that when investigating the perception of sensory events there are observed perceptual delays between different sensory modalities. However, there has been limited research investigating multisensory events such as balance to explore how sensory cues utilized together affect the perceived timing of events.

Perception and action have a close relationship but can subsequently be independent in certain circumstances as well. This applies directly to postural control, as SL and ML responses which do not included cortical input can produce initial postural responses [112, 179]. Conversely, it is the sensory feedback from the various senses that allow for LL responses to modulate and adjust early postural responses to produce the most accurate and precise response [112, 179]. Therefore, attempting to understand how perception is related to motor action of postural control could provide greater insight into the specific relationship perception has on different aspects of postural control. One could argue that perception may not be involved in early aspects of postural control but rather has a large effect via indirect modulation of postural responses. Though it has been observed with cognitive tasks completed during postural stance results in an increase of postural sway in both younger and older adults, with older adults exhibiting amplified effects [216]. These findings exhibit the importance of the cortex in postural control. Therefore, gaining a greater sense of how perception and action are related in the realm of postural control could result in improved methodology and techniques to evaluate postural control, specifically in older and clinical populations. Perceptual measures revolving around postural control have been typically quantified with the use of questionnaires. These questionnaires can inquire about the sense of fear, anxiety and postural confidence related to postural control [50, 49, 261]. These can be quick, practical and simplistic ways to understand how the perception of a postural event may be related to behavioural strategies related to postural control. However, questionnaires can lack a level of specificity or nuance in regards to how the individuals may perceive the event. Therefore, attempting to explore other methods and techniques to quantify an individuals perception during a postural task may be utilized as a starting point of gaining a greater understanding the relationship between perception and action during postural events.

1.9.2 Perception of Postural/Multisensory Events

There has been limited research investigating how multisensory events, specifically postural instability, are perceived by individuals [148, 149]. A postural perturbation poses a risk to an individual's serviceability. One would expect that the perceived timing of the onset of postural instability should be quite fast. However, these researchers found that the onset of a postural perturbation had to occur approximately 45 ms prior to a reference auditory stimulus in order to be perceived as simultaneous. The findings are interesting considering the importance of detecting and responding to postural instability, and the rapid processing speeds of sensory cues such as proprioceptive input [54, 151, 212, 161]. The delay of postural instability perception has been demonstrated to be increased in the elderly population [149], suggesting that perception of postural instability and postural responses, as well as control of posture and balance can decline with age [11]. Hence, further investigation and taking a critical approach to how multisensory events such as postural instability is perceived could provide insight into a relationship between perception and action.

1.9.3 Temporal Order Judgement Tasks

In order to investigate the perceptual latencies of various sensory modalities, a Temporal Order Judgement (TOJ) task can be utilized. A TOJ task is when an individual is presented with two different events and are required to make a forced choice about which event occurred first [248]. The response made by the individual is not based on reaction time, meaning the individual can take their time when making their decision. These binary choice responses are recorded and averaged, allowing a logistics function to be fit to the data to measure two critical parameters: the point of subjective simultaneity (PSS), which is a measure of accuracy between true and perceived simultaneity, and the just noticeable difference (JND), which is a measure of precision or variability of the participants choices. Research utilizing TOJ tasks has observed that perceptual delays appear to exist when comparing sensory modalities, exhibiting this task's potential usefulness in exploring perceptual processing of sensory events.

1.10 Virtual Reality

Implementation of new integrative techniques is vital in the progression of both basic and rehabilitative research to provide new methodologies to explore and diagnose posture and balance behaviour. A piece of technology that has become much more predominant in this area of research is virtual reality (VR). Virtual reality is a visual experience that allows individuals to be placed in a unlimited number of situations. This is a powerful piece of technology because it provides many advantages over visual constraints that are present within most research spaces. For instance, VR is not constrained by space, allows the isolation of visual information from the other sensory modalities, provides the researcher flexibility in altering the visual scene, and removes the associated danger and risk involved with certain situations (i.e., being at height or being exposed to fearful stimuli). Individuals can also use VR remotely, limiting the requirement of having a researcher or rehabilitative specialist present. VR being a novel and entertaining piece of equipment also allows the user to have a positive and enjoyable experience. However, there are limitations with VR such as the weight of the headset, movement constraints to the virtual environment, reduced peripheral vision in comparison to the real world, delays in the presentation of the virtual environment and differences in immersion of the individual in the virtual environment [177]. Each of these limitations can have a direct impact on the potential outcome and usefulness of VR in the context of research. These limitations can all result in a reduced ability to immerse an individual in a virtual environment [177]. This sense of immersion of presence is functionally one of the most important aspects and unique qualities of VRHMD [220], it is this attempt to replicate the real world or realistic environments in a virtual world. If an individual lacks a level of immersion due these various limitations it can result in a reduced ability to make conclusions about the observed effects of virtual scenes in comparison to real world scenes. Therefore, these limitations also need to be accounted for and acknowledged within the study design and need to be considered when discussing research results.

The implementation of VR has been utilized in sensorimotor training paradigms in clinical populations such as stroke and Parkinson's disease [259, 46, 221]. These studies used VR training and a force plate platform to understand balance in these clinical populations. The force platforms were able to tilt and add mechanical perturbations to the VR environment [259, 46]. The use of VR in these types of paradigms is uniquely insightful as static and dynamic visual information can be provided to an individual while also manipulating various characteristics of the visual stimuli. It is also important to understand the different categories of VR; two dimensional VR presentations (on a screen in front of the participant) are considered non-immersive, three dimensional VR presentations with a fixed perspective (cannot actively change visual perspective) are considered partially immersive, while three dimensional VR presentations with head movement are fully immersive [2]. The use of visual motion and the corresponding effects has been explored with the use of both physical and virtual visual scenes [137, 136, 138, 84, 240]. When virtual visual scenes - typically composed of dots and other shapes [85, 202, 31, 237, 9, 146, 87] - are projected onto a screen in front of participants, participants often experience a postural sway. This finding suggests that these shapes can produce a sense of self-motion to individuals. However, it is important to recognize that the visual scenes used in these studies lack a meaningful visual context relative to day-to-day life.

It is of interest to understand how individuals respond to realistic virtual environments as changes in physical height have been show to directly impact posture control, resulting in a reduced amount of sway and increased lower leg activity [217, 42]. There has also been some recent research starting to explore how virtual visual information can affect postural control under varying conditions. These studies have primarily focused on how postural threat affects postural control, many of which utilized a form of virtual height to evoke a sense of threat to the participants. Virtual height appeared to have similar effects to physical height in that participants had increased muscle activity at the lower leg muscles, and there was also earlier and larger COP onset after the external perturbation [49, 48]. During quiet standing studies with virtual height, there is an observed decrease in overall COP sway when compared to non-threatening virtual stimuli [50, 261]. This is indicative of an overall trend that is similar to that observed during studies examining postural responses at a physical height, individuals typically want to limit overall COM movement. This also demonstrates that VR environments can be evocative enough to produce the same sense of urgency and awareness that physical heights can provide. One aspect to note is that external perturbations have been primarily used in cohesion with these VR scenes, as opposed to the visual scenes being the primary modality of instability. One question that has not yet been fully assessed is whether visual perturbations that provide meaningful and realistic context to individuals can affect posture [125, 187]. The utilization of VR as a rehabilitative piece of equipment is of specific interest due to the increased reliance on visual information in the elderly population.

1.11 Overview of Dissertation

The overarching goals of this dissertation are to assess how postural instability is perceived by individuals and how this perception of postural events changes under differing visual conditions. Additionally, I wanted to explore how perceived self-motion evoked by visual motion using VR may be altered under differing visual conditions and how this may alter behavioural outcome measures related to balance control.

Chapter #2 was designed to first test how methodological design may impact the perception of postural instability onset. This study was motivated by previously conducted research utilizing TOJ tasks that observed postural instability onset perception was slow in comparison with an auditory cue. This study directly challenges the results of prior work by showing that 1) alterations to the stimulus onset asynchrony (SOA) distribution in the TOJ task, and 2) using an automated lean and release system as opposed to a manually operated lean and release system can both change the perception of postural instability onset.

Chapter #3 was a two-part experiment design based on Chapter #2 and explored how visual information may effect the perception of postural instability onset. The methodological alterations utilized in Chapter #2 were applied to each of these experiments to provide visual information to participants. The first experiment presented conditions that provided visual information and removed visual information; then a comparison was made to determine if visual information altered perception of instability onset. The second experiment expanded on this concept by altering the context of the visual information. Participants were provided with visual information in both conditions, but one condition utilized a virtual reality head mounted display (VRHMD) to expose the participants to a perceived threat (placing them at the top of a virtual sky scraper). This allowed us to determine how visual context may alter perceptual outcome measures related to postural instability onset.

Chapter #4 was designed to explore how visual perturbations can alter behavioural responses. This design utilized a VRHMD to present a variety of differing visual motion conditions, ranging from linear motion, rotation motion in the anterior and posterior directions and also attempted to alter perceived threat through the use of virtual height. As opposed to using the TOJ task, this study looked to explore how postural behaviour may change under different visual conditions. This allowed for the exploration of how perception of self-motion and perceived threat may alter postural responses.

Chapter 2

Investigating the Effect of Methodological Protocol on the Perceived Timing of Postural Instability Onset

2.1 Abstract

The perceived timing of uni-sensory events has been explored at length, where it is well established that there are pronounced differences in the perceived timing of stimuli detected by different sensors. In contrast, the perceived timing of multisensory events, such as the control of balance and posture control, have only been recently explored. Previous research investigating the perceived timing of postural instability onset found that postural perturbations need to occur significantly earlier than an auditory reference stimulus (~ 44 ms) in order for individuals to perceive these stimuli as simultaneous. This suggests that the perception of postural instability onset is slow, which could help explain fall perception and inform fall prevention programs. That postural instability onset perception may be slow is surprising due to the ecological importance of quickly detecting and producing responses to postural events. However, there are methodological concerns with respect to the way in which this prior work was conducted and measured. Specifically, using an unbalanced stimulus onset asynchrony (SOA) distribution of perturbation and sound stimulus pairings. Past work presented an SOA distribution that was not controlled between participants and was not equally distributed around true simultaniety (0 ms). Therefore, the present experiment was designed to determine if the methodological choices made in this previous research impacted their observed results. Here we attempt to reproduce the methodology utilized in previous research, primarily by comparing how an unequal SOA distribution versus an equal SOA distribution impact the point of subjective simultaneity. The results show that an unequal SOA distribution results in a perceived delay of the postural instability onset by 20.34 ms, while the equal SOA distribution resulted in a perceived delay of the auditory cue of 3.52 ms, this difference was not significant. Impor-

tantly, neither of these conditions were significantly different from true simultaneity (0 ms). Therefore, when utilizing a more controlled methodology there is no perceptual delay of postural instability onset in both the unequal and equal SOA distributions. Our approach highlights the importance of controlling methodological parameters when investigating the perception of sensory cues, and will help inform falls prevention strategies.

2.2 Introduction

Formation of an accurate perception of our world requires the central nervous system (CNS) to rapidly detect energies and self-motion from the environment using specialized sensors and to combine information from different sensory modalities. The CNS is challenged to determine what multisensory information belongs together, what does not, all while accounting for the different transmission and processing speeds of each of these modalities. This is known as the binding problem [128]. Consequently, the CNS determines the temporal order of events and these temporal decisions made by the CNS affect our perception and actions. There has been much research exploring the perceived timing of various sensory modalities; auditory [222, 23, 241], visual [223, 222, 23, 241], tactile [223, 222, 23] and vestibular [23, 24, 26]. This research has shown how the perceptual timing of these different sensory cues varies across each modality and how differing temporal and spatial characteristics of these modalities can affect perceived stimulus onset. However, there is limited research exploring the perceptual timing of multisensory events that have a direct impact on safety and survival.

Work assessing the perception of self-motion onset using temporal order judgement tasks (TOJ) has found that participants require self-motion to begin before a reference auditory stimulus in order to perceive these as occurring simultaneously, which suggests that the perception of self-motion is slow [47, 24, 26]. Similar results were also found for the perceived onset of postural instability in both younger adults [148, 149] and older adults [149]. Here, it was observed that younger adults indicated that a fall had to occur 44 ms before the reference auditory tone in order to be perceived as occurring simultaneously [148, 149], and this delay in the perceived onset of a fall was significantly longer in older adults (88 ms; [149]). These researchers had proposed that the cause of this delay may be due to the slower perception of vestibular inputs, which are stimulated during the postural event. The purpose of the present study is to assess an alternative hypothesis, that this delay may stem from the methodology utilized during the experiment.

The TOJ task presents two different stimuli with varying stimulus onset asynchronies (SOAs) and participants respond by stating which event they perceived to occur first. From these responses the point of subjective simultaneity (PSS), which is a measurement of accuracy relative to the point of true simultaneity (SOA of 0 ms), and the just noticeable difference (JND), which is a measurement of precision, can be determined [248]. The PSS is defined as the 50% probability of detecting one stimulus before the other, while the JND is defined as the interval between this 50% point and the 75% point [248]. The TOJ task utilizes a range of SOAs around true simultaneity (0 ms) to get a measurement of an individual's perception of the relative timing of two presented stimuli. Traditionally

SOAs are equally distributed around 0 ms and the SOAs are repeated the same number of times at each SOA (method of constant stimuli) to get an average response at each SOA. The benefits of this type of design are that researchers know that with SOAs being equally distributed around true simultaneity (0 ms) there is a reduced potential to introduce bias in the participants' responses.

In the works of Lupo and Barnett-Cowan, the distribution of SOA's was not controlled this precisely. In these works an experimenter was instructed to manually trigger a postural perturbation in response to a visual "go" signal [148, 149]. This methodology allowed for some trials to present the auditory reference stimulus to occur before, during and after the postural perturbation, however it also yielded a random distribution of SOAs. This protocol has also been used in other types of self-motion studies, more typically applied for when a participant is required to move their self [47, 24]. Manually triggered stimuli can also introduce the issue that SOAs are not repeatable. Typically the method of constant stimuli is employed in TOJ tasks, where a set of fixed SOAs are repeated numerous times in a random order. This was not possible when relying on a human experimenter to react to a stimulus to then manually trigger a postural perturbation; achieving the same SOA multiple times consistently through a manual trigger is basically impossible. The benefit of the method of constant stimuli is that SOAs are repeated several times in a TOJ task and the responses can be averaged to give a probability of how a participant perceives these specified delays at each SOA. With the lack of repeated SOAs researchers need to bin data within a certain window of time. In the case of Lupo and Barnett-Cowan's research, they utilized 10% of the total trials as the bin size [148, 149]. Therefore, the averaged bins contain responses to a variety of different SOAs which could also impact the outcome measures.

The present study was designed to assess these potential design flaws in previous research exploring the perception of postural instability onset. Since cortical activity related to postural events occurs rapidly, within the range of 90-150 ms [244, 173, 224, 62], the perceptual delays for fall onset are questionable, particularly as these fall-related cortical responses are comparable to what is observed in cortical activity related to auditory events, which occur within a range of 50-150 ms [188, 236, 132]. Additionally, research has exhibited that the continuous presentation of asynchronous stimuli can directly impact the PSS during a TOJ task [172, 249, 229, 71, 89]. Hence the goal of this study was to design a TOJ task that introduced controlled and repeatable SOAs across all participants. Given the importance of reproducibility [53] and falsifiability [199] in science, the present study served to replicate and extend on this prior work on the perceived timing of postural perturbations. The primary a priori hypotheses are:

1. An equal SOA distribution will result in a mean PSS that is closer to true simultaneity in comparison to an unequal SOA distribution.
2. An equal SOA distribution will result in a mean PSS that is not significantly different than true simultaneity.

2.3 Methods

Participants

Ten young (21-26 years; 5 men & 5 women) healthy young adults participated in the experiment, who were all free of musculoskeletal, auditory, visual, vestibular, or other neurological disorders. All participants reported having no auditory, visual, or vestibular disorders and gave their informed written consent in accordance with the guidelines of the University of Waterloo Research Ethics Committee.

Protocol

Participants made TOJ responses to a postural perturbation evoked by a lean-and-release mechanism and an auditory cue produced through headphones. Participants were first weighed to determine the 7-8% body mass lean angle that was adopted throughout the study. Participants were then fitted with a full body harness that allowed for the attachment of the lean cable at the level of the 2nd and 3rd thoracic vertebrae and the safety rope which was secured to the ceiling to prevent injury in the case of an inability to recover balance [35, 148, 149, 33]. The participants were positioned $\sim$ 1 m from the lean-and-release apparatus and their feet were positioned in a standardized position (heel centers 0.17 m apart, 14° between the long axes of feet [168, 148, 149]. The ground was marked with tape along the lateral borders of the feet and a piece of wood was used as heel stop to ensure the foot position was not altered through the duration of the study. Participants were not given any specific instructions on how to respond to the postural perturbation, to prevent any voluntary changes that could occur to the postural response adopted by the participants. However, the lean angle of 7-8% body mass produced a large enough perturbation to inherently evoke a stepping response in each of the subjects, it was not small enough to allow for a fixed support postural strategy [162, 35, 148, 149, 109].

Participants were instructed to make their TOJs with the use of two handheld buttons. The left button was pressed with their left thumb if they believed the auditory cue occurred first or the right button was pressed with their right thumb if they believed the postural perturbation occurred first. This study implemented two different trial types: Unequal SOA distribution and Equal SOA distribution. The participants wore a blindfold while also closing their eyes, the blindfold was a way to ensure the participants did not receive any visual cues if they were to accidentally open their eyes during the trial. The unequal SOA distribution consisted of the following based on the work of [148]: -534 ms, -449 ms, -364 ms, -279 ms, -194 ms, -109 ms, -24 ms, 61 ms, 146 ms, 231 ms, 316 ms (Figure 1). While the equal SOA distribution consisted of the following: -200 ms, -100 ms, -50 ms, -25 ms, 0 ms, 25 ms, 50 ms, 100 ms, 200 ms Figure 2.1. Each of these SOA distributions were repeated 8 times. Therefore, the participants completed 160 trials (88 trials with the unequal distribution and 72 trials with the equal distribution). Negative SOAs indicate that the postural perturbation occurred first and the positive SOAs indicate that the auditory cue occurred first. The timing of the SOAs were tested by recording the auditory cue arrival and load cell release, this was to ensure the accuracy of the presented SOAs.

As noted, this unequal distribution of SOAs was chosen to try and replicate the SOA distribution as closely as possible as was used by Lupo and Barnett-Cowan (2017)[148]. Due to the methodological changes this study was not capable of triggering the perturbations manually, the setup was completely automated. It should be noted that the work of Lupo and Barnett-Cowan (2018) [149] was able to replicate the work of Lupo and Barnett-Cowan (2017) [148] using the same manual triggering methodology but with a different sample of young adult participants. In the present study we averaged the minimum and maximum SOA from each individual from the Lupo and Barnett-Cowan (2017) data set [148], then 10% increases between the 11 bins were calculated, this resulted in 85 ms differences between each SOA. This also resulted in 63.6% of the trials in the unequal distribution conditions as presenting the postural instability first, which was close to the 66% that Lupo and Barnett-Cowan (2017) [148] reported using their design. Another difference within the present unequal SOA distribution was that each SOA was repeated an equal amount which was not the case in [148, 149]. For the equal distribution of SOAs about true simultaneity, the maximum and minimum SOAs were set to 200 ms and -200 ms. This range was chosen for the equal SOA distribution because previous research has exhibited that SOAs greater than 200 ms appear to be easily distinguishable for the participants [222, 148, 149]. The SOAs were subsequently reduced by 50% relative to the previous SOA, until 25 ms and -25 ms then 0 ms was chosen as the central point. The presentation of the unequal and equal SOA distributions was counterbalanced across participants. Additionally, the SOAs were fully randomized for each participant and after 45 consecutive trials participants were given a 3-minute break to sit down, this was to avoid fatigue over the course of the study. Each trial lasted for 15-20 seconds with a comparable delay between each trial. Participants were told to relax while keeping their arms and hands comfortably at their sides through the duration of the trials. The participants were then taken through 5 practice trials to allow themselves to get acquainted with the different stimuli and to help them relax when getting into the appropriate lean angle.

Lean and Release Apparatus & Stimuli

Figure 2.2 shows how the lean-and-release apparatus which consisted of three components: a crossbow release, a load cell, and an electromagnet. The crossbow release, load cell and electromagnet were attached to a metal vise which could be vertically moved and then tightened onto a steel tube frame which was secured to the floor. This ability to vertically change the position of the lean-and-release apparatus allowed for the accommodation of participants of various heights. The crossbow release was attached to the load cell and held a lean cable which was connected to the participant via a harness. The load cell was sampled at 100 Hz and was capable of measuring 454 kg of force. The load cell measurement allowed for the determination of postural perturbation onset, and it ensured that the lean angle adopted by the participant was maintained between 7-8% of their body mass – we attempted to get 10% [162, 109, 35], but the cross-bow release would not consistently release with individuals with higher weights. As opposed to the method used by Lupo and Barnett-Cowan (2017; 2018) [148, 149], who had an experimenter manually release the cable, the opening of the crossbow release in the present study was achieved with the use

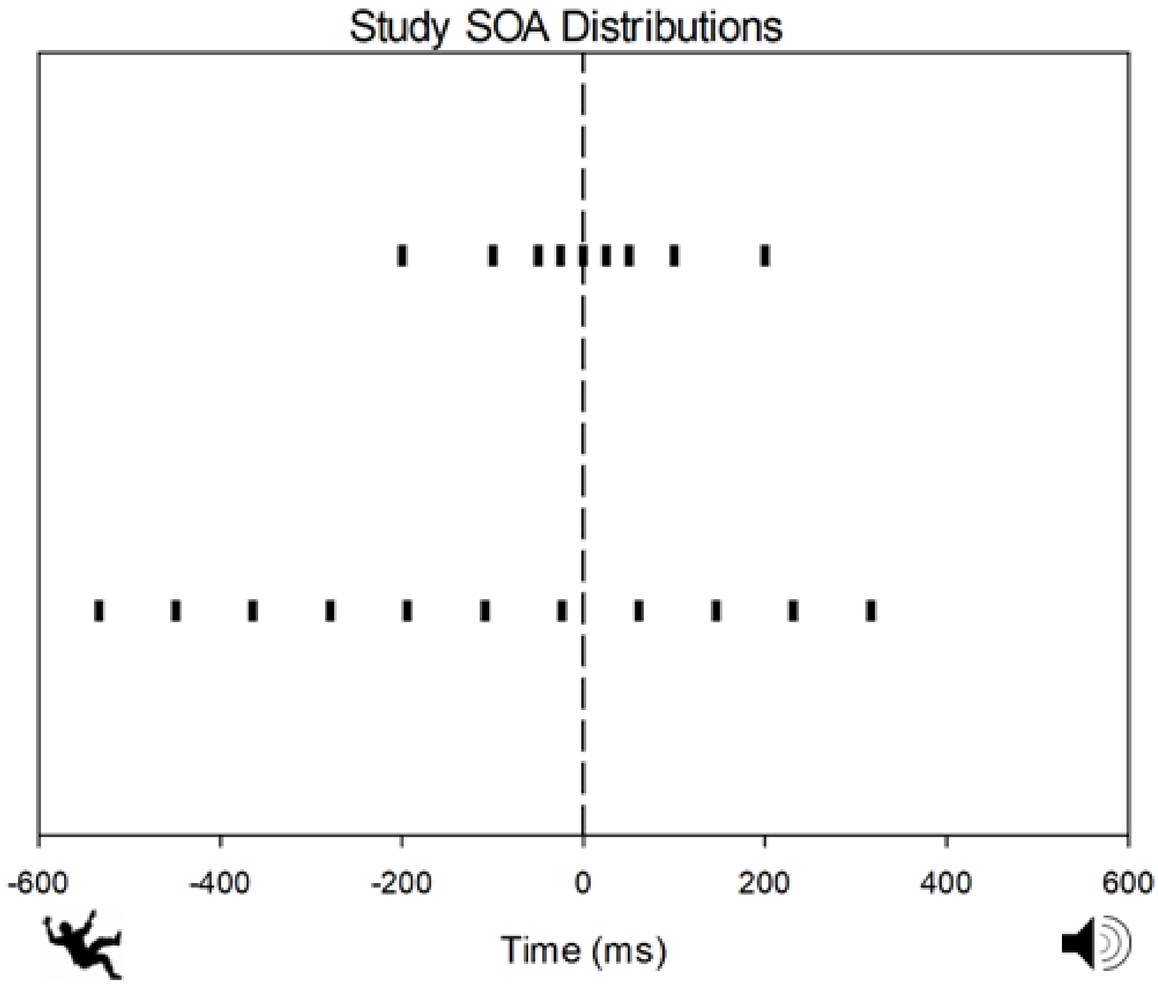

Figure 2.1: Equal (top) and Unequal (bottom) SOA distributions that participants were exposed to. The negative SOAs represent when the perturbation onset occurred first and the positive SOAs represent when the auditory cue occurred first. The equal SOA distribution at the top contains 4 SOAs in which the perturbation onset occurs first and 4 SOAs in which the auditory cue occurs first. The unequal SOA distribution at the bottom contains 7 SOAs in which the perturbation onset occurs first and 4 SOAs in which the auditory cue occurs first

of an electromagnet. The electromagnet was attached to the crossbow release arm via a rigid piece of metal to reduce the variability of initiation of the postural perturbation Figure 2.2. The electromagnet was activated via a 5 V pulse sent from a LabVIEW (National Instruments, Austin, Texas, USA) program. The activation of the electromagnet caused the rigid metal arm to open the crossbow release, resulting in the onset of the postural perturbation.

Auditory Stimuli

The auditory cue was generated via the same LabVIEW program that produced the 5 V pulse to the electromagnet. A 250 ms square wave sound burst played at 500 Hz was introduced to the participant via noise cancelling headphones (Sennheiser PXE 450) (c.f., [148, 149]). This auditory beep was super threshold to esnure individuals could clearly detect the cue above the white noise. White noise was constantly present throughout the study via a free cellphone application (White Noise Free). The white noise volume was manually adjusted to the point where each participant was unable to hear external noise from the lean-and-release mechanism. This would ensure that the participants were not receiving any additional auditory cues that may alert them to the upcoming postural perturbation while still allowing the participants to distinctly detect the onset of the auditory cue.

Data Analysis

The TOJ responses acquired from the various SOAs were plotted as a probability of the sound occurring first. The responses were assigned a binary number; postural perturbations were assigned the number (0) and the auditory cue were assigned the number (1). Responses at each SOA were averaged together to provide a single averaged probability for the participants' responses. Negative SOAs represent that the postural perturbation occurred first and the positive SOAs represent that the auditory cue occurred first. A two-parameter logistic function (Eq. 1) was fitted to each of the the participants' averaged responses as a function of SOA using Sigma Plot 12.5 with the inflection points of the logistic function (x_0) taken as the point of subjective simultaneity (PSS) and the standard deviation (b) was taken as the just noticeable difference (JND) [148].

$$y = \frac{1}{1 + e^{-(\frac{x - x_0}{b})}} \tag{2.1}$$

Once we retrieved these outcome measures from the logistic regression, we inspected the data to determine if there were any outliers which exceeded the 95% confidence interval of the average response. We did not exclude these participants initially if they exceeded this limit as these individuals to our knowledge performed the task correctly. However, we then utilized the R^2 and the p-value of the logistic regression fits to the participant's responses. We wanted to observe fits that produced $R^2 \geq 0.5$ [144] and a $p \leq 0.05$. If both

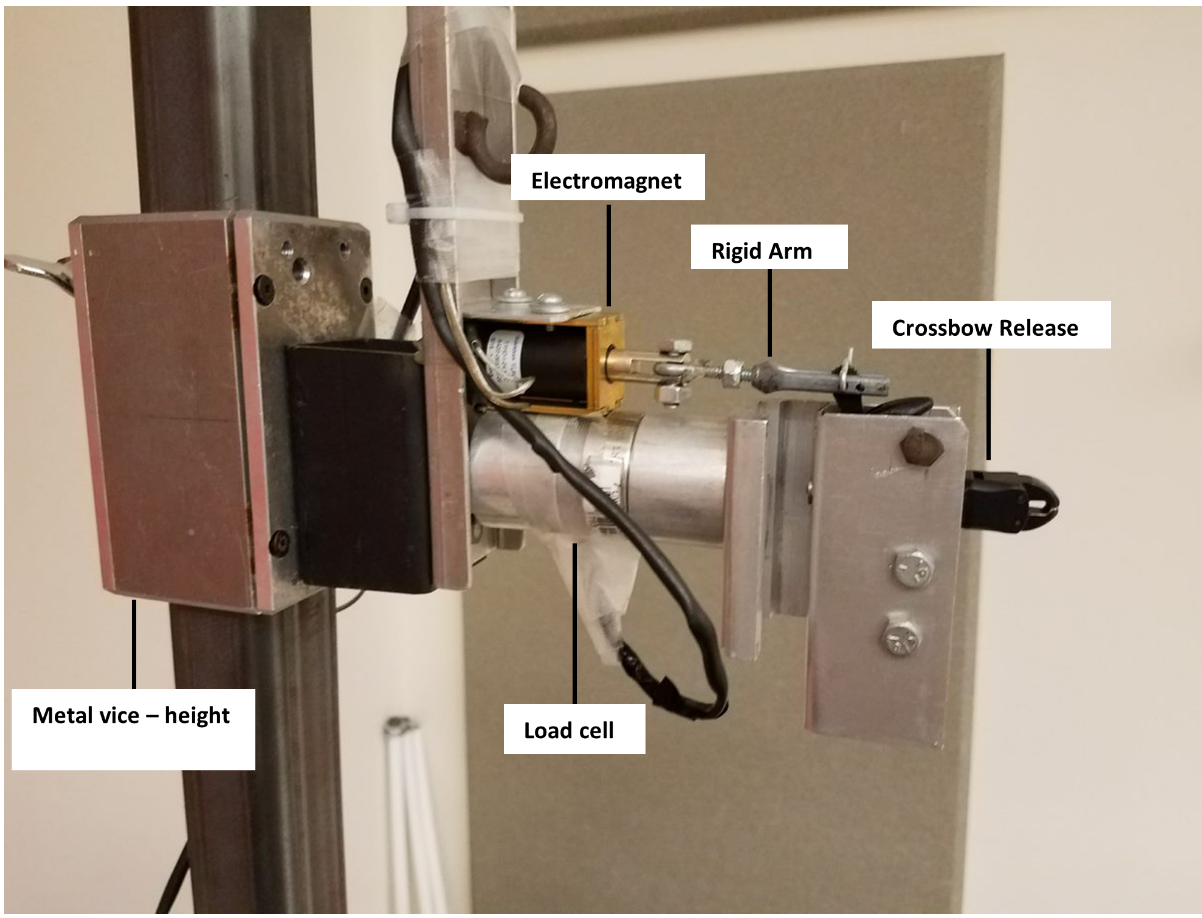

Figure 2.2: The lean and release setup used to automatically release participants at a lean angle of 7-8% of their body mass.

of these parameters were not met, we removed the participant's data from the analysis as we could not be confident that the logistic regression providing an accurate fit.

We used a within subjects' design to assess the hypothesis that postural instability will not be perceived significantly slower than the auditory cue, a one-sample t-test was conducted comparing the mean PSS value of the condition to true simultaneity (0 ms). The one-sample t-tests specifically assessed whether the mean PSS values were significantly different from zero. To investigate the effect of the distribution on mean PSS a paired sample t-tests was performed to compare the Unequal and Equal distribution conditions. If normality failed in any comparisons as assessed by the Shapiro-Wilk test then there was an attempt to normalize the data. If these attempts with Z-Score normalization were not successful, then non-parametric statistics would be performed. For each of the statistical tests a significance level of $\alpha = 0.05$ was utilized.

2.4 Results

No individuals violated the conditions that were set for this study. All participants data when fit with the non-linear regression logistic function produced fits that exhibited $R^2 \geq 0.5$ and a p-value ≤ 0.05.

The PSS and JND values of each individual were derived from the logistic regressions that were fit to the averaged responses at each SOA. These fits for the unequal and equal distribution are depicted in Figure 2.3. Similarly, to previous research by Lupo and Barnett-Cowan (2017; 2018) [148, 149] the PSS of the unequal distribution was negative (mean = -20.34 ms, SE = 18.67, median = -1.17 ms; Figure 2.4), indicating on average the onset of the postural instability needed to occur prior to the auditory cue to be perceived as simultaneous. The equal distribution produced a positive PSS (mean = 3.52 ms, SE = 11.97, median = 3.27 ms; Figure 2.4), indicating on average the auditory cue needed to occur prior to the postural instability to be perceived as simultaneous. Importantly, neither the unequal (One Sample Signed Rank Test (one tail); Z = -0.459, p = 0.348) nor the equal (One Sample T-test (one tail); t(9) = 0.294, p = 0.388) distributions produced PSS values that were significantly less than 0 ms (true simultaneity). This supported the initial hypothesis that individuals would not perceive the onset of postural instability slower than the auditory cue. When directly comparing the unequal and equal distribution PSS values there was an observed difference of 23.86 ms, however this difference was not statistically significant (Wilcoxon signed rank test; Z = -1.274, p = 0.232, 1 - β = 0.24).

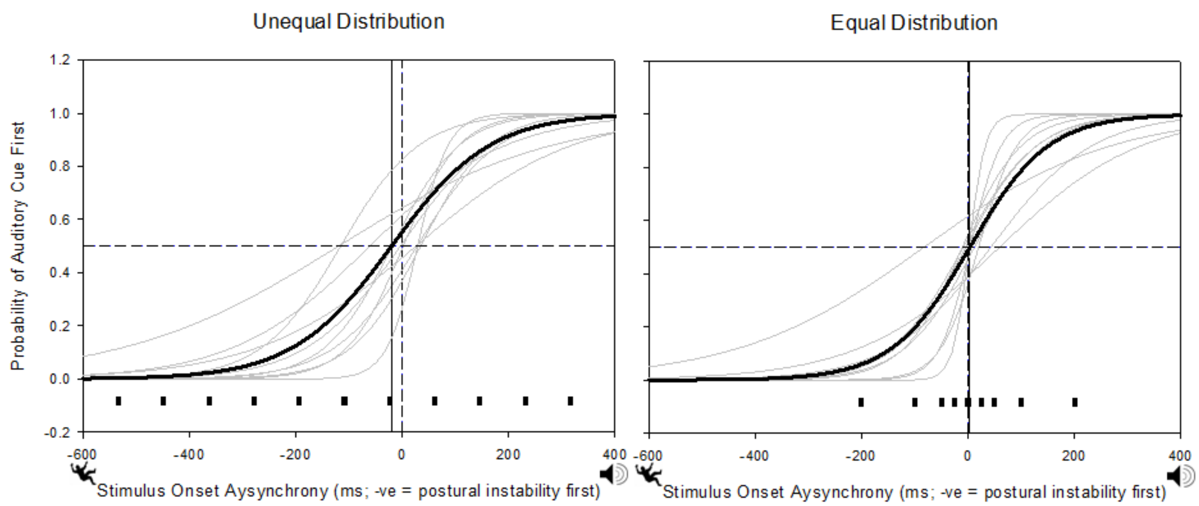

Figure 2.3: Logistic fits for individuals (light grey) and averaged (black) responses in each TOJ task. The solid vertical lines represent the mean PSS value for each condition. The average PSS from the unequal distribution was -20.34 ms and the average PSS from the equal distribution was 3.52 ms. An SOA of 0 ms represents true simultaneity and is indicated by the vertical dashed line. The horizontal dashed line represents 50% probability of the auditory stimulus perceived as occurring first. The small black hash marks at the bottom of the graphs represent the SOAs for the unequal distribution (left) and equal distribution (right).

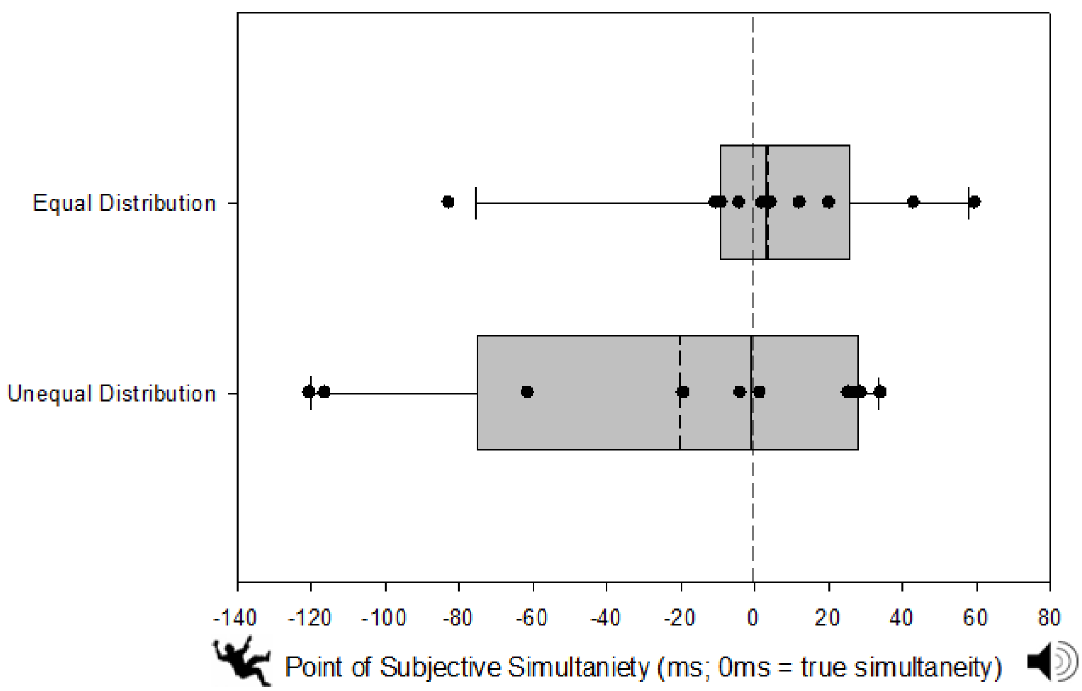

Figure 2.4: Mean PSS (dashed line), median PSS (solid line), and individual PSS values (circles) for the equal (top) and unequal (bottom) SOA distributions. Grey bars represent the 25-75th percentiles of the PSS data with error bars representing the 90th and 10th percentiles of data distributions. There were no statistically significant differences between the unequal and equal distribution PSS values.

The current study did not have an a priori hypothesis regarding the JND values, as the design was not expected to impact the precision of the responses. The JND values for the unequal (mean = 92.86 ms, SE = 16.42, median = 75.76 ms) and equal (mean = 73.82 ms, SE = 15.51, median = 66.08 ms) distributions exhibited a mean difference of 19.04 ms, which were not a statistically significant different from each other (Paired Sample T-test; t(9) = -1.373, p = 0.203, Figure 2.5).

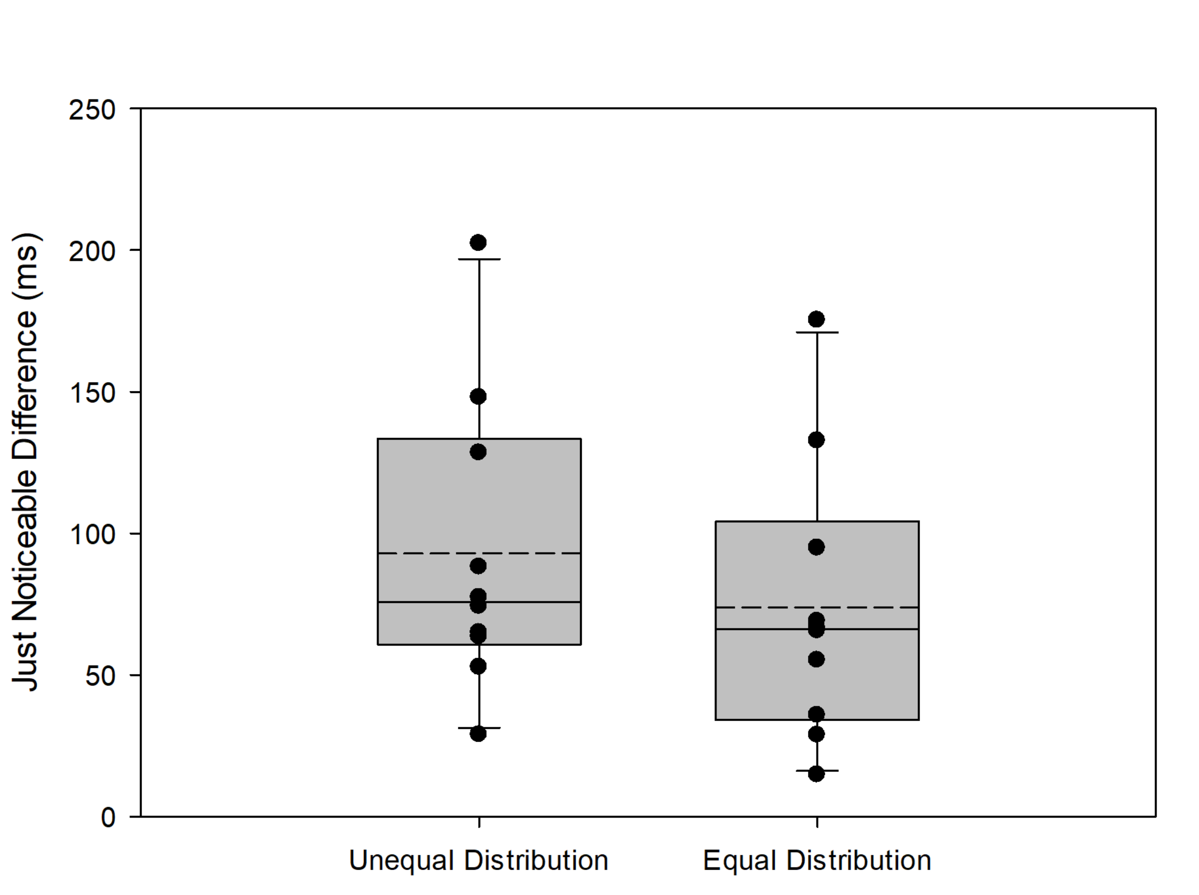

Figure 2.5: Mean PSS (dashed line), median PSS (solid line), and individual JND values (circles) for the equal (top) and unequal (bottom) SOA distributions. Grey bars represent the 25-75th percentiles of the JND data with error bars representing the 90th and 10th percentiles of data distributions. There were no statistical differences between the unequal and equal distribution JND values.

Additionally, the current study did not propose any a priori hypotheses regarding the PSS values from previous research conducted by Lupo and Barnett-Cowan (2017; 2018) [148, 149]. However, when comparing the compiled results from both Lupo and Barnett-Cowan (2017; 2018) [148, 149] (mean = -44.16 ms, SE = 8.23, median = -44.00 ms) to the unequal distribution PSS there was a difference of 23.82 ms, but this was not a significantly statistical difference (Mann-Whitney Rank Sum Test; U = 62.00, $p = 0.099$). When comparing the compiled PSS for Lupo and Barnett-Cowan (2017; 2018) [148, 149] and the equal distribution PSS there was a difference of 47.27 ms which was statistically significant (Independent Sample T-test; t(28) = 3.315, $p = 0.0025$). Thus, we were able to confirm that when a manual random distribution of SOAs is implemented, only here is there found an effect that a postural perturbation must precede a sound reference stimulus in order to be perceived as simultaneous.

2.5 Discussion

The aim of this study was to determine if methodological design characteristics of a TOJ task to measure the perceived onset of a postural perturbation can impact perceptual outcome measures, specifically the PSS. The primary methodological factors that were of greatest scrutiny were the SOAs, specifically the distribution of the SOAs around true simultaneity (0 ms) and the use of the method of constant stimuli of these chosen SOAs. The participants performed TOJ tasks in response to an auditory cue and a postural instability event under two different conditions: an unequal SOA distribution and an equal SOA distribution. There was a difference of 23.86 ms between the unequal PSS mean and the equal PSS mean (not significantly different) with the unequal PSS exhibiting a negative PSS average while the equal PSS mean was a positive value. This indicates that in the unequal distribution condition the participants required the postural instability to be presented prior to the auditory cue to perceive the stimuli as simultaneous, while this was reversed in the equal distribution condition. When looking at the median values of -1.17 ms for the unequal distribution and 3.27 ms for the equal distribution the difference is much smaller but the same effect holds true in regards to the presentation order of the stimuli. However, these differences in both conditions were not statistically less than true simultaneity (0 ms). This indicates that contrary to the conclusions drawn by prior work on the perceived timing of postural perturbations [148, 149] participants on average do not perceive the onset of the postural instability significantly slower than the auditory cue.

Our findings suggest that the methodology was likely a contributing factor of the perceived delay of postural instability in previous research [148, 149]. The present study attempted to utilize methodologies that are common within the realm of TOJ research. Utilizing an equal SOA distribution is commonly utilized within TOJ tasks [249, 263, 144, 228, 223, 222] as is the method of constant stimuli which is the repetition of the selected SOAs [249, 263, 144, 228, 223, 222]. A reason for implementing an equal SOA distribution opposed to an unequal distribution is because it has been observed that the PSS can be impacted by consistently presenting an asynchronous stimulus to individuals [172, 249, 229, 71, 89]. Several of these studies presented a fixed period of stimulus asynchronies then subsequently had the participants complete a TOJ task; they then observed a shifted PSS towards the formerly presented asynchrony [249, 229, 71, 89, 172]. Similarly, Miyazaki et al (2006) [172] explored the effects of a shifted gaussian distribution of stimuli during a tactile TOJ task and an audiovisual TOJ task. These gaussian distributions increased the frequency of trials towards one stimulus, meaning that participants would be exposed to an unequal distribution in these different gaussian distribution conditions. Each of these gaussian distributions presented the greatest number of trials with asynchronies at -80 ms and 80 ms. Two key findings were observed, during a tactile-tactile TOJ task the PSS shifted away from the peak gaussian distribution (negative distribution (-80 ms): PSS = 49 ms and positive distribution (80 ms): PSS = -38 ms), while the PSS shifted towards the peak gaussian distribution in the audiovisual TOJ task (negative distribution (-80 ms): PSS = -49 ms and positive distribution (80 ms): PSS = 86 ms)[172]. It was proposed that the tactile TOJ responses may be affected by 'Bayesian calibration/integration' while the audiovisual TOJ may be due to 'lag adaptation/temporal adjustment'. Bayesian calibration or integration is the concept that sensory estimates can be improved or impacted by prior information, this prior information is utilized to produce a more optimal estimate of sensory events. Lag adaptation or temporal adjustment is the concept that when individuals are continually presented with asynchronous stimuli, they will shift their perception of events in correspondence with this presented delay.

Comparatively, the average SOA presented in the unequal distribution is -106 ms, while the equal distribution is 0 ms. The average SOA presented to the individuals in the previous research by Lupo and Barnett-Cowan (2017; 2018) [148, 149] can not be defined due to the random nature of the presentation of the stimuli. Though if the unequal SOA distribution utilized in the current study is utilized as an analog of their research, then it could be assumed that it is around -106 ms as well. This would indicate that with an SOA shift of -106 ms Lupo and Barnett-Cowan (2017; 2018) [148, 149] produced a PSS of -44 ms while this current study produced a PSS of -20.34 ms and with a SOA shift of 0 ms the PSS was 3.52 ms. The present study and the previous research conducted by Lupo and Barnett-Cowan (2017; 2018) [148, 149] may have exhibited that the unequal SOA distributions evoked lag adaptation/temporal adjustment. As observed by the -44 ms PSS in Lupo and Barnett-Cowan (2017; 2018) [148, 149], the -20.34 ms PSS from the unequal distribution and the 3.52 ms in the equal distribution. However, it should be noted that within the current study the median value for the unequal distribution was much closer to 0 ms at -1.17 ms, perhaps indicating less of an effect of lag adaptation within the current study design. Miyazaki et al (2006) [172] proposed that lag adaptation/temporal adjustment was present in the audiovisual task due to the differences between auditory and visual detection, transduction and processing between the sensory modalities. Our methodology utilized an auditory cue and a multisensory event, postural instability, which affected the proprioceptive/somatosensory and vestibular systems (not visual in this case because eyes are closed). Therefore, it could be feasible that lag adaptation/temporal adjustment was affecting the perceptual responses in the unequal SOA distribution in comparison to the equal SOA distribution.

The methodology used for the present study attempted to re-assess the unequal SOA distribution utilized in Lupo and Barnett-Cowan (2017; 2018) [148, 149] but there were some critical differences still in the final methodologies used. As previously mentioned, the SOA distribution utilized in prior work was 11 bins based off the average maximum and minimum SOAs in Lupo and Barnett-Cowan (2017) [148]. However, unlike the previous research the unequal distribution in this study used the method of constant stimuli. This repetition of each of the SOAs differed from the randomized SOAs that were utilized in the previous research. With the repetition of the SOAs a conclusive average can be drawn, as opposed to the bins that were used in the previous research that consisted of a variety of different SOAs. At the extreme range of SOAs the merging of TOJ responses may be less of an issue, as determining which stimuli occurred first is more evident. However, averaging SOAs closer to true simultaneity could affect the perceptual outcome measures, as the accuracy and precision/variability of the responses could be an inaccurate representation at these more ambiguous SOAs. Therefore, the lack of replication in this current study of the -44 ms PSS observed in previous research could have been affected by how the averaged responses were calculated for each SOA.

The sample size within this study is important to consider, as previously stated the power of the comparison between the equal and unequal SOA conditions was 1 - β = 0.24. Indicating that there is a higher probability of type II error being present within our statistical analysis. With an apriori power analysis a population of 67 participants would be required to have a 1 - β = 0.95. This sample size was chosen to replicate what was previous conducted by [148] as they collected only 8 participants. With a greater number of participants it is possible that the variability observed within the population may have become more normalized. Therefore, it is important to consider the sample size as a potential limitation within the design of the study.

The lean angle adopted in the present study was standardized to the participants' weight, unlike Lupo and Barnett-Cowan (2017; 2018) [148, 149] which had all participants lean with a fixed cable length. This fixed cable length subsequently would result in a different amplitude of postural perturbation across participants. A smaller lean angle could result in a more slowly perceived onset of a postural instability while a larger lean angle could result in a more quickly perceived onset of instability. It has been observed that stimulus intensity can affect both response times and TOJ responses, with increased intensity resulting in quicker perception of that stimulus [186, 115, 32]. Other characteristics of the presented stimulus that can affect perception are duration [6] and location [263].

The duration of the auditory stimuli was the same across each study, but the duration of the postural event could vary between studies due to the differences in adopted lean angle. The location of the presented stimuli was consistent across the studies, with the auditory cues being presented through a pair of headphones and the postural instability being evoked via a lean and release cable on the back of the participants. Overall, this reinforces the importance of trying to standardize your stimuli across your population and why comparing across studies in this realm of research can be difficult.

Finally, it is important to consider the variability of responses between individuals. It is evident that individuals can differ greatly in the perceptual outcome measures of postural instability onset and auditory cue onset (Figures 2.4 & 2.5). Individual differences have been observed during perceptual tasks [175, 228, 71], one potential factor for individual differences could be related to attention. Attention towards one stimulus over the other has been observed to shift the perception of simultaneity in the direction of the attended stimuli [227, 223, 71]. Therefore, a consideration in TOJ tasks is that some individuals may be attending to one stimulus more than another, although in all studies participants were encouraged to attend to the perturbation onset and sound onset equally. It is also possible attention could be affected by fatigue; concentrating on the arrival of sensory cues could be fatiguing and that could be exacerbated in some individuals during a physical task such as the control of balance. This study tried to compensate for fatigue by providing breaks and allowing the individuals to rest if they requested, but more breaks could be provided in the future.

2.6 Conclusion

The current research appears to indicate that with a more controlled methodology the observed perceptual delay of postural instability onset is not present. This indicates the importance of understanding how methodologies can directly impact the outcome measures of a study. This specifically exhibits how an SOA distribution could impact perceptual outcome measures, such as the PSS. Utilizing a controlled methodological design allows for consistency across participants and allows for the ease of reproducibility. This consistency across participants is important to achieving meaningful results and meaningful comparisons. It is also important to consider potential methodological differences prior to comparing results to other research, as differences in equipment, stimuli and parameters could be significant.

Chapter 3

Perceived Timing of Postural Instability Onset when Altering Visual Context

3.1 Abstract

Temporal processing of sensory information plays a critical role in the perception of both internal and external events. Each sensory modality is processed at differing speeds requiring the central nervous system to account and compensate for these delays to ensure internal and external events are perceived in correct order. The control of balance is one such event that requires rapid responses to prevent falls and therefore is of interest to assess how individuals perceive the onset of instability. Previous research investigating perceptual delays of postural instability has been conducted with the eyes closed. Considering visual information is an important modality in the control of posture and balance, could visual information affect the perceived timing of postural instability? Two experiments utilizing temporal order judgement tasks between a postural event and an auditory cue at differing stimulus onset asynchronies were conducted to investigate the effect of visual information on perceived onsets of postural instability while manipulating: i) presence /absence of vision, ii) visual threat. The results show that without vision, postural instability onset need to occur 25.78 ms prior to the onset of sound to be perceived as simultaneous, and only 10.71 - 12.33 ms prior to sound onset with vision available. Notably none of these were significantly different from true simultaneity. When threatening visual information was presented participants were more precise in their judgements and the postural instability onset needed to occur 4.45 ms prior to auditory cue onset to be perceived as simultaneous. In sum, our results show that the availability of visual information may alter the perception of instability onset, particularly when visual information presents a threat, where judgments made need to be more precise.

3.2 Introduction

Perception of sensory events is a critical aspect of day-to-day life. The way in which we perceive the world and ourselves can have a direct effect on our decisions and actions. The central nervous system (CNS) is responsible for detecting and processing sensory cues to allow for the formation of these decisions. The maintenance of posture is uniquely challenging because it relies upon multiple sensory modalities to produce timely and accurate internal and external models of body motion relative to the constant force of gravity on Earth. Balance is monitored by three primary senses: the proprioceptive, visual, and vestibular systems. Each of these sensory systems provides cues about body motion, which needs to be integrated by the CNS to produce a reliable representation of body movement. This neural processing of multisensory information is constantly evaluated and needs to occur at a rapid speed to prevent falls.

Neural processing of sensory information, however, does not occur at the same speed across the various sensory modalities. Each sensory modality has different transduction times to generate a neural signal corresponding with each sensory modality, which travel at different speeds and distances before arriving to the cortex. Thus, the CNS must determine what signals are related to the same sensory event despite temporal asynchronies. Research has shown that despite these differences in temporal processing across sensory modalities humans can perceive multisensory stimuli as simultaneous [89, 88, 22]. Perceptual research has shown that when actively perturbing balance in the anterior direction, the postural perturbation needs to significantly precede an auditory cue by 44 ms to be perceived as simultaneous when measured with a temporal order judgement (TOJ) task [148]. Interestingly, this delay in the perceived timing of postural instability is doubled (88 ms) in older adults [149]. These findings suggested that the perceived onset of postural instability is slow and that this is exacerbated with age. However, as tested in the first experiment of my thesis it appears these delays are caused by the methodology adopted in this research. One aspect that was not discussed in my previous study was that this previous research investigating perception of postural instability did not provide visual information to the participants [148, 149] and neither did Chapter #2 of my thesis that was replicating these previous research designs. Therefore, providing visual information to individuals during a TOJ task is of interest because this could provide insight into how perception of postural instability may change when information from all sensory modalities is available to participants.

Visual information is known to be a more slowly processed sensory modality in comparison to auditory and proprioceptive cues [132, 23, 257]. Visual information has also been observed to have perceptual delays in comparison to auditory stimuli [130, 122, 113]. Although it has been shown that during active head motion the presence of visual cues does not statistically alter the point of subjective simultaneity (PSS; measure of accuracy) or the just noticeable difference (JND; measure of precision/variability) during a temporal order judgement (TOJ) task between the physical movement of the head and an auditory cue, there is a tendency to have less delay with visual cues present [47]. Thus, despite the increased availability of sensory information, individuals do not significantly perceive the onset of active head motion any quicker than in situations that did not provide visual cues.

Furthermore, they were also not more precise when making temporal order judgments in the presence of visual information. With respect to postural control, the control of balance can still be readily maintained without visual cues, but this does lead to an increase in centre of pressure (COP) sway [8, 16, 11]. This has led to the theory that visual information may not be critical in the initial stages of balance responses. However, visual cues about the environment have been shown to have a direct effect on the production of postural motor responses. These effects vary from individuals altering postural responses during external perturbations by decreasing postural sway when at a physical and virtual height [38, 42, 217, 49, 48] to the adoption of accurate stepping and reaching responses during rapid postural responses [264, 74]. Visual motion that evokes vection has also been observed to result in subsequent postural sway in responses [137, 138, 84, 240, 118, 136]. In addition, when individuals are asked about how they perceived their stability and posture when at a height, they reported a greater concern for posture [105] and reported decreased levels of stability and confidence in their posture [48]. The presence of meaningful and evocative environments subsequently alters how individuals utilize visual cues in the perception and action of balance control. This combination of research stresses the potential importance of visual context in the role of posture and balance and how visual information can affect both perception and action. Despite this, no formal analysis has been conducted on the effects of visual context and the perception of postural instability onset. This knowledge could provide us with insight on how sensory modalities, specifically vision, may alter and form our perception of a postural event.

Herein, we report a two-experiment design that assessed the effect of visual information on individuals' ability to perceive postural instability onset. Each study utilized a TOJ task to extract the point of subjective simultaneity (PSS) and the just noticeable difference (JND). The PSS is a measure of accuracy relative to the point of true simultaniety (SOA of 0 ms) and the just noticeable difference (JND), which is a measurement of precision/variability [248]. The PSS is defined as the 50% probability of detecting one stimulus before the other, while the JND is defined as the interval between this 50% point and the 75% point [248]. The first experiment utilized eyes open and eyes closed conditions to compare how the availability of visual information affects perception of postural instability. The second experiment was designed to compare how visual context, specifically perceived visual threat, affects perceptual thresholds of postural instability onset.

The first experiment had three main hypotheses. Firstly, it was expected that the availability of visual information during a postural perturbation would not significantly alter the PSS when compared to conditions without visual information based on prior work by Chung & Barnett-Cowan (2017) [47]. Secondly, it was expected that the perception of postural instability onset would not be perceived more slowly when compared to the auditory reference stimulus in both the eyes open and eyes closed conditions due to the slower processing speeds of visual information [132, 188, 236] and the slower perception of visual cues in comparison to proprioceptive cues [132, 23, 257]. Finally, it was expected that the JND would decrease in the eyes open conditions, because visual cues have been observed to reduce postural sway [84, 31] and visual cues have been shown to reduce the variability in perceptual upright tasks [63].

For the second experiment there were three main hypotheses that parallel those from the first experiment. Firstly, this second experiment wanted to re-test that the perception of postural instability onset would not be perceived significantly slower than the auditory cue. Secondly, it was expected with the presentation of a perceived visual threatening scene via virtual reality (VR), individuals' perception of postural instability onset would occur more rapidly in comparison to conditions presenting non-threatening visual information. This is in part due to the observed behavioural and psychological changes that occur when at both physical and virtual height [219, 55, 105, 50, 49, 261, 260, 262, 39]. Lastly, it was hypothesized that individuals would exhibit improved precision or a reduction in variability of their responses resulting in a decrease of the JND when at the virtual height. This is due to the perceived threat from the VR scene increasing attention which has been shown to reduce the JND in TOJ tasks [140].

3.3 Experiment #1

3.3.1 Methods

Participants

A total of 13 participants were originally recruited, free of musculoskeletal, auditory, visual, vestibular, or other neurological disorders. Two participants were excluded from analysis; one subject was unable to complete all the trials of the study and the other participant did not follow the instructions and responded as if the task were a reaction time test. This left a final sample of ten participants (aged 21-26; 5 males, 5 females). All participants reported having no auditory, visual, or vestibular disorders and gave their informed written consent in accordance with the guidelines of the University of Waterloo Research Ethics Committee.

Lean and Release Apparatus & Stimuli

Figure 3.1 shows the lean-and-release apparatus, which consisted of three components: a crossbow release, a load cell, and an electromagnet. The crossbow release, load cell and electromagnet were attached to a metal vice which could be vertically moved and then tightened onto a steel tube frame which was secured to the floor. This ability to vertically change the position of the lean-and-release apparatus allowed for the accommodation of participants of various heights. The crossbow release was attached to the load cell and held a lean cable which was connected to the participant via a harness. The load cell was sampled at 100 Hz and was capable of measuring 454 kg of force. The load cell measurement allowed for the determination of postural perturbation onset, and it ensured that the lean angle adopted by the participant was maintained between 7-8% of their body mass. Note that we attempted to achieve a value of 10% of their body mass [109, 162, 35], however the cross-bow release would not consistently release for individuals with higher weights. The opening of the crossbow release in the present study was achieved with the use of an electromagnet. The electromagnet was attached to the crossbow release arm via a rigid piece of metal to reduce the variability of initiation of the postural perturbation (Figure 3.1). The electromagnet was activated via a 5 V pulse sent from a LabVIEW (National Instruments, Austin, Texas, USA) program. The activation of the electromagnet caused the rigid metal arm to open the crossbow release, resulting in the onset of the postural perturbation.

Auditory Stimuli

The auditory reference stimulus was generated via the same LabVIEW program that produced the 5 V pulse to the electromagnet. A 250 ms square wave burst at 500 Hz was presented to the participant via noise cancelling headphones (Sennheiser PXE 450) (c.f., [148, 149]). White noise was constantly present throughout the study via a free cellphone application (White Noise Free). The white noise volume was manually adjusted to the point where each participant was unable to hear external noise from the lean-and-release mechanism. This would ensure that the participants were not receiving any additional auditory cues that may alert them to the upcoming postural perturbation while still allowing the participants to distinctly detect the onset of the auditory cue.

Procedure

Participants made TOJ responses to a postural perturbation evoked by a lean-and-release mechanism and an auditory reference stimulus produced through headphones. Participants were first weighed to determine the 7-8% body mass lean angle that was adopted throughout the study. Participants were then fitted with a full body harness that allowed for the attachment of the lean cable at the level of the 2nd and 3rd thoracic vertebrae and the safety rope which was secured to the ceiling to prevent injury in the case of an inability to recover balance [148, 149, 33, 35]. The participants were positioned ∼1 m from the lean-and-release apparatus and their feet were positioned in a standardized position (heel centers 0.17 m apart, 14° between the long axes of feet [168, 148, 149]. The ground was marked with tape along the lateral borders of the feet and a piece of wood was used as heel stop to ensure the foot position was not altered through the duration of the study. Participants were not given any specific instructions on how to respond to the postural perturbation, to prevent any voluntary changes that could occur to the postural response adopted by the participants. However, while the lean angle of 7-8% body mass produced a large enough perturbation to inherently evoke a stepping response in each of the subjects, it was not small enough to allow for a fixed support postural strategy [148, 149, 109, 162, 35].

Participants were instructed to make their TOJs with the use of two handheld buttons. The left button was pressed with their left thumb if they believed the auditory cue occurred first or the right button was pressed with their right thumb if they believed the postural perturbation occurred first. This study implemented two different trial types; eyes open (EO) and eyes closed (EC). During the EO trials the participants were instructed to look at an 'x' marked on a wall approximately 3 meters away [33]. During the EC trials the participants wore a blindfold while also closing their eyes, the blindfold was a way to

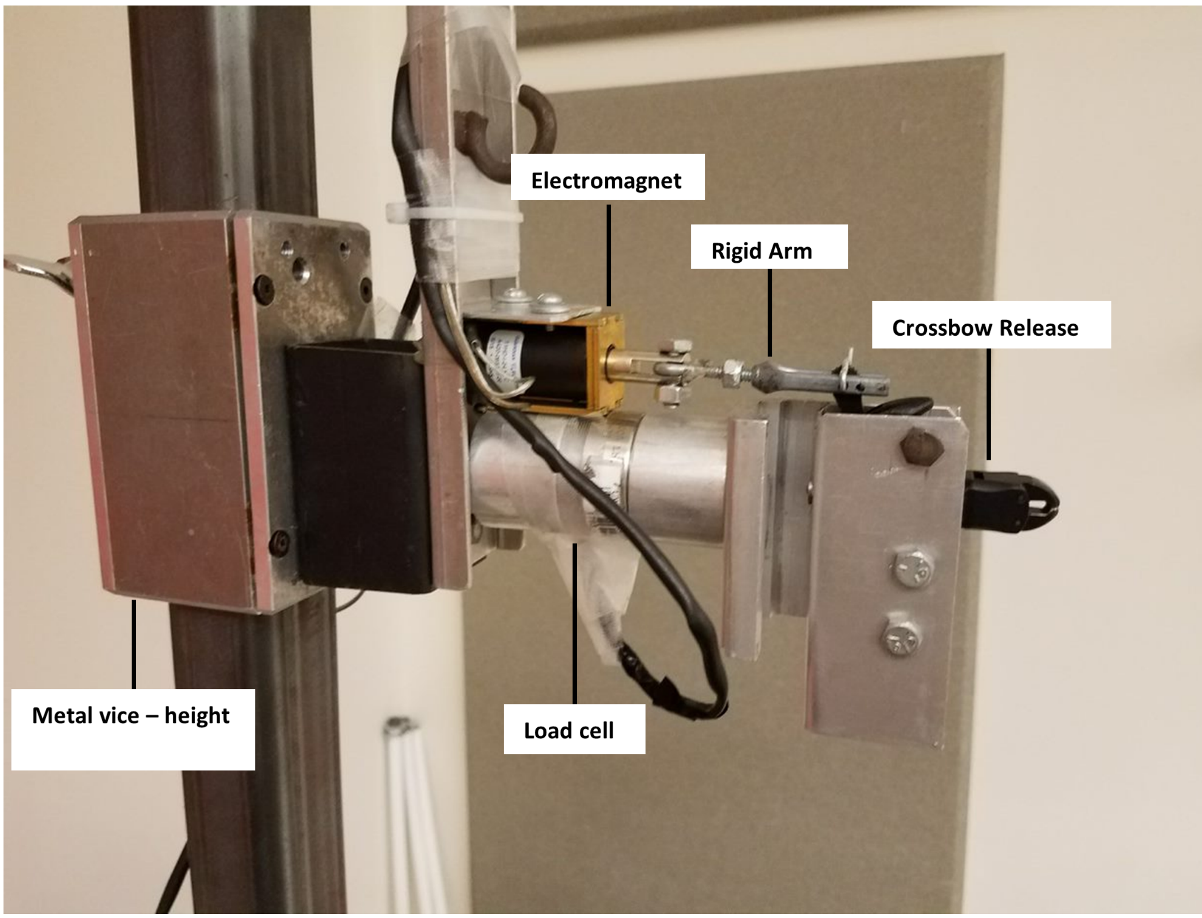

Figure 3.1: The lean and release setup used to automatically release participants at a lean angle of 7-8% of their body mass.

ensure that the participants did not receive any visual cues if they were to accidentally open their eyes during the trial. An equal stimulus onset asynchrony (SOA) distribution was utilized for each experiment, this had participants complete 144 trials (72 trials with vision and 72 trials without vision) with each SOA being repeated 8 times. The SOA distribution consisted of the following: -200 ms, -100 ms, -50 ms, -25 ms, 0 ms, 25 ms, 50 ms, 100 ms, 200 ms. Negative SOAs indicate that the postural perturbation occurred first and the positive SOAs indicate that the auditory reference stimulus occurred first. These SOAs were chosen because previous research exhibited that SOAs greater than 200ms were easily distinguishable for the participants [222, 148, 149] and we subsequently reduced each SOA by 50% to the previous SOA. The SOAs were fully randomized for each participant and after 24 consecutive trials participants were given a 3-minute break to sit down, this was to avoid fatigue over the course of the study. Each trial lasted for 15-20 seconds with a comparable delay between each trial. Participants were told to relax while keeping their arms and hands comfortably at their sides through the duration of the trials. The participants were then taken through 5 practice trials to allow themselves to get acquainted with the different stimuli and to help them relax when getting into the appropriate lean angle.

Data Analysis

The TOJ responses acquired from the various SOAs were plotted as a probability of the sound occurring first. The responses were assigned a binary number; postural perturbations were assigned the number 0 and the auditory reference stimuli were assigned the number 1. Responses at each SOA were averaged together to provide a single averaged value for the participants' responses. Negative SOAs represent that the postural perturbation occurred first and the positive SOAs represent that the auditory reference stimulus occurred first. A two-parameter logistic function (Eq. 1) was fitted to the participants' averaged responses as a function of SOA using Sigma Plot 12.5 with the inflection points of the logistic function (x_0) taken as the point of subjective simultaneity (PSS) and the standard deviation (b) was taken as the just noticeable difference (JND) [148].

$$y = \frac{1}{1 + e^{-(\frac{x-x_0}{b})}} \tag{3.1}$$

Once these outcome measures were retrieved from the logistic regression, they were visually inspected to determine if there were any outliers, this was data that exceeded the 95% confidence interval of the average response. We did not exclude these participants initially if they exceeded this limit as these individuals did not perform the task incorrectly. However, the R^2 and the p-value of the logistic regression fits to the participants' responses were utilized to determine which participants to include in the final analysis. The criteria that was set required the observed fits to produce an $R^2 \geq 0.5$ and a p-value of ≤ 0.05. If these parameters were not met then the participant's data was removed from the analysis as the logistic regression would be deemed to not have an accurate fit.

This experiment used a within subjects' design to assess the hypothesis that postural instability will not be perceived significantly slower than the auditory reference stimulus, and a one-sample t-test was conducted comparing the mean PSS value of the condition to true simultaneity (0 ms). The one-sample t-tests specifically assessed whether the mean PSS values were significantly different from zero. To investigate the effect of the presence of vision on the mean PSS and JND values paired sample t-tests were performed to compare the EO and EC conditions. If normality failed in any comparisons as assessed by the Shapiro-Wilk test we attempted to normalize the data. If these attempts with Z-Score normalization were not successful, then non parametric statistical tests would be performed. For each of the statistical tests a significance level of $\alpha = 0.05$ was utilized.

3.3.2 Results

When conducting the analysis, one participant was removed from the final findings. This participant's data did not meet the outlined criteria revolving around the fit of the logistic regression. Here, the fit of this participant's eyes open (EO) data produced an $R^2 = 0.3771$ with $p = 0.0785$, and the fit of the eyes closed (EC) data produced an $R^2 = 0.3775$ with $p = 0.0783$. Figure 3.2 shows the logistic fits for the remaining included data from each participant (grey lines) along with the averaged logistic fit for all participants (black line) plotted for each condition. This representation allows for a visualization of how all participants perceived the sensory stimuli, the y-axis indicates the probability that the individual perceived the auditory reference stimulus first as a function of SOA. The average PSS (Figure 3.3) and JND (Figure 3.4) values for all participants were subsequently derived from these logistic fits and the mean point of subjective simultaneity (PSS) and just noticeable difference (JND) values were subsequently calculated.

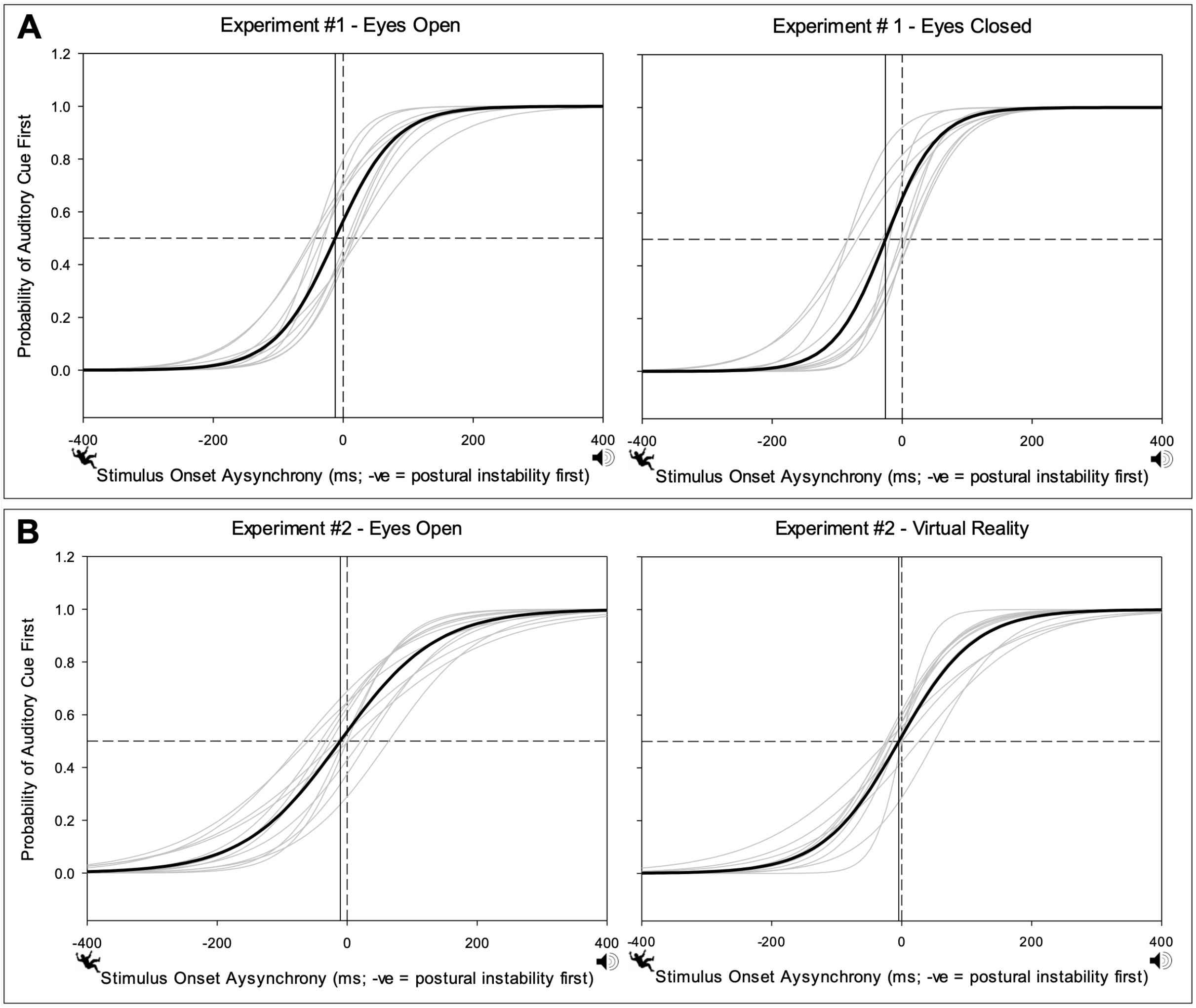

Figure 3.2: Logistic fits for both the Eyes Open versus Eyes Closed conditions (Panel A: Experiment #1) and the Eyes Open versus Virtual Reality (Panel B: Experiment #2). Light grey logistic function fitted lines represent each individual, while the black logistic function represents the mean of the individuals. The solid vertical line represents the mean PSS value for each condition. An SOA of 0 ms represents true simultaneity between stimuli and is exhibited by the vertical dashed line. The horizontal dotted line represent the 50% probability of the auditory reference stimulus occurring first, where the PSS is the time at which the logistic function crosses this 50% mark.

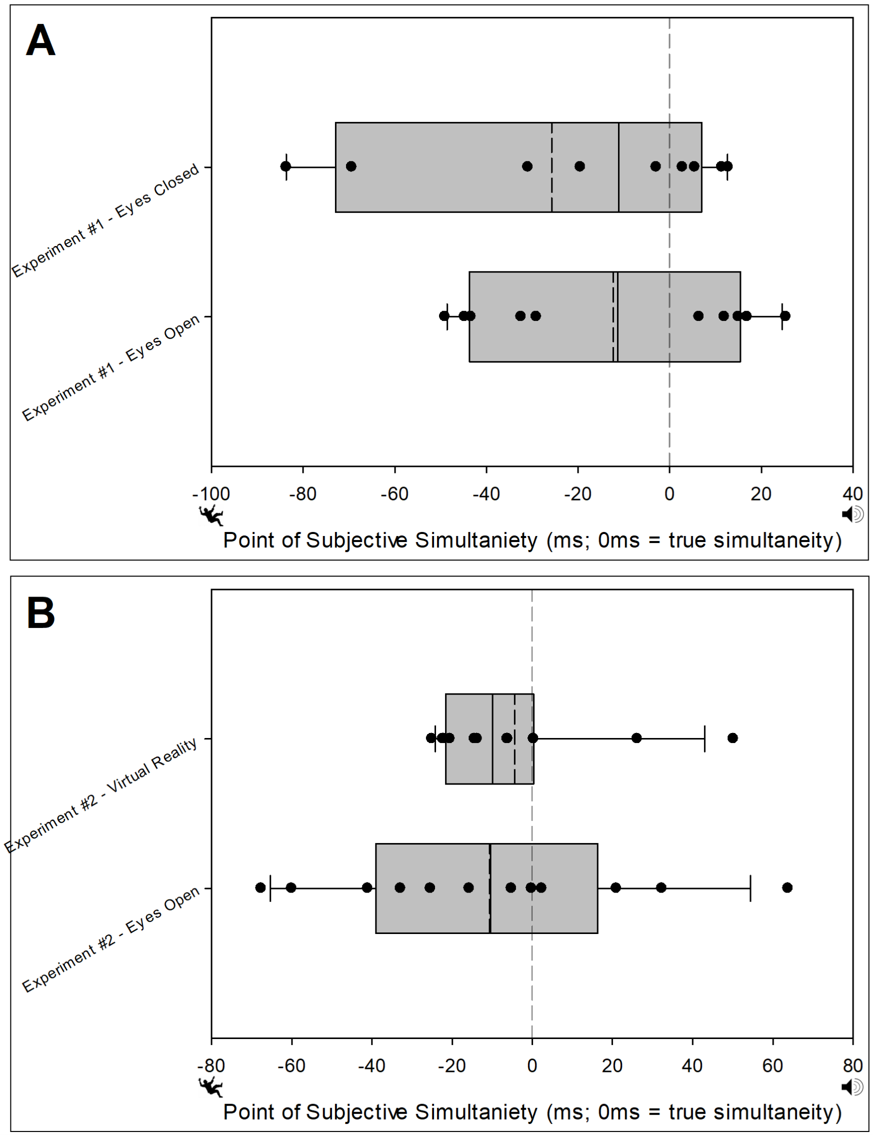

Figure 3.3: Experiment #1 is represented in Figure A and Experiment #2 is represented in Figure B. Each circle represents a participants PSS, the mean PSS is represented by the dashed lines and the solid line represents the median PSS. The grey bars represent the 75th percentile of the PSS data with the error bars representing the 90th and 10th percentile of data. A) There was no statistically significant difference between the Eyes Closed (EC) and Eyes Open (EO) PSS values. B) There was no statistically significant difference between the Virtual Reality (VR) and Eyes Open (EO) conditions.

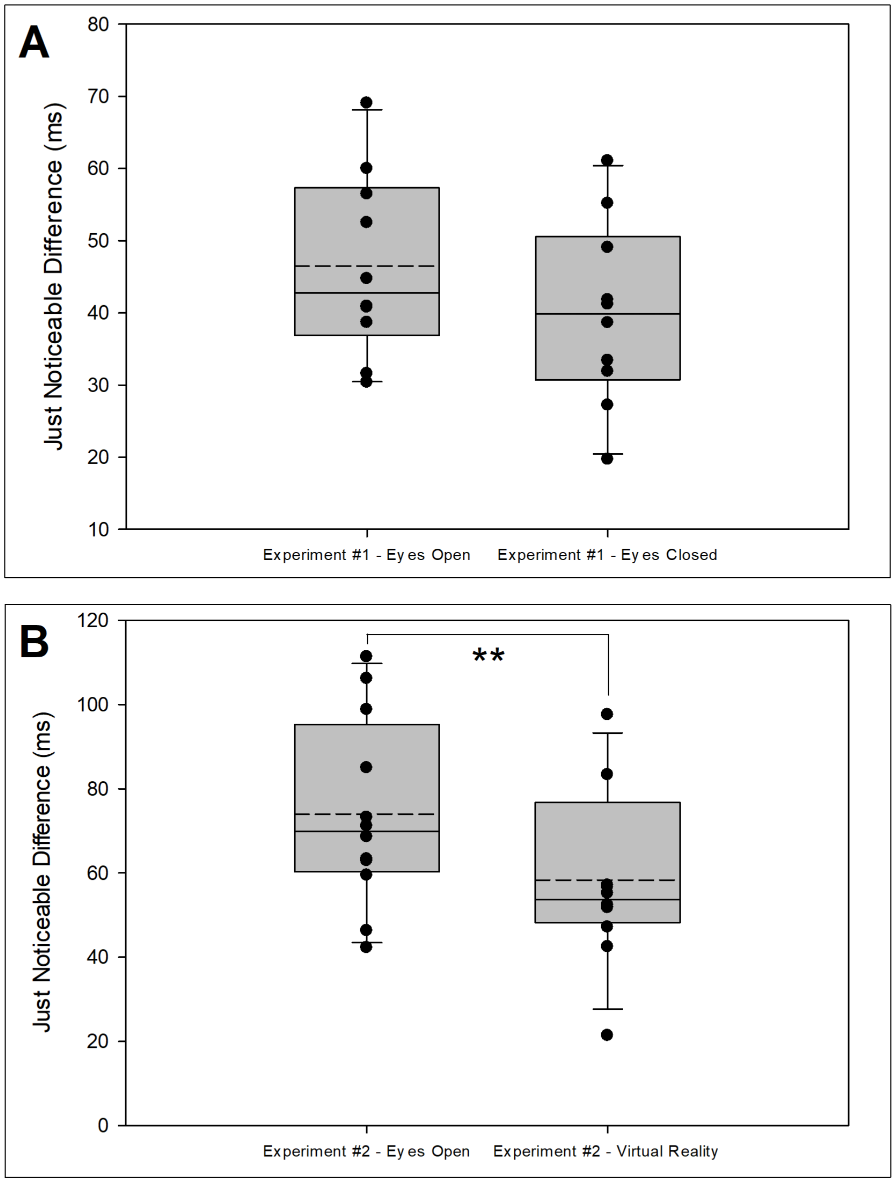

Figure 3.4: Each circle represents a participants JND, the mean JND is represented by the dashed lines and the solid line represents the median JND. The grey bars represent the 90th percentile of the JND data with error bars. A) There was no statistically significant difference between the Eyes Closed (EC) and Eyes Open (EO) JND values. B) There was a statistically significant difference between the Virtual Reality (VR) and Eyes Open (EO) conditions (** - represents a p-value < 0.01).

The results show that the EC condition yielded a negative PSS average as seen in figure 3.3A (PSS mean = -25.78 ms, SE = 12.40; median = -11.19 ms) indicating that the postural perturbation was required to precede the auditory reference stimulus in order to be perceived as simultaneous. Specifically, this indicated that the postural instability needed to occur 25.78 ms prior to the auditory reference stimulus in order to be perceived as simultaneous in the EC condition. For the EO condition, the average PSS was also in the negative direction (PSS mean = -12.33 ms, SE = 9.44; median = -11.35 ms). Despite both conditions yielding negative average PSSs, it was found that both the EC (One Sample Signed Rank test (one tailed); Z = -1.478; $p = 0.08$) and the EO (One Sample T-test (one tailed); t(9) = -1.307; $p = 0.112$) conditions did not demonstrate median and mean PSS values that were significantly less than zero, indicating that neither the absence or presence of vision results in a statistically significant difference of the PSS from true simultaneity. These findings support our initial hypotheses that the EC and EO conditions would not be significantly different from true simultaneity.

The observed difference between the mean PSS values of the EC and EO conditions was: 13.44 ms (Figure 3.3A), indicating that in this sample population the addition of visual information tended to slightly decrease the PSS towards true simultaneity. However, upon comparing EC and EO conditions via a paired sample t-test, there was not a statistically significant difference between the mean PSS values (Paired Sample T-test; t(9) = 1.170; $p =$ 0.272; 1 - β= 0.30). This supported the initial hypothesis (motivated by Chung & Barnett-Cowan 2017 [47]) that there would not be a significant change in PSS when provided with visual information. An interesting finding was that the EC condition in the current study did not yield a positive PSS mean as was found in the Equal distribution condition (PSS mean = 3.52 ms, SE = 11.97, median = 3.27 ms) in Chapter 2 of this thesis. The equal distribution condition was also an eyes closed condition, with the only differences being that the number of breaks provided in this study increased slightly. When statistically comparing these two independent groups EC PSS means between each other there was not an observed statistical difference between the PSS means (Independent Sample T-test; t(18) = 1.699; $p = 0.106$).

The mean JND values for the EC and EO conditions were as follows (EC JND = 39.88 ms, SE = 38.04 and EO JND = 46.48 ms, SE = 21.49), these conditions exhibited a difference of 6.6 ms (Figure 3.4A). This was a percent change of 16.5% and a paired sample t-test of the JND means exhibited no significant differences between the EC and EO conditions (Paired sample T-test; t(9)= 1.565; $p = 0.152$) (Figure 3.4A). However, that the standard error observed in the EC condition was noticeably larger than the EO condition.

The individual means for the PSS and JND exhibited a broad range of responses which displayed considerable variability across the participants for the EO and EC conditions (Figure 3.3A & 3.4A). This variability can also be observed in Figure 3.2A; the grey lines represent each individuals' logistic fit to their averaged responses at each SOA. These individual plots provide a visual depiction of how the PSS and JND values varied across participants for the EO and EC conditions exhibiting the variance between individuals and how that impacts the PSS (when logistic curve crosses 0.5/50% on the y-axis) and the JND (defined as the interval between the two stimuli that the participants can determine which stimuli occurred first on 75% of the trials – visual represented by the slope of the logistic curve).

3.3.3 Discussion

The first experiment sought to assess how visual information presented during a postural perturbation affected individuals' perception of instability onset. Specifically, this experiment was designed to assess whether the presence of visual feedback significantly altered the PSS and JND during a TOJ task between instability onset and the auditory reference stimulus. The results showed that the visual feedback provided to individuals during the postural perturbation did not significantly influence the perceived timing of the postural instability onset, though like Chung & Barnett-Cowan (2017) [47], it was found that there was a tendency for the PSS to move closer to true simultaneity. The results also indicated that the visual information did not significantly influence the PSS, JND or the delay of instability onset perception relative to the auditory reference stimulus. These findings support the initial hypotheses that the presence of visual information would not significantly affect measures related to perception of postural instability onset. Regarding the sample size of this experiment, a 1 - β= 0.30 for the comparison between the PSS of the EO and EC conditions was determined. Indicating an increased probability of type II error being present within the statistical analysis. With a subsequent apriori power calculation a population of 77 participants would be required to have a 1 β= 0.95. This finding indicates that the sample size is a potential limiting factor in the lack of statistically significant effects within this experiment.

Previous research investigating how both young and older adults perceive postural instability onset observed that the postural event needed to occur prior to the auditory cue to be perceived as simultaneous [148, 149]. This indicates that the PSS averages were significantly shifted away from true simultaneity (0 ms) in the direction of the SOAs in which the postural event occurred first. However, the second chapter of this thesis attempted to replicate that previous research conducted by Lupo & Barnett-Cowan (2017; 2018) [148, 149] while also utilizing an SOA distribution that was equally distributed around true simultaneity (0 ms). This previously observed statistically significant delay of postural instability onset was no longer observed in the results of Chapter 2, which indicates that the methodological design, specifically the SOA distribution, affects the PSS. The present experiment also utilized an equal SOA distribution, and it was also observed that this experiment again did not replicate these findings by Lupo & Barnett-Cowan (2017; 2018) [148, 149]. Thus postural instability onset does not need to precede an auditory reference stimulus with the eyes closed or eyes open to be perceived as simultaneous. This appears to reinforce the concept that an equal SOA distribution can prevent the introduction of lag adaptation that can occur when continually presenting asynchronous stimuli to the participants [172, 249, 229, 71, 89]. Though it is important to note that the PSS average of the EC condition in the current study (PSS mean = -25.78 ms, SE = 12.40; median = -11.19 ms) differed from that of equal distribution in chapter two of this thesis (mean = 3.52 ms, SE = 11.97; median = 3.27 ms). Though this difference was not statistically significant, it can be observed that this current experiment produced a

PSS mean that was negative indicating that for this population of participants the postural instability needed to occur prior to the auditory reference stimulus in order to be perceived as simultaneous, while this was reversed in the equal distribution condition in chapter 2 of this thesis. This would appear to indicate the possible effect of variability between individuals, which can be visually observed in figures 3.2A, 3.3A and 3.4A. The role of variability will be discussed further in the general discussion of this chapter.

Visual information can be critical to the control of balance, however posture and balance can also be maintained without this information, though there is typically an increase in postural sway [8, 16, 11]. This reinforces the concept that the control of balance utilizes visual information but relies heavily on proprioceptive information and vestibular information to a lesser extent. Proprioceptive feedback provides humans with precise information about limb and body orientation, which is critical in accurately correcting and reorienting body position. In addition, proprioceptive information is transduced and processed at rapid speeds; cortical activation in response to proprioceptive cues can range between 90-120 ms [232, 112] and reaction times in response to proprioceptive information has been observed to range between 60-150 ms [54, 151, 212, 161]. Comparatively, processing speeds are slower in the visual system; cortical activations in response to visual motion have been observed to occur at 130-200 ms [188, 236, 132] while reaction times to visual stimuli have been observed to occur at around 200-230 ms [257, 131, 23]. This slower processing speed of visual information could be due to a lack of effect on perception of onset when the eyes are opened compared to when the eyes closed. As previously discussed, we believe that the methodology differences are likely to be the driving factor in the observed decreases in PSS values in comparison to previous research. This subsequently makes it more difficult to observe the potential effect of visual information. As mentioned there is a shift in the PSS and JND between the EO and EC conditions but these changes are not significant. This lack of significant effect of visual information may also indicate that individuals do not rely heavily on visual input during this perceptual task. In addition, to sensory specific event related potentials (ERPs) there is a large negativity observed in the fronto-central parietal areas when individuals are posturally perturbed, called the perturbation evoked potential N1 [62, 243]. This cortical response occurs in the range of 90-150 ms [62, 243]. This ERP and others (i.e. P1 ERP) are believed to represent the arrival of sensory information and potentially represents early components of cortical processing of this sensory information. If these ERPs were to be used as a proxy of perception this could provide insight into why the perception of postural instability is not delayed in comparison to the auditory cues. Subsequently, it could be argued that visual motion information may not be critical in the initial perception of postural instability onset because of the slower processing speed, in comparison to other sensory modalities such as proprioception.

Within the realm of perceptual research, TOJ tasks are a method to investigate perceptual thresholds. Uni-modal perceptual tasks have found that visual stimulus onset typically needs to precede auditory stimulus onset to be perceived as synchronous [130, 122, 114], that touch onset needs to occur prior to visual onset [223, 222, 88, 89], that touch onset needs to be presented prior to sound onset [185, 89], and that vestibular stimulation onset needs to precede vision, touch and auditory stimulus onset [23]. This breadth of research implies that touch is perceived more slowly than visual cues, however touch alone does not fully encompass proprioceptive feedback that is experienced in balance control. In addition, balance control is not a uni-modal sensory event it is a complex multisensory event, composed of utilizing all sensory modalities. Research investigating how individuals perceive self-motion and heading direction found that visual information paired with somatosensory information was the most accurate and precise at determining egocentric heading followed by the somatosensory system [190]. This indicates that the utilization of several sensory modalities allows for the most accurate and precise responses, but also that proprioception/somatosensation is critical in perception of movement direction. It has been observed during active head rotations that the presence of visual information does not significantly reduce either the PSS or JND during a TOJ task, and that there is a persistent perceptual delay of the head motion across the eyes closed and eyes open tasks when compared to an auditory reference stimulus [47]. These researchers proposed that perhaps the sensory integration of several modalities could have led to the lack of change across visual conditions, and that individuals may be re-weighting sensory cues to rely more heavily on proprioceptive and vestibular feedback. Based on this research, it could be assumed that within the context of Experiment #1 individuals may be relying more heavily on proprioception to detect the onset of postural instability due to the lack of significant change between the EC and EO conditions for both the PSS and JND. There was a 13.44 ms difference of the PSS and a 6.6 ms difference of the JND between EC and EO, but this could be caused by individual variability or perhaps the re-weighting of sensory cues.

The concept of multisensory integration and sensory reweighting applies to situations in which the CNS adapts the utilization of sensory information when producing responses to an event [195]. In conditions with no visual information, the CNS will naturally need to adapt to upregulate the reliance/weighting of other sensory modalities related to the control of balance. Hence with no visual information available we know that the perceptual thresholds are driven by proprioceptive and vestibular feedback. Sensory weighting is adjusted based on the reliability of sensory information and sensory re-weighting research has shown how altering sensory reliability of visual, proprioceptive and vestibular cues can alter balance responses [195, 165, 154]. Though research has come to the strong conclusion that proprioceptive information is most commonly the most relied upon sensory modality in the control of posture and balance [195, 57]. However, the reliability or relevance of the visual information in Experiment #1 could have resulted in a decreased weighting of this information in the determination of perceptual instability onset. The visual context provided to the individuals in the first experiment was an 'X' on a grey wall. This visual information provides little meaningful context about the environment and few visual cues to provide feedback about self motion. However, visual cues are still present and are still being processed and because of this perhaps the JND (precision or variability of the response) decreases. Research in the realm of balance control has observed that visual cues taken from the environment can be utilized in a feed forward manner to alter motor responses to instability [264]. Therefore, it could be within the context of this experiment that the visual information was seen as low priority in comparison to proprioceptive feedback due to the limited usefulness of the cues. Providing visual information that is more relevant to the task may subsequently alter how postural instability onset is perceived with visual feedback, reducing both the PSS and JND. This is the goal of the second experiment, to alter the visual context to determine if the type of visual information (i.e., threatening versus non-threatening) provided alters perception of postural instability onset.

3.4 Experiment #2

3.4.1 Methods

Participants

A total of 14 participants (6 male and 8 female) free of musculoskeletal, auditory, visual, vestibular, or other neurological disorders. One participant was removed from analysis because they were not able to complete all trials in the experiment, resulting in 13 participants (6 male and 7 female; aged 19-24) being analyzed. All participants gave their informed written consent in accordance with the guidelines of the University of Waterloo Research Ethics Committee.

Apparatus, Stimuli & Procedure

The apparatus, stimuli and procedure were the same as experiment 1 besides the following exceptions. This experiment implemented the use of an Oculus Rift™CV1 VR HMD. The headset has two lenses that display a 960 X 1080 resolution to each eye, resulting in a total HD screen resolution of 1920 x 1080. The refresh rate of the system is 90 Hz and has a 100- degree horizontal field of view. The virtual image presented to the participants put them at the edge of a tall building in a city setting (Figure 3.5). They were instructed to look at the top of the building was in front of the participant to limit eye movement during the trials.

Data Analysis

The data analysis was identical to that performed in the previous experiment regarding the fitting of the logistic function (Eq. 1). The same parameters were utilized to determine if a participant's data was not included in our final analysis.

A within subject's design was utilized to re-assess the hypothesis that postural instability does not need to occur prior to an auditory reference stimulus in order to be perceived as simultaneous. A one-sample t-test was conducted to compare the mean PSS value of each condition relative to true simultaneity (0 ms). To address the hypothesis that virtual height will cause a decrease in both the PSS and JND in comparison to the non-threatening visual scenes, paired sample t-tests were performed to compare between the EO and VR conditions for the PSS and JND, separately. In addition, an independent paired sampled t-test was performed to compare the PSS and JND means of the EO condition from experiment #1 and EO condition from experiment #2. This would provide insight into whether different populations of participants produce similar results for the same perceptual task. If normality were to fail in any comparisons as assessed by the Shapiro-Wilk test we attempted to normalize the data. If these attempts with Z-Score normalization were not successful, then non-parametric statistical tests were performed. For each of the statistical tests a significance level of $\alpha = 0.05$ was utilized.

3.4.2 Results

When conducting our analysis, we removed one participant from our final findings. This participants data did not meet our outlined criteria revolving around the fit of the logistic regression. The fit of the VR data points produced an $R^2 = 0.4213$ and $p = 0.0585$.

Figure 3.2B above shows the logistic fits for each participant (grey lines) along with the averaged logistic fit for all participants (black line) plotted for each condition. The PSS and JND values for all participants were subsequently derived from these logistic fits (Figure 3.3B & 3.4B). The EO (EO mean PSS = -10.71 ms; median PSS = -10.47, SE = 11.02) and the VR (VR mean PSS = -4.45 ms; median PSS = -9.98, SE = 6.44) conditions produced average PSS values that were both close to true simultaneity. This can be observed in Figures 3.3B and 3.4B. These results indicate that the postural instability needed to be presented 10.71 ms prior to the auditory cue to be perceived as simultaneous in the EO condition. While the postural instability needed to be presented 4.45 ms prior to the auditory cue to be perceived as simultaneous in the VR condition. The VR PSS means did get closer to true simultaneity at -4.45 ms showing a slight decrease in comparison to the EO PSS.

Performing one sample t-tests on the EO PSS (One Sample T-test; $t(11) = -0.972$; $p = 0.176$) and the VR PSS (One Sample Signed Rank Test; $Z = -1.020$; $p = 0.170$) found the

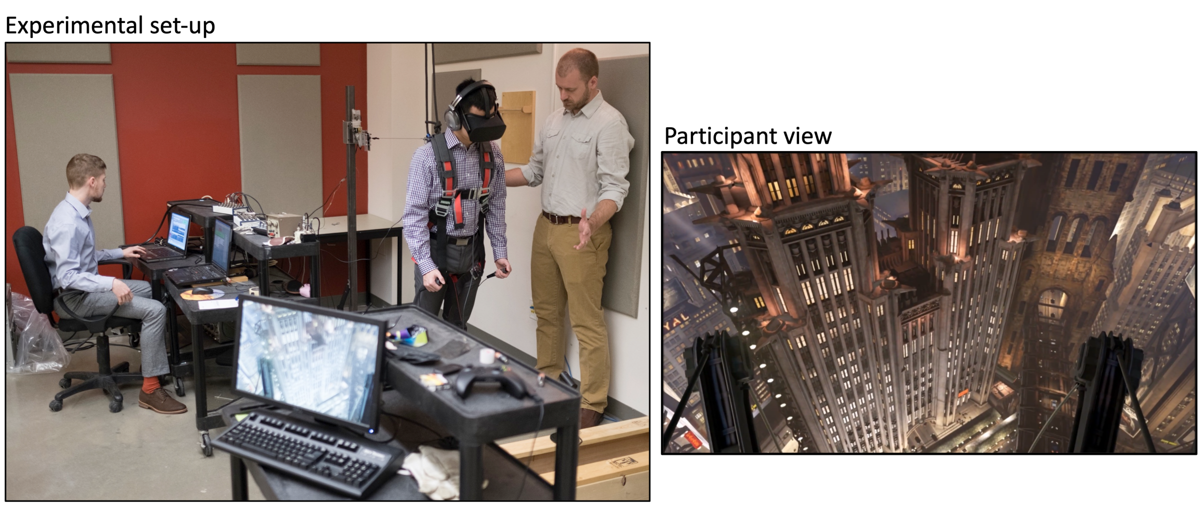

Figure 3.5: Left: lean and release setup showing a participant leaning forward while wearing a VRHMD and noise cancelling headphones. Right: the visual environment depicting being at the top ledge of a skyscraper that participants observed during the VR conditions.

PSS from each condition was not significantly less than 0 ms (i.e., true simultaneity). This lack of statistical differences coincides with the observations from the previous experiment in which the PSS means were not significantly different from true simultaneity (0 ms). In addition, comparing the EO and VR PSS means (Paired Sample T-test; t(11) = -0.798; p = 0.442) revealed that there was no statistically significant difference. These findings indicate that the visual context provided to the individuals between the two conditions did not alter the PSS means significantly.

The mean JND values of the EO (EO JND = 73.99 ms, SE = 6.41) and VR (VR JND = 58.31 ms, SE = 5.95)) conditions showed a relatively large amount of difference of 15.68 ms, or a change of 26.89%, as seen in Figure (3.2B and 3.4B). When performing a paired t-test on the EO and VR JND means ((t(11) = 3.416; p = 0.00576; 1 - β = 0.64) it was observed that the difference was significant. This indicates that the VR environment resulted in the participants being more precise or exhibiting less variability with their responses.

Across both PSS and JNDs, individual responses exhibited a wide range of variability across participants (Figures 3.2B, 3.3B and 3.4B). This is similar to what was observed in experiment #1. To check how experiment #1 and experiment #2 compared independent sample t-tests across the EO conditions for both the PSS and JND were conducted. There was no significant difference observed between the PSS means (Independent Sample T-test; t(21) = -0.109; p = 0.914), but there was a significant difference between the JND means (Independent Sample T-test; t(21) = -3.469; p = 0.00242), specifically a difference of 27.51 ms or a 59% change. Indicating that across these two different populations there was a significant change in the precision/variability of the TOJ responses between the experiments.

3.4.3 Discussion

Experiment #1 showed that visual feedback alone in comparison to no visual feedback does not significantly alter how individuals perceive the onset of postural instability. Experiment #2 sought to assess whether visual context increasing perceived threat alters the PSS (accuracy) and JND (precision) during a TOJ task between instability onset and the auditory cue (comparator stimuli). Overall, no significant change was observed between the EO and VR conditions across the PSS means but there was a significant difference between the JND means; indicating that the perceived threatening visual feedback provided to the individuals' improved the precision of the individuals responses. Similar to experiment #1, the PSS means were not observed to be significantly different from true simultaneity (0 ms). This replicated the findings from Experiment #1 of no observed delay in the perception of the postural instability onset when compared to the auditory cue. Interestingly, the JND means between the EO condition of Experiment #1 and the EO condition of Experiment #2 exhibited a significant difference. This was not an outcome we would expect as the EO conditions and methodology remained consistent across each sample of participants. Regarding the sample size of this experiment, a 1 - β = 0.64 for the comparison between the JND of the EO and VR conditions was determined. Indicating an improved level of power and a reduced probability of type II error in comparison to our previous experiment. With a subsequent apriori power calculation a population of 27 participants would be required to have a 1 - β = 0.95. This finding indicates that these statistical observations are more reassuring and that the JND may be a meaningful outcome measures when investigating perceptual changes during postural perturbations.

With the findings revolving around the PSS means, it could be assumed there are some parallels about why there was not a significant change between the EO and VR conditions or a significant delay in the perception of postural instability onset compared to the auditory cue. Primarily, this would appear to indicate that the methodological design utilizing an equal distribution around true simultaneity (0 ms) and utilizing the method of constant stimuli had the largest impact on the PSS means. This may further indicate that a bias or lag adaptation could have been introduced into the responses of the participants in previous research [148, 149]. It will be reiterated that it is likely proprioceptive feedback that is playing a prominent role in the perception of instability onset. This is due to the proprioceptive systems quick processing speeds [232, 112], high relative weighting among sensory cues in the control of balance [195], and its accuracy and precision of self-motion detection [190]. However, with the introduction of the perceived threatening virtual height it could be assumed that the weighting of this visual information has increased, in comparison to the EO condition. Yet despite this the PSS means are still not significantly different, this perhaps indicates that the perception of postural instability onset remains largely unaffected by what may be considered extraneous sensory cues.

Importantly, the JND (precision) of the TOJ responses was significantly affected by the perceived visual threatening VR scene, with the VR condition reducing the JND means by 26.89%. Precision is the consistency or variability of a response or action. In the context of a TOJ task this means that the individuals were more consistent (a reduction in variability) in their responses at each SOA. Research utilizing VR and threatening visual scenes has consistently observed that individuals experience psychological effects such as increased arousal, increased fear, increased anxiety and reduced confidence in balance [219, 55, 105, 50, 49, 261, 260, 262, 39] These psychological effects likely alter an individuals' attention to the situation as arousal, fear and anxiety can all heighten one's awareness. Alertness and attention in TOJ tasks has be shown to exhibit no effect on the PSS but rather causes a decrease in the JND or temporal precision of TOJ responses [140]. Li et al, (2018) [140] argued that this could be due to phasic arousal, which is the shift of arousal based on stimulus conditions provided to the individual. The presentation of emotionally evocative images has also been shown to improve temporal precision [141], indicating that visual cues have a top-down effect on cortical regions involved with TOJ task precision.

Research has explored the cortical substrates involved in a variety of sensory TOJ tasks with the use of functional magnetic resonance imaging and magnetoencephalography. The regions that have been shown to be involved in these various TOJ tasks include: temporal parietal junction [55], supramarginal gyrus [55, 40, 231] right posterior parietal cortex [256], bilateral inferior parietal cortices [231], superior and middle temporal gyrus [231], insula [231, 55] and frontal gyri [231, 55]. This clearly suggests that the inferior parietal lobe could be a region of the cortex where TOJ decisions are made. Trying to understand how visual context affects this neural substrate involved with TOJ responses could lead to a greater understanding of cortical processing in perceptual tasks. Visual processing has been shown to diverge along the dorsal and ventral pathways. The dorsal pathway defines the 'where' or spatial perception such as motion and occurs in parietal regions, while the ventral pathway defines the 'what' or object recognition or where objects are located occurs in temporal regions [27]. However, Battelli et al (2007) [27] proposed a 'when' pathway which is related to the timing or perception of events which occurs in the right parietal lobe, specifically the inferior parietal lobe. This inferior parietal lobe contains regions such as the supramarginal gyrus [55, 40, 231] and the temporal parietal junction [55] which are the regions that have been observed to be active during TOJ tasks. Therefore, it is possible that the visual system modulates perceptual TOJ responses through the middle temporal cortical region, which project to these inferior parietal regions and may have resulted in the observed decrease of the JND in the VR condition.

Research has explored how individuals respond to both reaction time tasks and TOJ tasks, to try and determine if these tasks are utilizing the same processing pathways and to also determine if there is a link between perception and action. A theory referred to as "one system two decisions", implies that motor and perceptual responses utilize the same internal processing pathways but at different decision making levels [41]. This has been explored by comparing reaction time responses and PSS estimates from TOJ tasks responses on the same stimuli (i.e. participants need to respond once they observed a change to the visual cues (reaction time task), and then subsequently at the end of the trial to indicate which visual cue changed first (TOJ task)) [41]. These researchers observed an association between the two responses, where the reaction times and TOJ responses differed together at the various SOAs by means of correlational analysis [41]. However, they also observed that there was great variability in the TOJ responses in comparison to the reaction time responses. This finding would imply that the motor and perceptual responses utilize the same pathways but are processed at different cortical levels. This experiment did not collect behavioural measures so direct comparisons between postural responses and the perceptual measures cannot be made. However, when individuals are exposed to perturbations at physical and virtual height when compared to non-threatening situations EMG onset decreases [38, 217, 42, 49], COP sway amplitude increases and COP onset decreases [217, 49]. Therefore, it appears that perceived threat can impact motor responses and can reduce the variability of perceptual responses (JND) but does not appear to influence the perceptual speed of processing (PSS).

The observed differences in the EO responses across the two populations (Experiment #1 vs. Experiment #2) was an unexpected finding. The significant change revolved around the JND but this did not extend to the PSS. The first consideration was to check the order of presentation of the conditions in each experiment, due to the loss of some participants in Experiment #1 there were more participants that performed the EC task first than the EO task first. Though it might be expected that precision of the response may improve due to the EC conditions occurring first , however this was not observed. The primary belief is that this was due to variability differences, primarily caused by individuals in Experiment #2 being less precise at the larger SOAs (i.e. -200 ms, -100 ms, 100 ms, 200 ms). It was observed in Experiment #1 that no individuals made an inconsistent choice at the -200 ms and 200 ms SOA, while in experiment #2 only 3 participants achieved this same level of precision. Due to the nature of how the logistic regression is fit to binary responses these precision differences can alter the slope of the curve and subsequently the JND. What specifically caused these differences between the two populations is something that is unresolved, but perhaps this could be related to attention or fatigue. Factors such as collecting individuals at different times of the day could have caused this shift if some individuals were collected at the end of the day this could have resulted in greater fatigue or reduced attention. For the future this is a factor that should be considered and made note of when running a multi experiment design, to limit potential differences between the methodology.

3.5 General Discussion

It is important to note potential limitations or considerations about the study design which should be considered for the future. It is known that the stimulus amplitude can play a critical role in how sensory modalities are perceived by individuals [91]. Research has exhibited under most circumstances that visual information needs to be presented prior to auditory information due to quick transduction times of auditory information [91]. However, it has been observed in some research that the auditory cues needed to be presented prior to visual information to be perceived as simultaneous [206]. The potential reasoning for this is believed to be due to the stimulus characteristics, specifically the stimulus intensity [32]. Hence controlling the stimulus intensity of the presented cues could be important to gaining meaningful conclusions. Within this study design an auditory test was not conducted on the participants (though all participants were within the young healthy population) and the dB level of the auditory cue was not maintained at the same level across the participants. The approach used for controlling the auditory stimulus was to adjust the white noise for individuals using the method of adjustment to the point they could not hear the lean and release mechanism activate. This would prevent the participants from getting any external clues about when the onset of instability was to occur. The auditory reference stimulus was then gradually increased to a level that could be clearly detected above the white noise using the method of adjustment. This level of intensity was subsequently subjective for each individual participant, which would hopefully allow for subjective relativity of the auditory cues.

It is important to re-iterate the implementation of the controlled methodology across these two experiments to help potentially reduce biases in the responses of the individuals through the SOA distribution. Subsequently these experiments did not observe the same delays in the PSS as the previous researchers, indicating the importance of utilizing an equal SOA distribution that employs the method of constant stimuli. Additionally, it is worth noting that the use of a lean and release paradigm may not be ideal as there could be a learning effect or change in central set over the course of the experiment. Central set is the knowledge or expectation of an event and results in descending commands to both sensory and motor systems for an anticipated stimulus [97]. The lean and release paradigm always puts individuals in a forward lean, so they always know that they are going to experience the postural instability forward. It is possible that some individuals utilized this knowledge and subsequently were able to improve their responses with this anticipation of the known perturbation direction. Therefore, utilizing a more randomized perturbation may benefit this area of research, such as a multi-directional motion platform.

Another factor that needs to be considered in this research is the variability between individuals. Variability between participants is inevitable but it is important to recognize this variability and try to understand why it may be occurring. The differences across individuals can be clearly observed in Figures 3.2, 3.3 and 3.4 across both experiments, as a range of values across the spectrum can be seen for both the PSS and JND. It was statistically observed when comparing the JND means between the EO group from Experiment #1 and Experiment #2, that there was a difference of 27.51 ms or 59% change. There was no methodological change between those two conditions besides the individuals that participated and as discussed earlier, individuals in Experiment #2 were less precise at the largest SOAs (-200 ms and 200 ms). Therefore, it appears that perception of instability is quite variable among individuals or was caused by an unknown factor. Our methodology across experiments is not designed to address these levels of variability and it is difficult to determine what potentially caused this variability. Though factors such as differences in sensory re-weighting, previous experience, psychological effects such as fear of falling, differences in attention or even fatigue could play a role in observed variability. Re-weighting of sensory modalities can be a subjective matter between individuals, research has proposed that trained athletes may rely more on proprioceptive information than untrained individuals [94]. This may also relate to experience with instability, it is possible those who exercise or participate in sport may have different experiences with instability and this may alter how these individuals perceive these events. Finally, psychological effects such as fear of falling, attention or arousal may also be differing across individuals. It was previously discussed how fear of falling, anxiety and arousal has been shown to change when at physical and virtual heights [219, 105, 50, 49, 261, 260, 262, 39]. Each of these factors could be affecting the attention of the individuals for the TOJ task, this attention could be heightened or reduced depending how the participant perceives the stimuli that is presented. In addition, fatigue could directly affect arousal and attention as well. Fatigue could be a factor prior to arrival at the laboratory or could even progress during the completion of the study. There was an attempt to try and limit fatigue by providing breaks and talking with the participants between blocks, but the time of day when the participants were collected was not controlled between the experiments. In the future, utilizing qualitative measurements through questionnaires to potentially account for some of this variability could provide a greater understanding of potential causes of these differences.

3.6 Conclusion

In conclusion, visual information appears to have a limited effect on the perception on postural instability onset. Visually threatening stimuli significantly decreased the JND of TOJ responses. We can conclude that the perception of instability onset is not delayed with visual context or without, which differs from previous research. This indicates that variability between individuals and methodology may be important facets to try and control or monitor in future research on the perceived timing of postural perturbations. Future directions of this research may seek to confirm how proprioceptive feedback can affect perception of postural instability onset, perhaps through sway referenced platforms or non-compliant surfaces. In addition, utilizing more randomized perturbation strategies such as a moving platform may be ideal to limit potential learning effects. Overall, this area of research may still provide insight into how sensory information is utilized in forming humans' perception of postural instability events.

Chapter 4

The Effect of Visual Motion with Altered Visual Characteristics on Postural Responses

4.1 Abstract

Visual information is critical for the control of balance and posture as it provides information about the external environment and the body's motion through the environment. Postural responses have been observed to be produced by presenting visual motion stimuli to participants. These visual motion cues are believed to give the sense of self-motion which results in compensatory postural adjustments. These postural responses have been observed to occur in response to both linear and rotational visual motion. In addition, visual context such as visual threat (heights) have been observed to directly impact postural sway parameters during quiet stance and during physical perturbations. These findings and the evolution of virtual reality (VR) enable the present experiment to assess how visual motion with differing visual characteristics affects balance and posture. We implemented the use of linear and rotational visual motion in an attempt to mimic physical motion related to moving and falling in an Earth gravitational environment. Visual motion could occur in the anterior or posterior direction while also presenting a visual scene that either places the individual at ground level or at a top of a set of stairs. The primary goal was to investigate how postural responses to visual motion were affected by perceived threat, specifically virtual height. Force plates, accelerometers, and electromyography were used to assess responses to visual perturbations. There did appear to be an effect of visual motion duration on the AP COP sway but otherwise there were very few statistically significant effects. However, the small size of the responses in these other statistical effects raise the question of biological significance as the grand mean averages across all measures were quite small. Importantly, drawing conclusions from the data based on averages alone is premature as there were some clear individual differences between participants that suggest the sample was composed of individuals who responded to a much greater extent than others. This potential difference across the population in regards to how visual information

is utilized in the perception of self-motion and forming postural responses to visual motion cues is an important observation that can potentially help screen and treat those that are more or less visually dependent and prone to falls.

4.2 Introduction

Visual feedback is a critical aspect of self-motion perception in the control of balance. Visual motion cues provide context to individuals about the direction and speed of self-motion [202]. Visual motion provided to the retina is referred to as optic flow which occurs from a central point called the focus of expansion (FOE) [202]. Research exploring the effect self-motion perception has on posture control has observed that visually moving scenes or optic flow can produce postural responses. The seminal research conducted by Lee and Lishman (1975) [136] explored this effect by utilizing a visual surround that moved in isolation from the floor. It was observed when the surround moved forward that individuals would perceive this optic flow as self-motion in the backwards direction and subsequently move forward with the visual surround, and vice versa for the backwards direction. Additionally, research utilizing star fields/dots [237, 31] has found similar results but some research has also found that using differing fixation points can produce postural responses that move individuals in the opposite direction of the visual motion [37, 83]. This research also found that postural responses to visual motion are not fixed responses but rather are dependent on how the individuals perceive self-motion and environmental motion, suggesting a role of differing sensory weightings between individuals.

With the advancement of technology, the assessment of the role of visually induced self-motion on posture control can make use of tools such as virtual reality head mounted displays (VRHMD). The use of VRHMD allows for the presentation of rich visual scenes that can be modified to the researcher's choosing. A common methodology utilized in self-motion research is moving star fields in various directions to expose individuals to controlled optic flow stimuli [202, 31, 237]. These cues provide a strong contrast to give a sense of self-motion however these cues have little contextual relevance in the real world. Providing environments with more contextual relevant features and scenes started to occur with VR only relatively recently [50, 49, 127, 17, 45, 125]. Within the context of standing balance and physical perturbations, virtual height/threat has been observed to alter behavioural outcome measures of balance, increase EMG amplitude [49], reduce COP sway during quiet stance [50] and increase COP amplitude during perturbations [49].

Another aspect of interest is the effect of visual motion characteristics on the perception of self-motion and how this alters postural responses. Visual motion characteristics tend to vary across studies, with many studies utilizing long periods of sinusoidal visual motion [85, 202, 127, 17]. These long periods of visual stimuli (i.e., 20 seconds or more) allow researchers to ensure a sense of self-motion is achieved and gain a more prolonged effect. Though there are some cases of more transient visual motion (e.g., 2 second stimuli) that have also been observed to affect postural responses [37, 182]. The interest with more transient and shorter visual stimuli is that they align with the length of some postural events that can occur in daily life (i.e. falling, tripping or slipping). It has also been suggested that there may be two different mechanisms for processing transient visual information and continuous visual information [83]. With transient visual information a short-latency mechanism may be employed where more automatic posture responses occur, while continuous visual information may employ a different mechanism for monitoring longer latency responses that are related to self-motion perception for longer types of visual stimuli such as driving or walking [83]. This segregation of short and long types of responses suggests that visual information can drive postural responses over relatively short stimulation periods. There has been an exploration of both linear [136, 31, 37, 83] and rotational visual motion [240, 147] with both types of visual motion evoking postural responses. However, a large majority of the research has focused on linear visual motion in the anterior-posterior direction in a sinusoidal fashion using longer periods of motion. Rotational visual motion in the anterior-posterior direction is an interesting type of visual motion because it can mimic the type of optic flow that would be experienced during a fall due to the multiple axes it moves through. Naturally, as mentioned previously, the directionality of visual motion has been explored with both the expansion and contraction of the visual scene. Here it has been observed to alter the direction of the postural response [202, 125].

The purpose of the present study was to assess how visual motion with differing visual characteristics and context, specifically perceived threat, affect balance control. This approach will help determine how the visual characteristics of visual motion alter postural responses and whether the presented visual scene has any effect in manipulating these postural responses. This research could help determine how different visual motion characteristics could be utilized as a tool to probe postural control, which could be utilized in clinical tasks such as fall prevention training [45]. It is hypothesized that the perceived threat will increase COP sway, increase head and torso accelerations and increase the EMG response. This is based off of postural perturbation research done at a virtual height [49]. It is hypothesized that postural responses will be amplified in the rotational visual motion conditions because they are designed to mimic rotational (i.e., falling down movement) of the body in postural perturbations, while linear motion responses will be smaller because they mimic translational motion such as walking. Additionally, it is hypothesized that participants will move in the opposite direction of the visual motion, as observed in visual motion research [202, 125]. Finally, we want to determine if longer visual motion produces increased postural sway.

4.3 Methods

4.3.1 Participants

A total of 20 participants (aged 21-31 years old; 11 males and 9 females) free of musculoskeletal, auditory, visual, vestibular, or other neurological disorders participated in the study. All participants gave their informed written consent in accordance with the guidelines of the University of Waterloo Research Ethics Committee.

4.3.2 Virtual Reality

Participants wore an Oculus Rift CV2 HMD which has two lenses that display a 960 X 1080 resolution to each eye and a resultant HD screen resolution of 1920 x 1080. The refresh rate of the system is 90 Hz and has a 100-degree horizontal field of view. The visual focus and the lens width can be individually adjusted to each participant to ensure a clear image for the participant even with the use of corrective lenses. The virtual image presented to the participants was inside a home in the Tuscany region of Italy, two different positions were presented to the participants, ground level and at the top of a set of stairs, (Figure 4.1; Tuscany Demo, Oculus) [72]. In addition, participants were exposed to two different types of virtual perturbations; a linear perturbation that mimics walking/sliding (Figure 4.2) and an inverted pendulum perturbation which approximates a fall (Figure 4.3). The visual perturbations were designed to mimic the physics that may be experienced during a physical perturbation, hence both perturbations are modelled to consider gravity, height, and mass of an average human. Each of these measurements are standardized to allow for direct comparisons between participants and to ensure the same visual stimulus is being applied to each participant. When the visual perturbation was initiated the VR computer utilized a serial port to send a 5V pulse to an analog-to-digital board to allow for the synchronization of the EMG, force plate and accelerometer data.

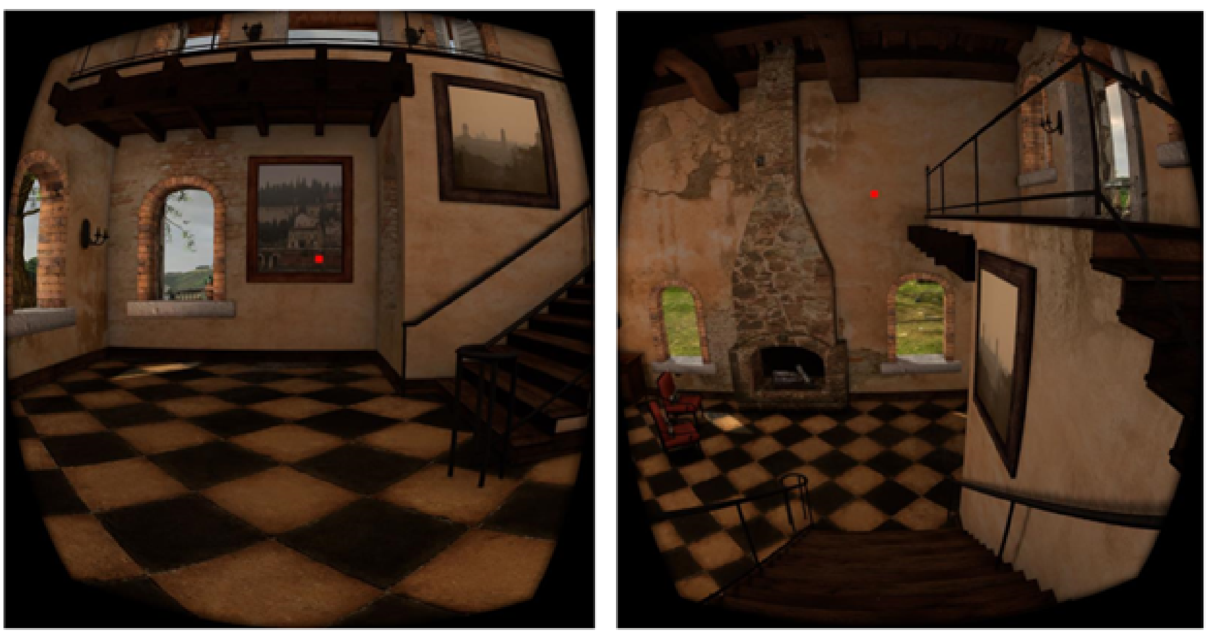

Figure 4.1: Depiction of the two different visual conditions that participants were exposed to. The left panel shows the ground condition, the right panel shows the top of the stairs condition. The red dot is the fixation point that each participant was instructed to fixate on at the beginning of each trial.

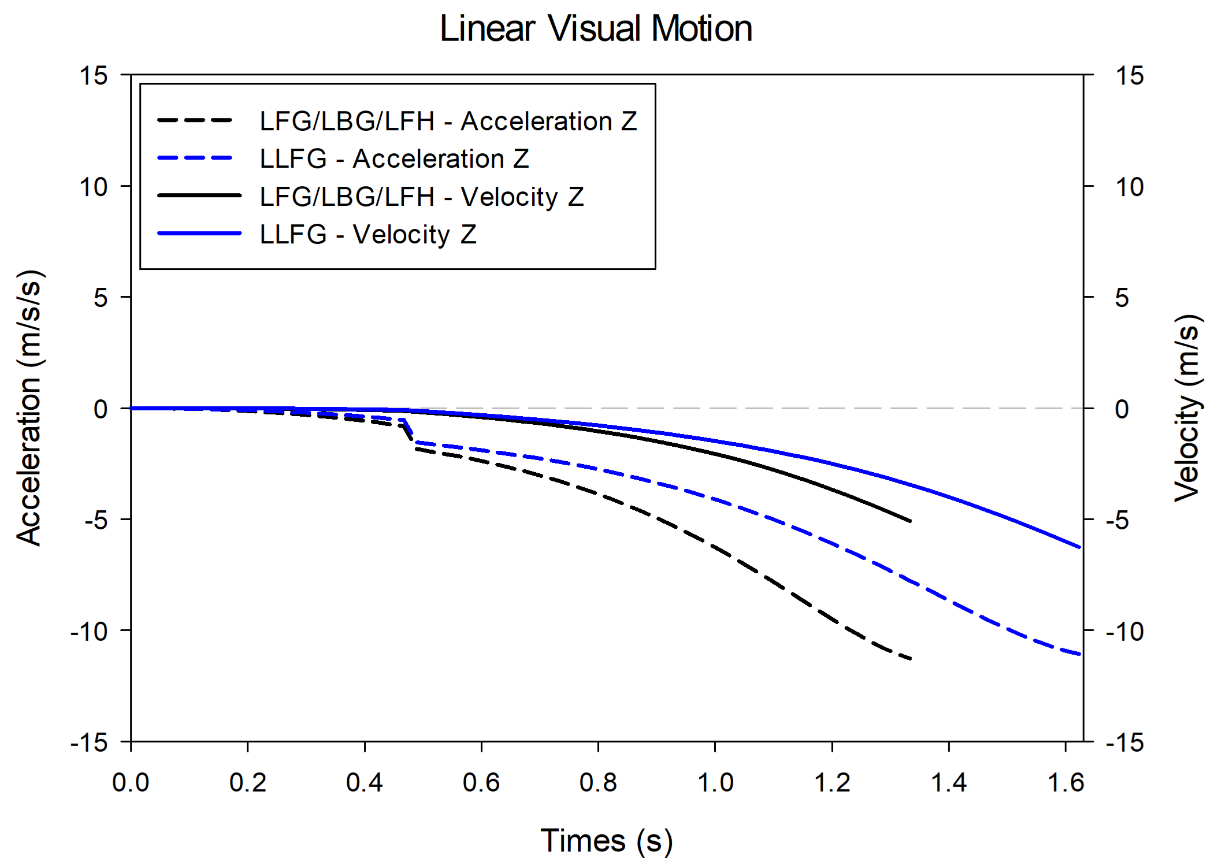

Figure 4.2: Plot of the linear visual motion characteristics for different conditions in acceleration (left y axis) and velocity (right y axis) as a function of time. The blue lines represent movement of the visual scene for the LLFG condition and the black lines represent movement of the visual scene for the LFG, LBG and LFH conditions.

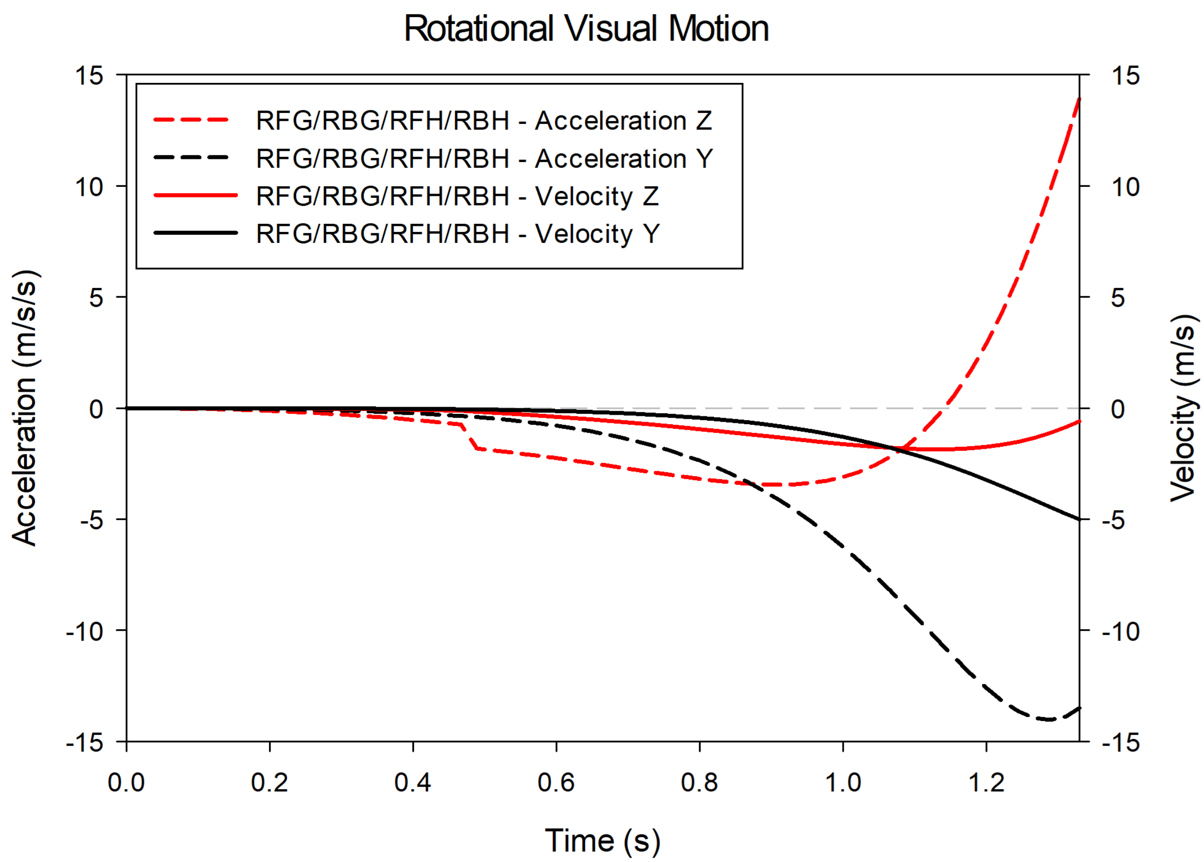

Figure 4.3: Plot of the rotational visual motion characteristics for the RFG, RBG, RFH and RBH conditions in acceleration (left y-axis) and velocity (right y-axis) as a function of time. The black lines represent movement of the visual scene in the z-axis and the red lines represent movement of the visual scene in the y-axis.

4.3.3 EMG

Bilateral EMG signals were collected from medial gastrocnemius (MGAS) and tibialis anterior (TA) with the use of surface EMG, the lateral malleolus of the fibula was used as the ground reference [243]. Participants were instructed to dorsi flex and plantar flex at their left and right ankle and the researchers subsequently palpated for the TA and MGAS muscle bellies respectively. The muscles and ground location were abraded with the use of NuPrep and then cleaned with alcohol swabs. The impedance of the electrodes will be tested to ensure they are reduced below 20 kOhms [225, 135]. Following the cleaning of the various electrode sites the Ag/Cl electrodes were placed on the sites. Two electrodes placed $\sim$ 2 cm apart were placed on the muscle bellies, while a single electrode was placed on the lateral malleolus of the right leg for the ground. A Bortec wireless EMG system was worn around the participants waist, the appropriate leads were attached to the electrodes and the EMG system was connected to the EMG amplifier which applied a gain of 500. The EMG signal was collected via the LabVIEW program used to collect the force plate data, this data was collected at 1024 Hz [225, 135] to allow to synchronization across the various pieces of data. This data was stored offline for post processing and statistical analysis.

4.3.4 Force Plates

Throughout the duration of the study participants placed each foot (without shoes) on a Bertec force plate. Participants adopted a narrow stance throughout the duration of the collection in order to provide an increased challenge to balance control, the feet were placed as close together as possible without touching [242]. The borders of the feet were marked with tape to ensure that the foot location was consistent across trials. The force plates were placed next to one another but a small distance ($\sim$ 5 mm) was be left between the plates to ensure they were not in contact. Each force plate recorded moments about the x-axis (Mx), moments about the y-axis (My) and force in the z-axis (Fz). These pieces of information were collected with the use of a custom LabVIEW program that sampled at a frequency of 1024 Hz [135]. This frequency was chosen to allow for easier synchronization across the various data measurements and because the accelerometers' collection frequencies were limited to powers of two. The data was stored offline for post processing and statistical analysis.

4.3.5 Accelerometers

Head and torso accelerations were recorded with the use of accelerometers (Shimmer3 IMUs - Shimmer Sensing Inc., Dublin, Ireland). A total of two Shimmer3 IMU accelerometers and one Shimmer3 Bridge Amplifier were used in the collection; the first accelerometer was placed on the side of the VR HMD, the second accelerometer was placed on the sternum of the participant. The accelerometer placed on the sternum was secured with the use of an elasticized compression band to ensure the accelerometer did not shift during the collection, while the accelerometer attached to the VR HMD was secured with the use of Velcro. The bridge amplifier received a 5V pulse from the VR computer (triggering computer) to mark the onset of the visual perturbation and allow for synchronization of the accelerometry data. The accelerometers were collected on a separate computer using the Consensys software (Shimmer Sensing Inc., Dublin, Ireland); the data was sampled at 1024 Hz which is identical to the force plates and EMG collection frequencies. The accelerometers were sampled over the entire duration of the collection and were streamed for visual inspection and saved directly to a storage drive. Post-processing of the data was completed to isolate each of the individual trials with the use of the 5V pulses to indicate the onset of each individual trial. These individual trials were subsequently cropped from the data and analyzed separately.

4.3.6 Procedure

Participants were provided with a detailed overview of the study and a consent form upon arrival. Once they understand the study protocol and signed the consent form the participants were instructed to remove their shoes and then EMG electrodes were applied bilaterally to the TA and mGAS. The force plates were zeroed and then the participant stood on the force plates with each foot on a separate plate and were instructed to adopt a narrow stance, but not have the medial aspects of their feet touching ($\sim$ 1 mm apart). The borders of their feet were then marked with tape to allow for consistent foot position throughout the trials. The VR headset was then fitted to the participant to ensure the headset was comfortable and the lens position was adjusted to provide the clearest image.

Once the VR headset was fitted and adjusted to the participant, an immersion phase was used to get the participants accustomed and immersed within the virtual environment. The participants were instructed to search for various objects within the environment including: a fireplace, chandelier, table, chair, doorway and stairs. This active searching task helped immerse the participants within the environment and it provided context about the environment to the participants would conduct the study in. Participants were exposed to eight different virtual perturbations which varied in direction (forward/backward), perturbation type (rotational/linear) and visual context (ground/height) (Figure 4.4). Each trial was repeated 10 times lasting approximately 10-15 seconds and the trials were completely randomized. Participants were instructed to stand quietly with their hands at the side throughout the duration of the trials, while maintaining their gaze on a red square several meters in front of the virtual character (Figure 4.1). When the trial was complete, participants were allowed to bend their knees, move their torso and look around before the subsequent trial began to prevent any stiffness or fatigue. The time between trials ranged from 15-20 seconds, but this was occasionally longer when participants requested a break at any point during the collection. The researchers actively monitored postural sway on the LabVIEW program to initiate the trial when the participant was not swaying too overtly. Breaks were provided to the participants in 20 trial intervals to reduce the likelihood of physical fatigue, sickness, or eye strain.

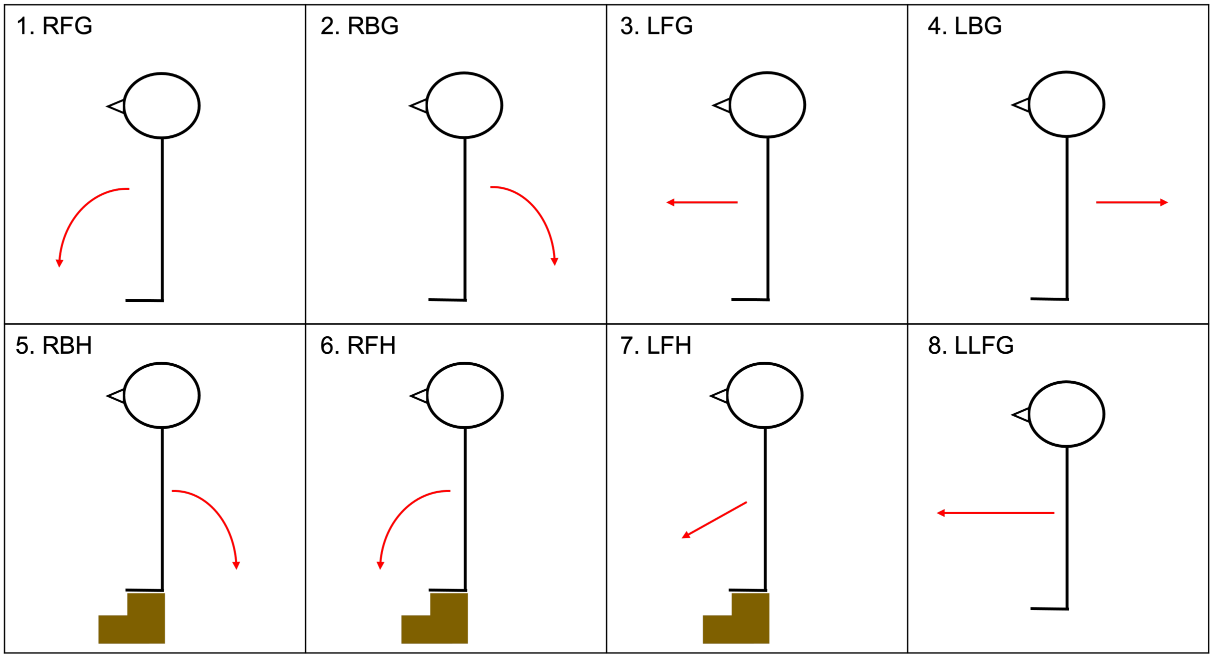

Figure 4.4: The eight visual motion conditions participants were exposed to within Virtual Reality: 1. Rotation Forward Ground (RFG), 2. Rotation Backward Ground (RBG), 3. Linear Forward Ground (LFG), 4. Linear Backward Ground (LBG), 5 .Rotation Backward Height (RBH), 6. Rotation Forward Height (RFH), 7. Linear Forward Height (LFH), 8. Long Linear Forward Ground (LLFG)

4.3.7 Data Analysis

Force Plates

The first step to post-processing the force plate data was to low pass filter the signal, 5 Hz second order Butterworth filter will be utilized due to the low frequency content present within balance responses [43, 49]. The raw data collected from the force plates was recorded in volts and converted into units of force and moments. The forces and moments from the two force plates were then combined and used to calculate estimates of centre of pressure (COP) in both the anterior-posterior (AP) and medio-lateral (ML) directions with the following equations.

$$APCOP = \frac{Mx}{Fz} \tag{4.1}$$

$$MLCOP = \frac{My}{Fz} \tag{4.2}$$

Two windows were utilized to calculate the chosen outcome measures, the first window was a 1000 ms window that occurred prior to the onset of the visual motion (pre-stimulus) and the second window was the duration of the visual motion (during-stimulus), either

1300 ms or 1600 ms. The 1300 ms window corresponded to the length of the visual motion in conditions 1-7 and the 1600 ms window corresponded to condition 8. There were two primary measures that were calculated over each of these windows, the mean and the standard deviation of the COP. The mean COP allowed for the determination of potential tonic changes in the COP and a generalized determination of directionality (can be confirmed with visual inspection) of the COP response. The standard deviation of the COP provides a measure of variability of the COP which can allow for a characterization of postural sway over each of the chosen windows [125]. This was calculated for each participant over each task and the subsequent grand mean averages were calculated from the individual averages. The variables (mean and standard deviation) from the pre-stimulus window and during-stimulus windows were subtracted to obtain difference scores of the mean ($\Delta\text{Mean}_{\text{AP/ML COP}}$) and standard deviation ($\Delta\text{STD}_{\text{AP/ML COP}}$) across these windows. These difference scores were the primary outcome measure to quantify whether there was an effect of the visual motion on the COP. These differences scores were utilized as a method to quantify each individuals average response to the visual motion stimuli in each condition. The pre-stimulus period captured the natural sway characteristics of each individual and removed this response from the during-stimulus window. Subsequently allowing for characterization of the average postural response for each condition for each individual. Together these differences scores could be averaged at the group level to gain an understanding of the averaged postural responses across all participants.

The first statistical measures that was conducted were one sample t-tests of the $\Delta\text{Mean}_{\text{AP COP}}$, $\Delta\text{Mean}_{\text{ML COP}}$ and $\Delta\text{STD}_{\text{AP COP}}$, $\Delta\text{STD}_{\text{ML COP}}$ for each task. These one sample t-test utilized a comparator mean = 0 as the null hypothesis indicating no change between the pre-stimulus window and the during-stimulus window, if there was a significant difference from zero this would indicate that there was an observable change in the COP sway. This was a method to quickly confirm whether there were changes in postural sway during the visual motion. With these results the analysis was subsequently focused on the $\Delta\text{STD}_{\text{AP COP}}$ in the anterior-posterior (AP) direction, due to the observed significant change and the focus of the visual motion in the AP direction.

To explore the effect of height and visual motion type two 2x2 Repeated Measures ANOVAs were run with significance level of $\alpha = 0.05$ on the $\Delta\text{STD}_{\text{AP COP}}$. The first 2x2 Repated Measures ANOVA tested the effect of height by comparing: RFH and RBH vs. RBG and RFG, the second 2x2 Repeated Measures ANOVA tested the effect of visual motion type by comparing: RFG and RBG vs. LFG and LBG. There were two additional paired t-tests run because the design was unbalanced (we did not have LBH due to design constraints) and we added in the LLFG to explore the effects of a longer visual motion. Therefore, LFH was compared against RFH to explore visual motion type effects and LLFG was compared against LFG to explore the effects of duration.

Accelerometers

Accelerometer data was used as a method to determine if the virtual perturbations evoked torso movement and/or head movement. It should first be noted that data of three participants was corrupted, there were collection issues of the sync pulses in these participants -

making it impossible to determine where each trial began. The raw acceleration data was low pass filtered at 10 Hz with a 2nd order Butterworth filter because human movement is known to be low frequency; research has shown to typically utilize cutoff frequencies between 0.5-10 Hz [75]. Similar to the COP data, the mean and standard deviation were calculated over the two windows (pre-stimulus and during-stimulus), this was done for both accelerometers at the head and chest. The difference scores were calculated for both ($\Delta\text{Mean}_{\text{AP Head Accel}}$) and standard deviation ($\Delta\text{STD}_{\text{AP Head Accel}}$). We directly focused on the anterior-posterior axis to mimic what was done with the COP data.

All of the same analyses were run that were outlined in the COP analysis section above. As the goal was to investigate if there were any changes in head and chest accelerations across the various task conditions.

Electromyography

The post processing of the raw EMG signal first had the data baseline corrected and then a band pass filtered at 30-250 Hz with a dual pass 2nd order Butterworth filter. The EMG signal was then was full wave rectified. Next this rectified signal was run through a low pass filter at 6Hz with a dual pass 2nd order Butterworth filter. This filter was applied to perform a linear envelope and the mean amplitude was then calculated to quantify the size of the EMG response of both the tibialis anterior (TA) and medial gastrocnemius (MGAS). Utilizing the same strategy as the COP analysis, the mean amplitude pre-stimulus and during-stimulus was calculated and a $\Delta\text{Amp}_{\text{TA/MGAS}}$ was determined.

All of the same analysis were run that were outlined in the COP analysis section above. As the goal was to investigate if there were any changes in muscle response across the various task conditions.

4.4 Results

The first step was to visualize the grand mean average of the data from the various measurements in the times series domain, the COP data can be observed in Figure 4.5, the head accelerations can be viewed in Figure 4.6, the chest accelerations can be viewed in Figure 4.7, the left EMG can be viewed in Figure 4.8. As can be visually observed there appear to be some postural responses in the anterior-posterior (AP) direction of the COP data and some in the head accelerations, but the other measurements did not exhibit much observable change during the various tasks.

This was confirmed when running the one sample t-tests of the ΔMean for each of the outcome measures (AP COP, ML COP, AP Head Accel, AP Chest Accel) when compared to a mean = 0, which would indicate no change. There were not many observed statistical differences between ΔMean measurement across the various measurements (Tables 4.1, 4.2, 4.3, 4.4). The significant differences that were observed exhibited ΔMean that were very small, the largest observed difference occurred in $\Delta\text{Mean}_{\text{AP COP}}$ during the LFG task ($t(19) = 2.22$; $p = 0.0195$) exhibiting a $\Delta\text{Mean}_{\text{AP COP}} = 0.6205$ mm. While the smallest observed difference occurred in $\Delta\text{Mean}_{\text{AP Chest Accel}}$ during the RBG task (t(16) = 1.988; p = 0.032) exhibiting a $\Delta\text{Mean}_{\text{AP Chest Accel}}$ = 0.007 mm. Despite these statistically significant differences the ΔMean themselves are quite small, as are the standard errors for each measurement. Overall these results appear to indicate a lack of a tonic shift or change in direction across the tasks for each measurement. Therefore, the choice was made to primarily focus on the ΔSTD for further analysis of these measures.

The one sample t-tests of the ΔAmp for the Left TA and Left MGAS were also compared to a mean = 0, which would indicate no change. There were only two statistically significant differences observed in the Left TA (Table 4.5) and none in the Left MGAS (Table 4.6). They occurred in LFG (t(19) = 2.740, p = 0.013) and LFH (t(19) = 2.191, p = 0.041). When pairing these results with the time series data, figure 4.8, and observing the group averaged ΔAmp values these changes are very small likely indicating limited EMG activity across the individuals for each of the tasks.

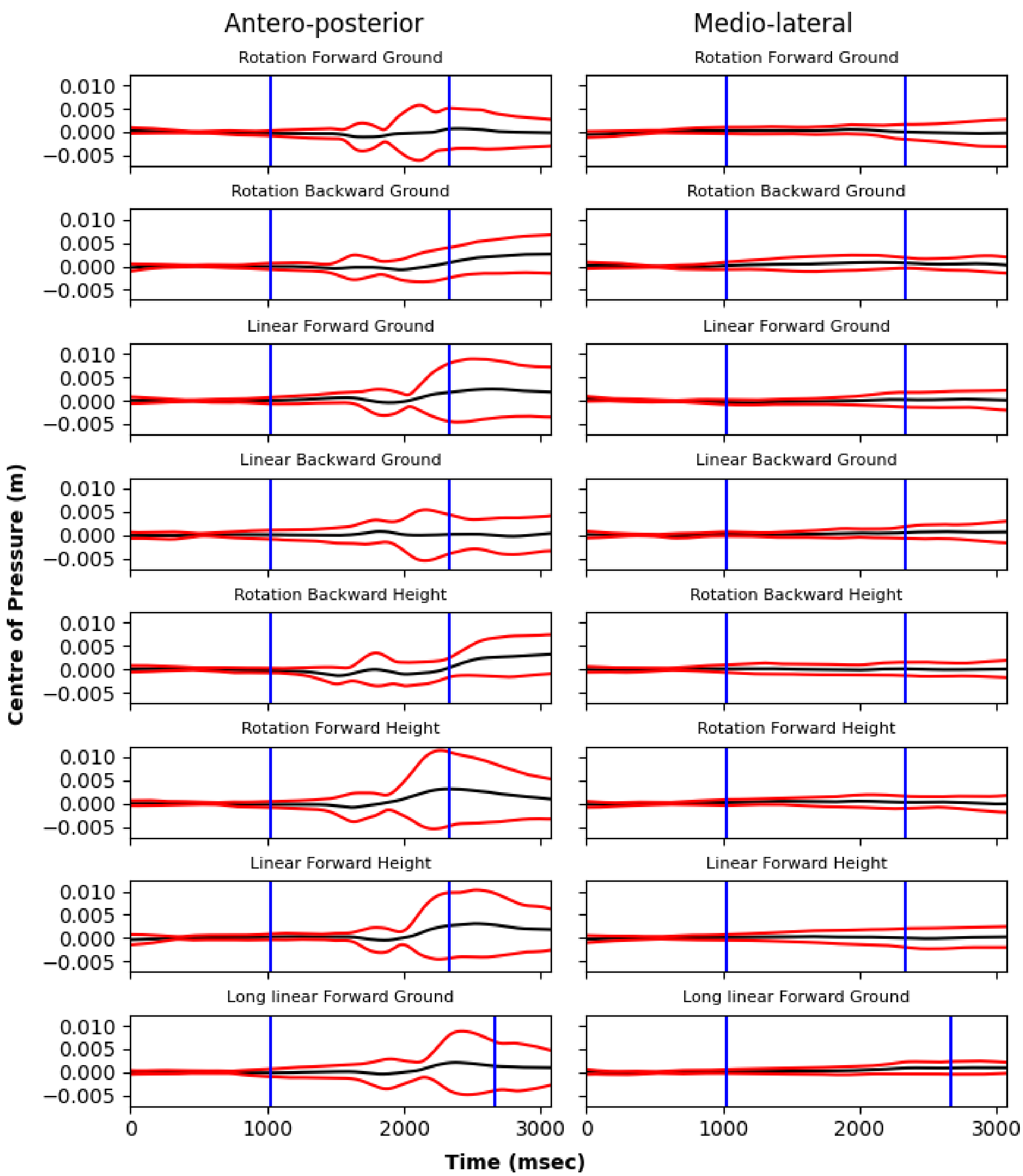

Figure 4.5: Grand mean averages (black lines) for the anterior-posterior COP (left) and the medial-lateral COP (right). The blue lines indicate the start (left blue line) and end (right blue line) of the visual motion and the red lines represent the 95% confidence interval of the averaged data.

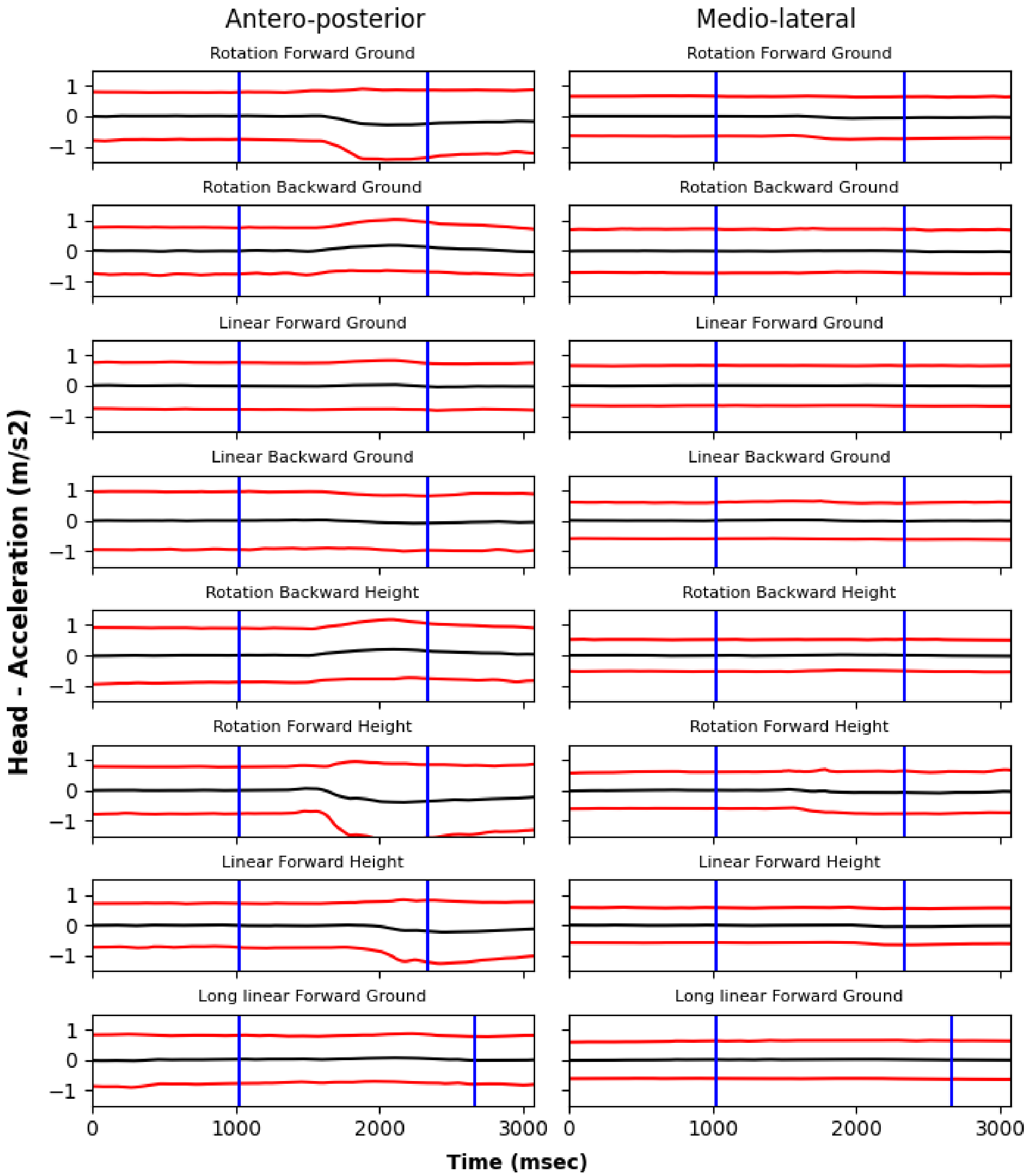

Figure 4.6: Grand mean averages (black lines) for the anterior-posterior (left) and medial-lateral (right) head accelerations. The blue lines indicate the start (left blue line) and end (right blue line) of the visual motion and the red lines represent the 95% confidence interval of the averaged data.

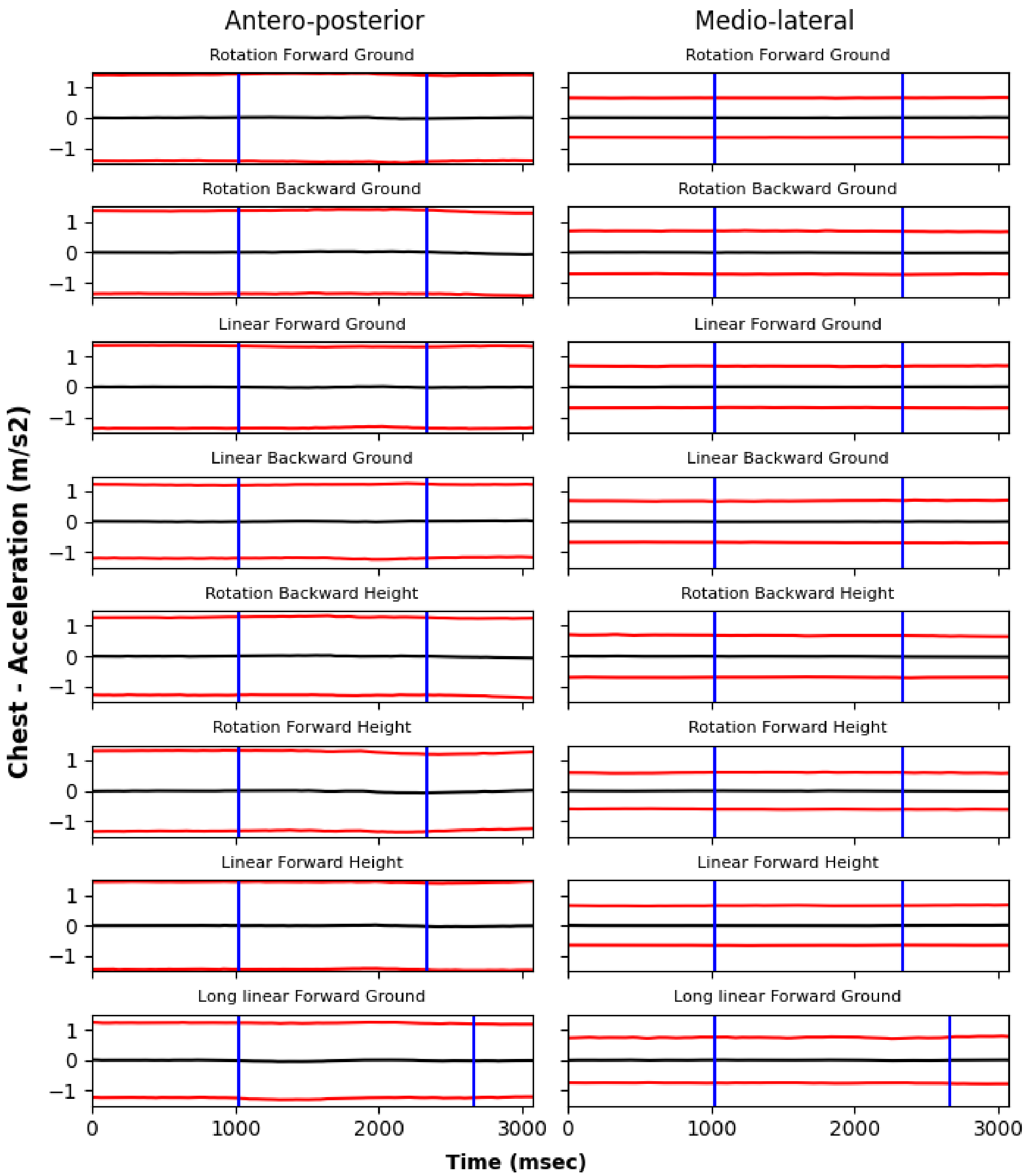

Figure 4.7: Grand mean averages (black lines) for the anterior-posterior (left) and medial-lateral (right) chest accelerations. The blue lines indicate the start (left blue line) and end (right blue line) of the visual motion and the red lines represent the 95% confidence interval of the averaged data.

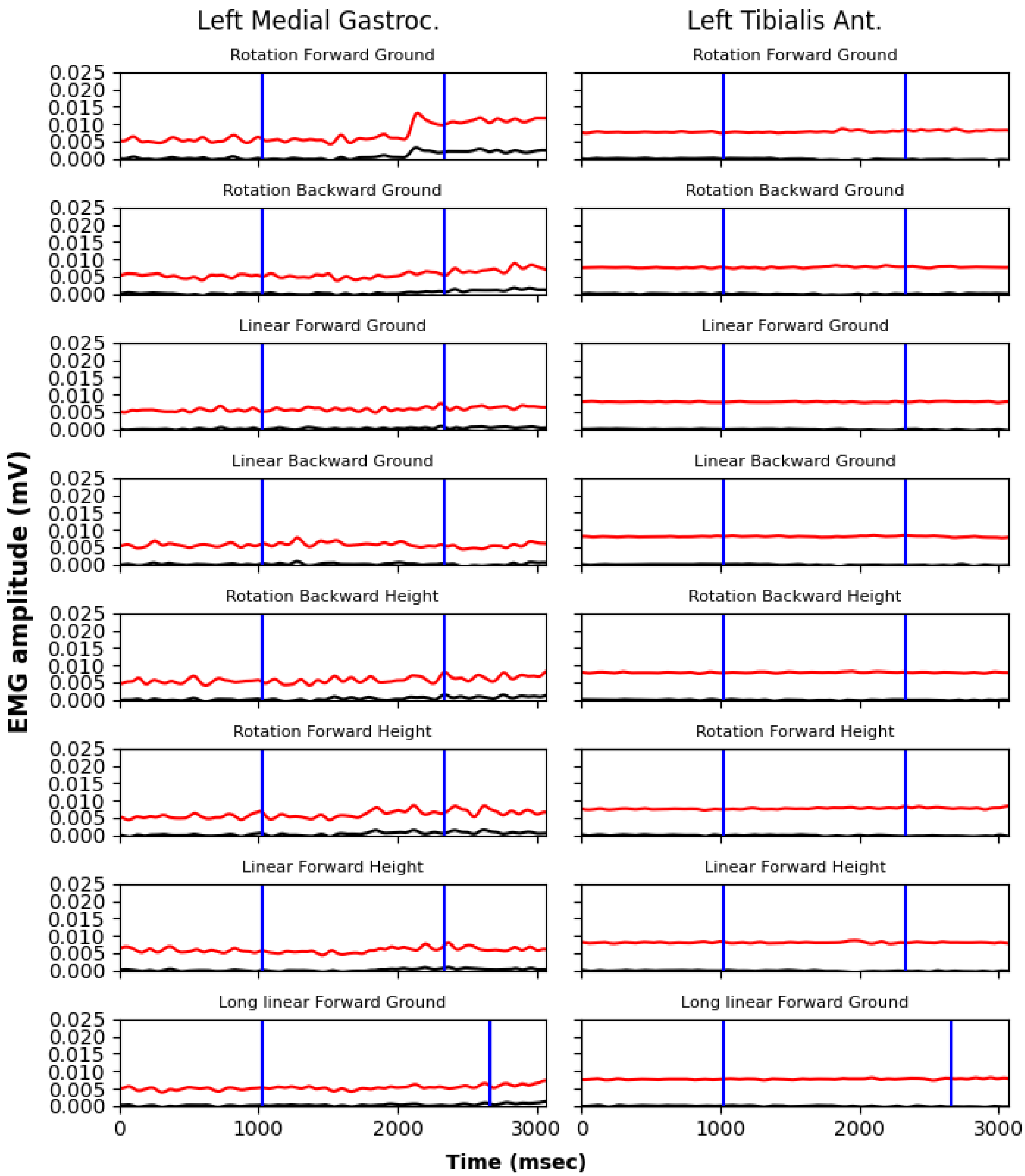

Figure 4.8: Grand mean averages (black lines) of the linear envelope for the Left TA (left) and MGAS (right). The blue lines indicate the start (left blue line) and end (right blue line) of the visual motion and the red lines represent the 95% confidence interval of the averaged data

Table 4.1: One sample t-test results (one tail) of the mean $\Delta\text{Mean}_{APCOP}$ versus 0 across participants.

Δ**Mean**$_{APCOP}$				
Task	**Mean**	**Std Error**	**t-value**	**p-value**
RFG	-0.2480	0.3517	-0.7051	0.7554
RBG	-0.0957	0.2486	-0.3851	0.6478
LFG	0.6205	0.2799	2.2168	0.0195*
LBG	0.1580	0.4415	0.3580	0.3622
RBH	-0.3379	0.3323	-1.0169	0.8390
RFH	0.7307	0.4448	1.6427	0.0584
LFH	0.4442	0.2197	2.0222	0.0287*
LLFG	0.4665	0.3607	1.2934	0.1057
n = 20; Mean = averaged $\Delta\text{Mean}_{APCOP}$ across all participants				

Table 4.2: One sample t-test results (one tail) of the mean $\Delta\text{Mean}_{MLCOP}$ versus 0 across participants.

Δ**Mean**$_{MLCOP}$				
Task	**Mean**	**Std Error**	**t-value**	**p-value**
RFG	0.407	0.207	1.965	0.032*
RBG	0.398	0.284	1.402	0.089
LFG	-0.191	0.167	-1.141	0.866
LBG	0.280	0.132	2.112	0.024*
RBH	-0.023	0.233	-0.098	0.539
RFH	0.299	0.213	1.401	0.089
LFH	0.154	0.262	0.587	0.282
LLFG	0.469	0.134	3.504	0.001*
n = 20, Mean = averaged $\Delta\text{Mean}_{MLCOP}$ across all participants				

Table 4.3: One sample t-test results (one tail) of the mean $\Delta\text{Mean}_{APChestAccel}$ versus 0 across participants.

Δ**Mean**$_{APChestAccel}$				
Task	**Mean**	**Std Error**	**t-value**	**p-value**
RFG	0.003	0.002	1.326	0.102
RBG	0.007	0.003	1.988	0.032*
LFG	-0.003	0.003	-1.078	0.852
LBG	0.003	0.004	0.778	0.224
RBH	0.005	0.004	1.176	0.128
RFH	-0.001	0.007	-0.146	0.557
LFH	-0.002	0.003	-0.723	0.760

LLFG	0.003	0.003	0.870	0.199
n = 17, Mean = averaged $\Delta\text{Mean}_{APChestAccel}$ across all participants				

Table 4.4: One sample t-test results (one tail) of the mean $\Delta\text{Mean}_{APHeadAccel}$ versus 0 across participants.

Δ**Mean**$_{APHeadAccel}$				
Task	**Mean**	**Std Error**	**t-value**	**p-value**
RFG	0.030	0.014	2.092	0.026*
RBG	-0.002	0.005	-0.370	0.642
LFG	-0.004	0.004	-0.976	0.828
LBG	-0.005	0.013	-0.367	0.641
RBH	-0.007	0.008	-0.836	0.792
RFH	0.027	0.028	0.989	0.169
LFH	0.008	0.007	1.091	0.146
LLFG	-0.013	0.016	-0.813	0.786
n = 17, Mean = averaged $\Delta\text{Mean}_{APHeadAccel}$ across all participants				

Table 4.5: One sample t-test results (one tail) of the mean $\Delta\text{Mean}_{AmpLeftTA}$ across participants.

Δ**Amp**$_{LeftTA}$				
Task	**Mean**	**Std Error**	**t-value**	**p-value**
RFG	0.0001	0.0001	1.866	0.078
RBG	0.0001	0.0001	1.253	0.226
LFG	0.0000	0.0000	2.624	0.017
LBG	0.0001	0.0001	1.085	0.292
RBH	0.0000	0.0000	1.363	0.189
RFH	0.0000	0.0000	0.970	0.344
LFH	0.0001	0.0000	2.104	0.049
LLFG	0.0001	0.0000	1.995	0.061
n = 20, Mean = averaged $\Delta\text{Amp}_{LeftTA}$ across all participants				

Table 4.6: One sample t-test results (one tail) of the mean $\Delta\text{Mean}_{AmpLeftMGAS}$ versus 0 across participants.

Δ**Amp**$_{LeftMGAS}$				
Task	**Mean**	**Std Error**	**t-value**	**p-value**
RFG	0.0003	0.0002	1.368	0.187
RBG	0.0000	0.0000	1.078	0.294
LFG	0.0001	0.0001	1.105	0.283

LBG	0.0001	0.0001	1.097	0.286
RBH	0.0001	0.0001	1.998	0.060
RFH	0.0002	0.0001	2.067	0.053
LFH	0.0000	0.0001	0.307	0.762
LLFG	0.0001	0.0001	1.446	0.164
n = 20, Mean = averaged $\Delta \text{Amp}_{LeftMGAS}$ across all participants				

Next the ΔSTD was tested for each of the output measures (AP COP, ML COP, AP Head Accel, AP Chest Accel) and it was within these one sample t-test comparisons that there were observed statistical differences, Table 4.7 shows the $\Delta \text{STD}_{\text{AP COP}}$, Table 4.8 shows the $\Delta \text{STD}_{\text{ML COP}}$, Table 4.9 shows the $\Delta \text{STD}_{\text{AP Chest Accel}}$, and Table 4.10 shows the $\Delta \text{STD}_{\text{AP Head Accel}}$. It was observed that there was a statistically significant difference in ΔSTD across every task and measurement except for the $\Delta \text{STD}_{\text{AP Chest Accel}}$ of the LLFG. The largest differences were in the $\Delta \text{STD}_{\text{AP COP}}$ (range: 1.294 mm - 1.779 mm) and were in the anterior-posterior direction, which was the direction of the visual motion. The $\Delta \text{STD}_{\text{ML COP}}$, $\Delta \text{STD}_{\text{AP Head Accel}}$ and $\Delta \text{STD}_{\text{AP Chest Accel}}$ exhibited smaller differences and standard error in comparison to the $\Delta \text{STD}_{\text{AP COP}}$ data. This would appear to indicate that the motion of the COP in the ML direction and the acceleration of the Head and Chest are very small. This can be confirmed by visually inspecting the grand mean data in time series (Figures 4.5, 4.6, 4.7). A choice was made to narrow the focus of the COP sway to the anterior-posterior direction for further analysis, as this was the axis of the visual motion and because of the relatively small sway in the ML COP compared to the AP COP.

Table 4.7: One sample t-test results (one tail) of the mean $\Delta \text{STD}_{APCOP}$ versus 0 across participants.

Δ**STD**$_{APCOP}$				
Task	**Mean**	**Std Error**	**t-value**	**p-value**
RFG	1.574	0.699	2.252	0.018*
RBG	1.430	0.477	2.998	0.004*
LFG	1.194	0.464	2.573	0.009*
LBG	1.349	0.371	3.632	0.001*
RBH	1.294	0.553	2.343	0.015*
RFH	1.702	0.731	2.327	0.016*
LFH	1.488	0.658	2.259	0.018*
LLFG	1.779	0.673	2.644	0.008*
n = 20; Mean = averaged $\Delta \text{STD}_{APCOP}$ across all participants				

Table 4.8: One sample t-test results (one tail) of the mean ΔSTD_{MLCOP} across participants.

Δ**STD**$_{MLCOP}$				
Task	**Mean**	**Std Error**	**t-value**	**p-value**
RFG	0.1889	0.1131	1.6710	0.0556
RBG	0.3340	0.0798	4.1843	0.0003*
LFG	0.1991	0.0806	2.4697	0.0116*
LBG	0.3167	0.0630	5.0255	0.0000*
RBH	0.1914	0.0724	2.6427	0.0080*
RFH	0.2502	0.0722	3.4670	0.0013*
LFH	0.4351	0.0928	4.6905	0.0001*
LLFG	0.4915	0.1027	4.7849	0.0001*
n = 20, Mean = averaged ΔSTD_{MLCOP} across all participants				

Table 4.9: One sample t-test results (one tail) of the mean $\Delta STD_{APChestAccel}$ across participants.

Δ**STD**$_{APChestAccel}$				
Task	**Mean**	**Std Error**	**t-value**	**p-value**
RFG	0.005	0.002	2.343	0.016*
RBG	0.009	0.002	4.164	0.000*
LFG	0.003	0.001	2.648	0.009*
LBG	0.004	0.001	2.961	0.005*
RBH	0.004	0.002	1.850	0.041*
RFH	0.006	0.002	3.222	0.003*
LFH	0.005	0.001	4.188	0.000*
LLFG	0.009	0.002	3.777	0.001*
n = 17, Mean = averaged $\Delta STD_{APChestAccel}$ across all participants				

Table 4.10: One sample t-test results (one tail) of the mean $\Delta STD_{APHeadAccel}$ across participants.

Δ**STD**$_{APHeadAccel}$				
Task	**Mean**	**Std Error**	**t-value**	**p-value**
RFG	0.025	0.013	1.979	0.033*
RBG	0.013	0.004	2.977	0.004*
LFG	0.005	0.001	3.971	0.001*
LBG	0.017	0.006	2.704	0.008*
RBH	0.018	0.007	2.623	0.009*
RFH	0.042	0.021	2.064	0.028*
LFH	0.019	0.009	2.081	0.027*

LLFG	0.007	0.005	1.422	0.087
n = 17, Mean = averaged $\Delta STD_{APHeadAccel}$ across all participants				

The next step was to assess the effect of height and visual motion type through the 2x2 Repeated Measures ANOVAS and the two paired t-tests to explore the effect of visual motion type (LFH vs. RFH) and the effect of longer visual motion (LLFG vs. LFG). Note that all of these test results are compiled into Figures 4.9 and 4.10. First, when examining the effect of height on the responses there were no statistically significant main effects or interaction effects for the ΔSTD across all measures. Next, when examining the effect of visual motion type there were three cases of a significant effect; $\Delta STD_{\text{AP Head Accel}}$ exhibited an interaction between visual motion type and direction (F(1,16) = 4.96, p = 0.04, β = 0.45), $\Delta STD_{\text{AP Chest Accel}}$ exhibited an effect of both visual motion type (F(1, 16) = 5.95, p = 0.03, β = 0.55) and direction (F(1, 16) = 4.70, p = 0.05, β = 0.43). As discussed previously the $\Delta STD_{\text{AP Head Accel}}$ and $\Delta STD_{\text{AP Chest Accel}}$ both exhibited mean values across all conditions within the ranges of 0.007 m/s^2 - 0.025 m/s^2 and 0.003 m/s^2 - 0.009 m/s^2. These ΔSTD accelerations are very small and have a very small standard error as seen in Tables 4.9 and 4.10. Next the paired t-test comparing LFH vs. RFH (effect of visual motion type) exhibited a significant difference in $\Delta STD_{\text{AP Head Accel}}$ (Z(16) = 2.25, p = 0.02). The paired t-test comparing LLFG vs. LFG (effect of duration) exhibited significant differences in $\Delta STD_{\text{AP COP}}$ (Z(19) = 2.58, p = < 0.01) and $\Delta STD_{\text{AP Chest Accel}}$ (t(16) = -3.05, p = < 0.01, β = 0.818).

		2 (forward/backward) x 2 (ground/height) RM ANOVA				**2 (rotation/linear) x 2 (forward/backward) RM ANOVA**		
		F	***p***	**β**		**F**	***p***	**β**
AP COP	**Direction**	F(1, 19) =1.58	0.22	0.11	**Motion**	F(1, 19) = 1.15	0.30	0.06
	Height	F(1,19) = <0.01	0.98	0.05	**Direction**	F(1, 19) = <0.01	0.98	0.05
	Dir x Height	F(1, 19) = 0.55	0.47	0.05	**Mot x Dir**	F(1, 19) = 0.63	0.44	0.05
AP Head	**Direction**	F(1, 19) = 2.47	0.14	0.20	**Motion**	F(1,16) = 0.87	0.37	0.05
	Height	F(1, 19) = 4.17	0.06	0.38	**Direction**	F(1,16) = <0.01	0.94	0.05
	Dir x Height	F(1, 19) = 1.66	0.22	0.11	**Mot x Dir**	**F(1,16) = 4.96**	**0.04**	**0.45**
AP Chest	**Direction**	F(1, 19) = 0.69	0.42	0.05	**Motion**	**F(1,16) = 5.95**	**0.03**	**0.55**
	Height	F(1, 19) = 0.95	0.35	0.05	**Direction**	**F(1,16) = 4.70**	**0.05**	**0.43**
	Dir x Height	F(1, 19) = 3.25	0.09	0.28	**Mot x Dir**	F(1,16) = 0.96	0.34	0.05
TA Left	**Direction**	F(1, 19) = 0.61	0.44	0.05	**Motion**	F(1,19) = 1.37	0.26	0.08
	Height	F(1, 19) = 1.33	0.26	0.08	**Direction**	F(1, 19) = 0.12	0.74	0.05
	Dir x Height	F(1, 19) = 0.43	0.52	0.05	**Pert x Dir**	F(1, 19) = 0.79	0.39	0.05
GA Left	**Direction**	F(1, 19) = 1.58	0.22	0.11	**Motion**	F(1,19) = 0.459	0.51	0.05
	Height	F(1, 19) = <0.01	0.96	0.05	**Direction**	F(1, 19) = 0.77	0.39	0.05
	Dir x Height	F(1, 19) = 0.50	0.49	0.05	**Mot x Dir**	F(1, 19) = 1.31	0.27	0.08

Figure 4.9: 2 x 2 Repeated Measures ANOVAs - (forward/backward) x (ground/height) and (rotation/linear) x (forward/backward). Bolded data represents a significant difference.

	LFH vs RFH paired t-test			LLFG vs LFG paired t-test		
	t/Z	*p*	β	t/Z	*p*	β
AP COP	t(19) = - 1.19	0.25	0.206	**Z(19) = 2.58**	**<0.01**	-
AP Head	**Z(16) = 2.25**	**0.02**	-	Z(16) = 1.25	0.23	-
AP Chest	Z(16) = 0.88	0.40	-	**t(16) = - 3.05**	**<0.01**	**0.818**
TA Left	Z(19) = 0.00	1.00	-	Z(19) = - 0.19	0.87	-
GA Left	Z(19) = -1.64	0.11	-	t(19) = - 0.71	0.49	0.10

Figure 4.10: Paired t-tests comparing LFH vs. RFH and LLFG vs. LFG. Bolded data represents a significant difference.

The most interesting finding of these was the potential effect of duration on the AP COP sway between LFG and LLFG (the median difference was 0.41mm), as the AP COP was the parameter in which largest responses were observed. However, the statistical effects in the other measures may just exhibit an effect of very small responses and very little variability. With the general lack of potentially biologically significant statistical effects the next step was to look at the individuals that composed these averages. Each individuals' averaged responses of ΔSTD (AP COP, AP Head Accel and AP Chest Accel) and ΔAmp (Left TA and Left MGAS) for each task were plotted and can be seen in Figures 4.11, 4.12, 4.13, 4.14, 4.15.

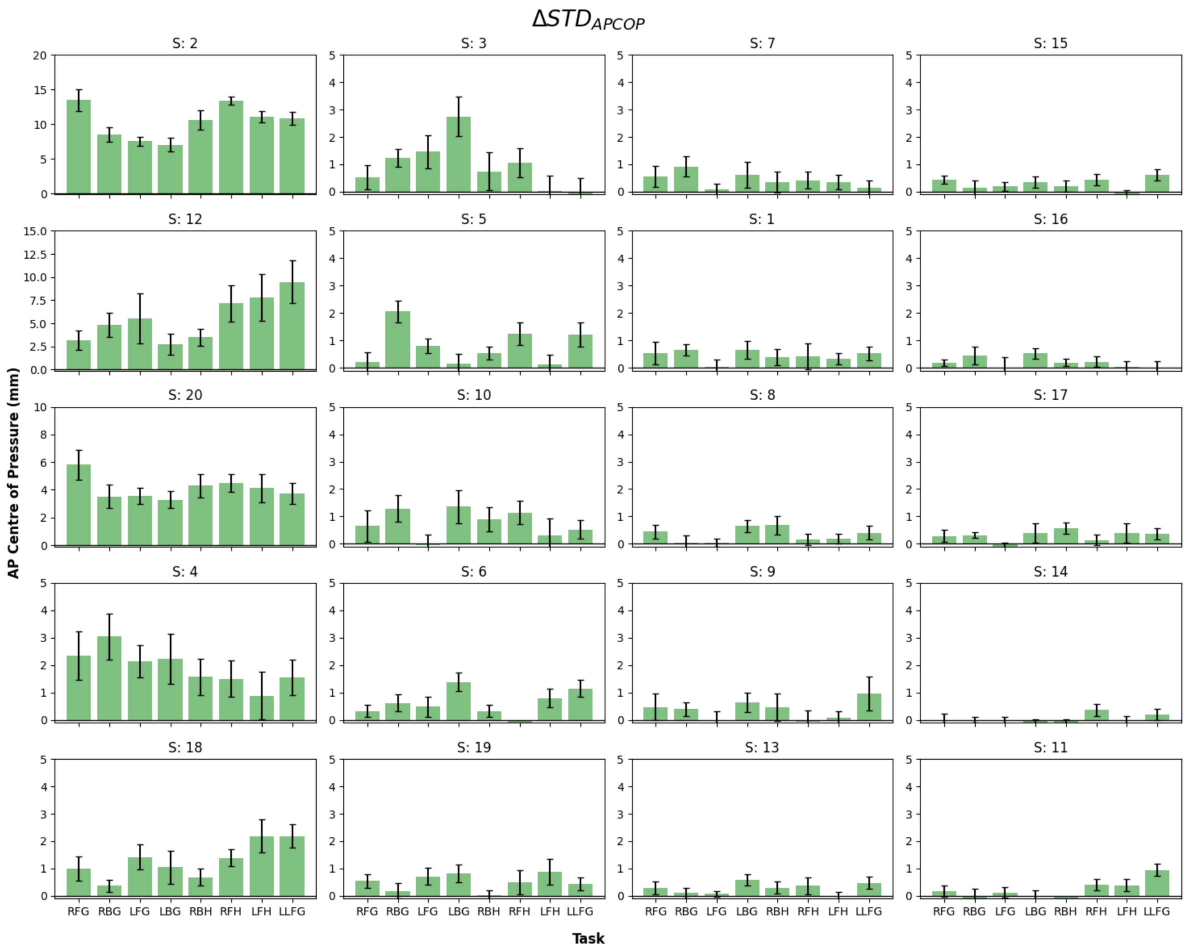

Figure 4.11: Individual averaged $\Delta \mathrm{STD}_{\mathrm{AP\ COP}}$ for each task - **NOTE**: Subject 2, Subject 12 and Subject 20 have differing y-axis scales than other individuals to accommodate for the larger values.

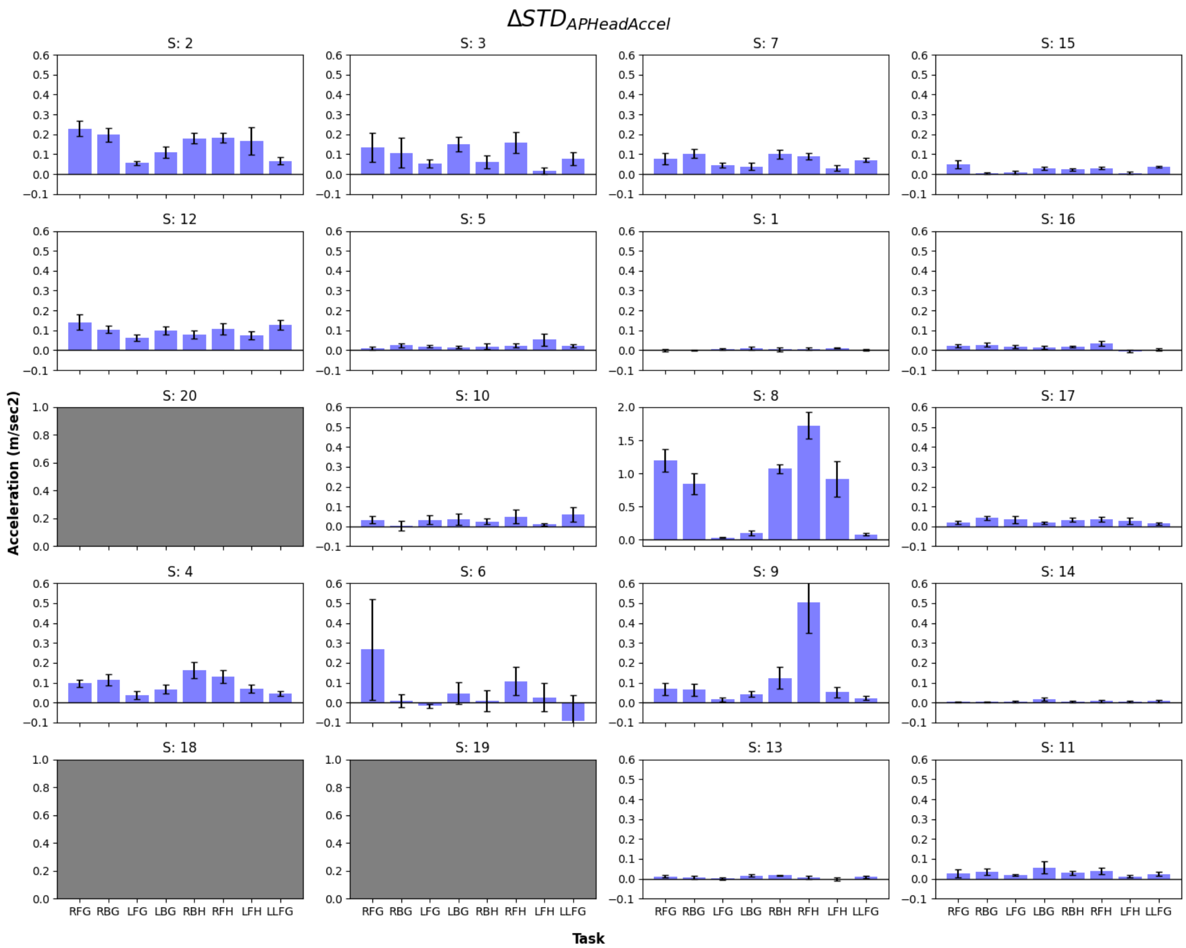

Figure 4.12: Individual averaged $\Delta STD_{AP\ Head\ Accel}$ for each task - **NOTE**: Subject 8 has a different y-axis scale compared to all other individuals to accommodate for the larger values. The grey boxes indicate accelerometer data that was not usable.

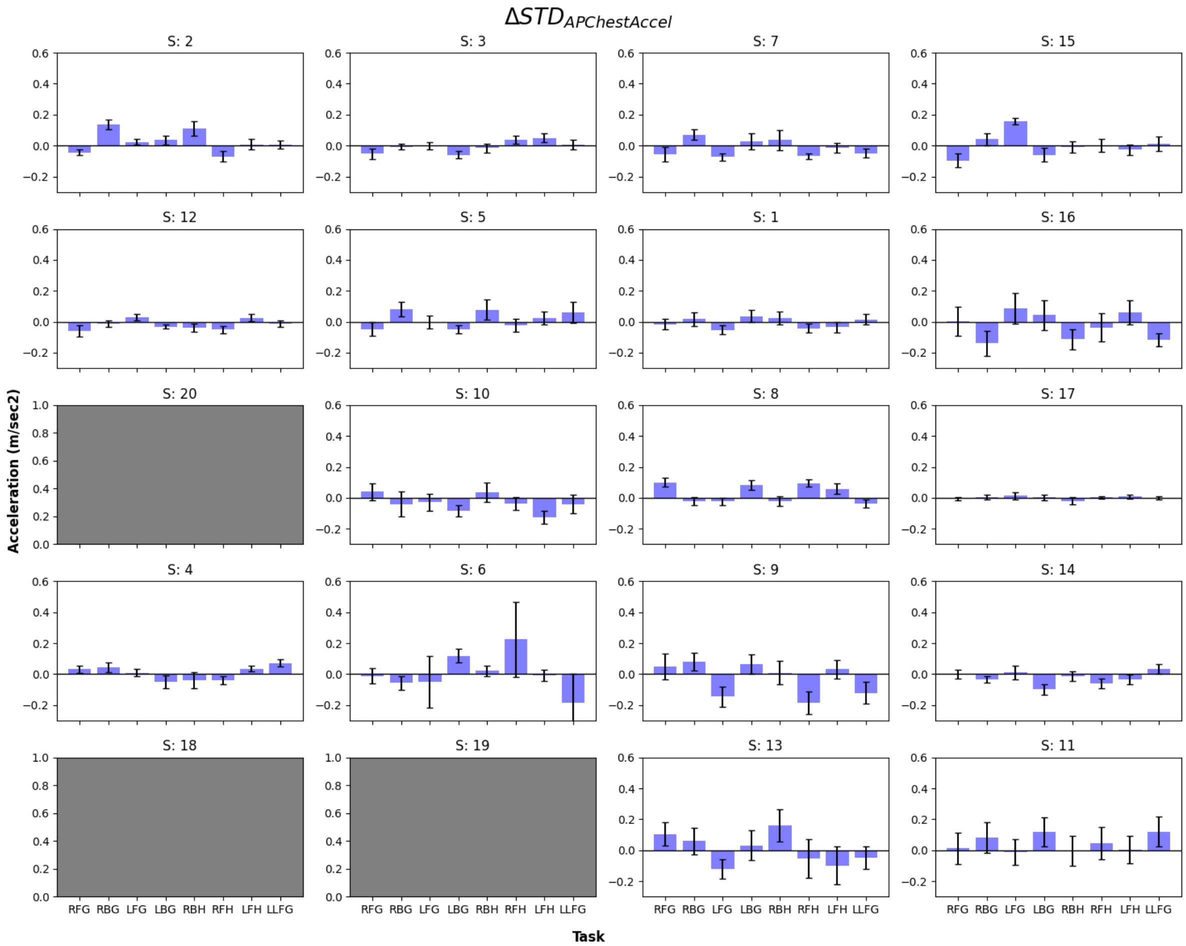

Figure 4.13: Individual averaged $\Delta\text{STD}_{\text{AP Chest Accel}}$ for each task - **NOTE**: All y-axes scales are the same in this figure. The grey boxes indicate accelerometer data that was not usable.

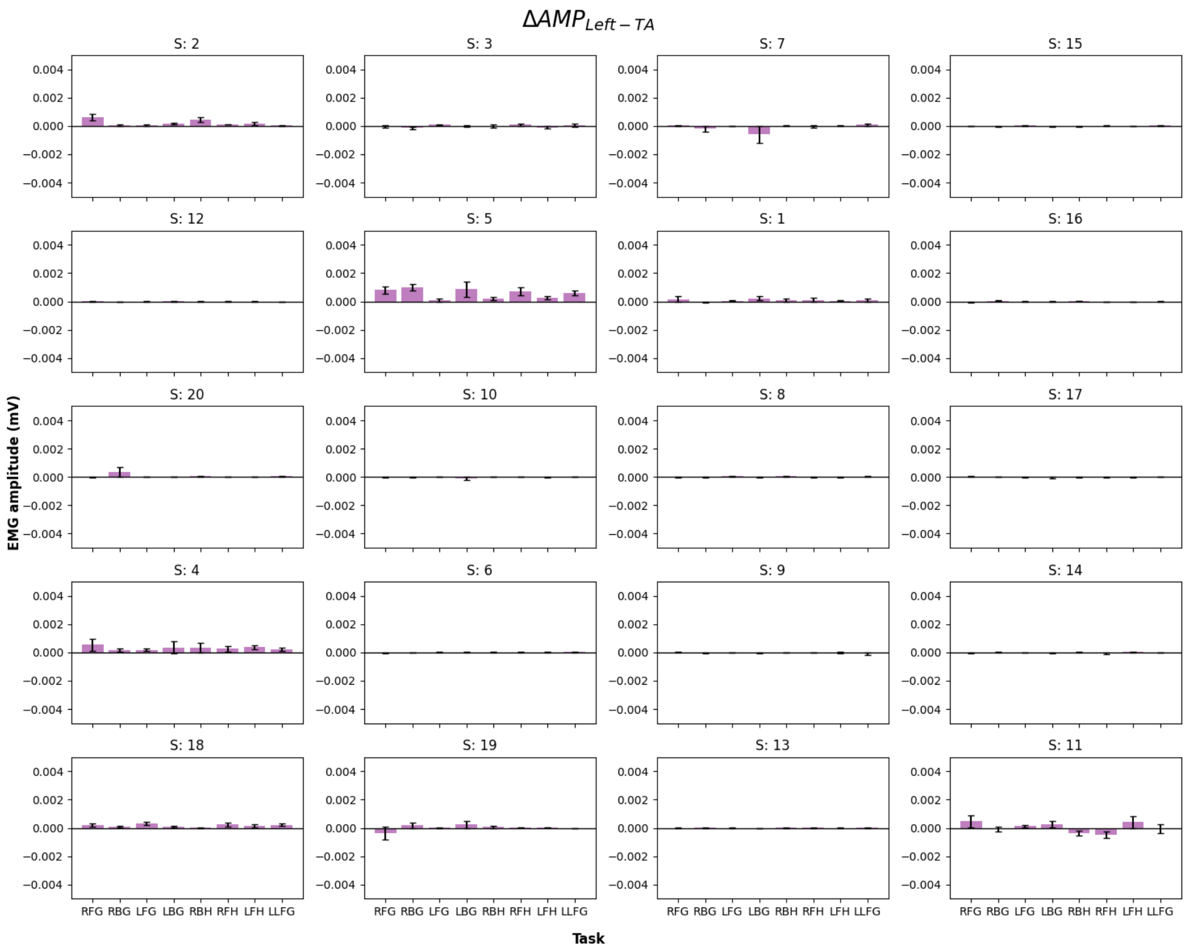

Figure 4.14: Individual averaged $\Delta\text{Amp}_{\text{Left TA}}$ for each task - **NOTE**: All y-axes scales are the same in this figure.

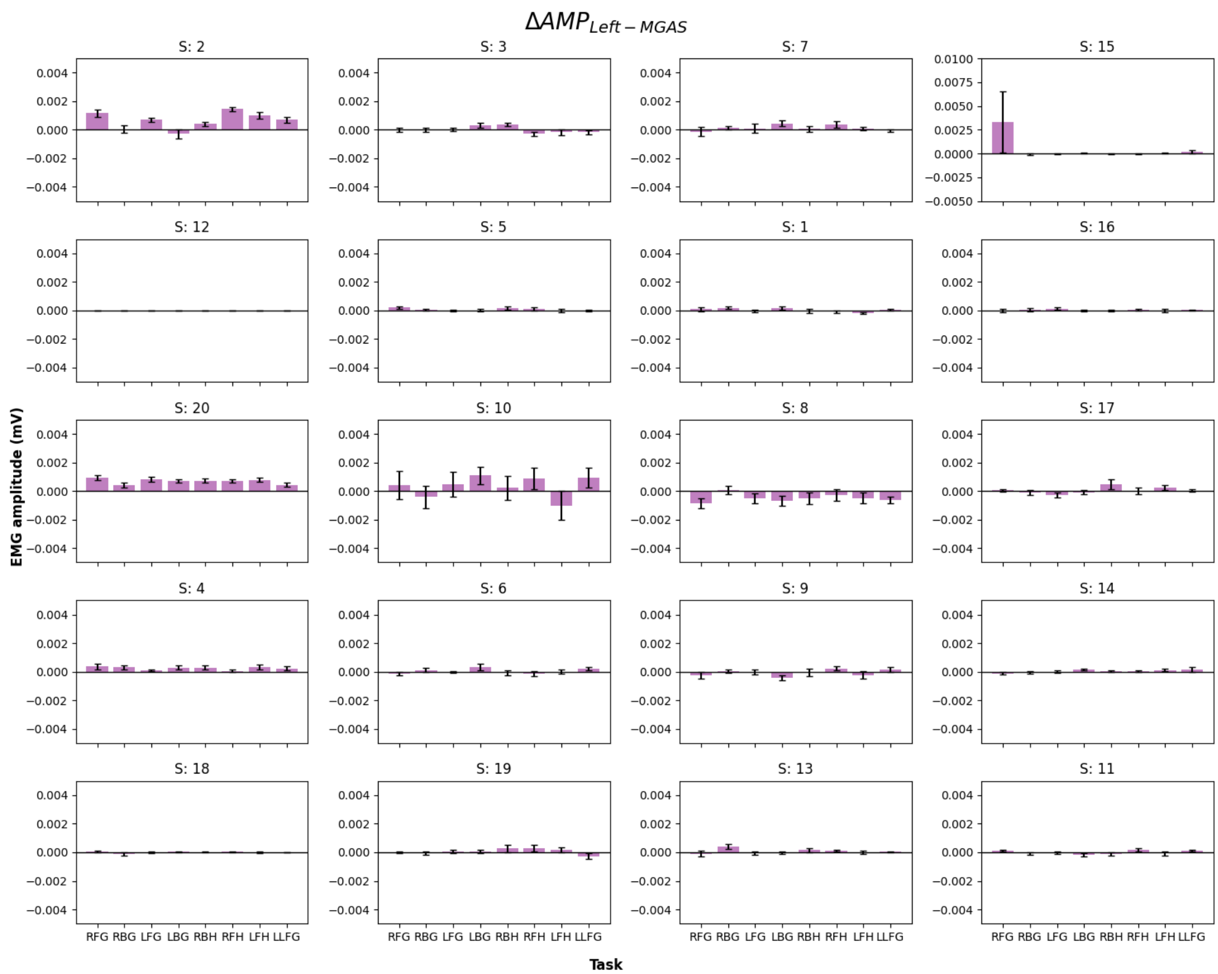

Figure 4.15: Individual averaged $\Delta \mathrm{Amp}_{\mathrm{Left\ MGAS}}$ for each task - **NOTE**: All y-axes scales are the same in this figure.

It is in these figures above that large individual differences can be observed, specifically in the $\Delta STD_{AP\ COP}$ and $\Delta STD_{AP\ Head\ Accel}$. These figures clearly show how the majority of individuals do not exhibit much of a response to visual perturbations, however a select few do show relatively large responses to the visual motion. Specifically, Subject 2, Subject 12, Subject 20 and Subject 4 show large responses in comparison to all the other subjects in regards to COP sway. Subject 2 and Subject 20 also exhibit some EMG activity in the Left MGAS, and Subject 2 through visual inspection may even be exhibiting some activation differences across tasks. In regards to head accelerations, there are again differences across individuals with some individuals potentially exhibiting head motion instead of COP sway. This is most obvious in Subject 8, who exhibits much larger head accelerations than everyone else with a specific trend in the rotational visual motion, however they did not appear to exhibit much COP sway. Definitive conclusions can not be made from these observations but these results exhibit the range of responses between the collected variables.

4.5 Discussion

The goal of this study was to assess how differing visual characteristics during visual motion would alter postural responses. This was based off of visual motion research which has shown postural responses to continuous visual motion [202, 237, 31] and more transient visual motion [118, 37]. Prior to collection there was a specific goal to address more time locked measures of postural control, including onset time, peak amplitude, directionality responses and muscle activiation and inhibition. However, the chosen analysis measures and the direction of the analysis needed to be changed due to the large individual differences observed across the participants. The overall lack of consistency across participants resulted in an inability to have reliable and accurate measurement parameters for transient responses. Hence, a more generalized approach needed to be taken for the data analysis to allow for group comparisons to be made. This subsequently led to the focus on the variability/sway of the participants response over the stimulus period, which is a common measurement in the realm of continuous visual motion paradigms. However, this a starting point to lead to a greater understanding of why certain individuals exhibited larger postural responses than others within the transient visual motion paradigm.

Responses to visual motion during continuous visual motion have been observed to have a range of postural sway across studies: 4 mm - 4.7 mm [83], 4.4 mm [237] and 1.7 mm [125]. These values provided a general idea of what to expect in regards to postural sway (note: the measures utilized in this study cannot be directly compared to these values, as the outcome measures are difference scores but please refer to the Appendix A.1 to see the absolute STD values across subjects - the average response from the during-stimulus across all trials was 2.7 mm). In regards to the head and chest accelerations, it was expected that if there was an observed response then the larger responses would likely be for the head in comparison to the chest, following what might be observed within an inverted pendulum [126]. As for the electromyography (EMG) signals, we did not expect to see large responses as limited EMG activity has been previously observed in visual motion research [202].

The second aspect of the study was motivated to assess the combined effects of perceived threat via virtual height along with visual perturbation. Virtual height has been observed to affect postural responses during both standing balance [50, 261] and physical perturbations [49]. It was observed that there was postural sway present during the period of the visual motion across the measures of interest. Though the measure of greatest interest was the $\Delta STD_{AP\ COP}$ due to the larger scores in comparison to the other measurements. However, there did not appear to be any effects of virtual height on the postural responses.

The one major statistical finding was the significant difference of the $\Delta STD_{AP\ COP}$ between the LFG and LLFG trials. This finding would appear to indicate that the duration of the visual motion does have an effect on postural sway, unfortunately this study only had a single longer visual motion task but this is interesting none the less. Research has found that visual self-motion perception or vection can take up to 10 seconds to be detected [194] but that this delay could be decreased down to 1.7 seconds with the utilization of a pre-oscillation period and oscillations added during a linear motion [194]. These parameters were not covered in our study but the interesting aspect of this is that the sense of visual self-motion or vection is adaptable. As previously discussed longer visual motion is typically utilized to evoke a sense of self-motion, but constant velocity profiles always seem to be utilized [194, 170, 234], and to my knowledge those utilizing a curvilinear visual motion velocity profile such as the present study have not been reported. This could indicate that the longer presentation of our curvilinear velocity or perhaps just a faster visual motion causes an increased sensation of visual self-motion resulting in increased AP COP sway. Additionally, it is important to consider the power of this statistical analysis, with a $1 - \beta = 0.15$ the power of the statistical effect is weak. This is important to consider due to the relative small responses and small amount of variability within the population. An apriori power analysis revealed that 280 participants would need to be collected to achieve a $1 - \beta = 0.95$. This indicate that collecting more individuals would likely not be beneficial within this experiment and exhibits the potential limitations of this outcome measure.

In regards to the other statistical findings there is a question of whether the statistical differences observed through the various comparisons are biologically significant. This can be visually inspected in Figures 4.6, 4.7, 4.8, where it does not appear that the average responses across the individuals exhibit biological significance in the head and chest accelerations nor for the EMG responses. The most interesting finding was the observable individual differences, where there were some individuals who had much stronger reactions to the visual perturbations than others in both AP COP and Head Accelerations (Figures 4.11 and 4.12). This finding was surprising as previous research has not directly discussed such a difference across individuals in regards to postural responses evoked by visual motion.

Understanding why there was not a consistent response across individuals is of great interest, particularly as the success of falls prevention programs often depend on being tailored to the needs of the individual. It is first important to note that the effect of adaptation caused by repeated exposure to visual motion conditions was explored, first trial responses were not observed to be significantly different than the last five trials A.3. Research has shown that repeated exposure to visual motion stimuli causes a reduction is postural responses in both younger and older adults [**?**]. The lack of adaptation across trials could be a function of large differences between individuals as some participants respond consistently while others show little to no response. It could also be caused by the relatively broad measurements that needed to be utilized to acquire group effects, with a more responsive population of participants and more transient measurements it is possible that adaptation would be observed. Subsequently, other factors need to be considered for the cause of the observed individual differences.

As previously stated, research has predominately utilized continuous visual motion to evoke a sense of self-motion. These longer visual motion stimuli ensure that a sense of self-motion is detected by the individuals and results in postural responses. This does seem to be confirmed to some extent with our observed significant difference between the LFG and LLFG tasks. Though postural responses to visual motion have been observed to occur in response to more transient motion [118, 37]. Additionally, even responses to continuous motion have exhibited an initial transient response to visual motion stimuli [83] indicating that vection or visual self-motion may not need to be present to produce postural responses. However, our results indicate that this may not be the case for all individuals, as we observed individuals exhibiting no postural responses to the stimuli.

The visual characteristics utilized within this study tried to create a more naturalistic transient motion. Participants were exposed to two differing types of visual motion, a translational motion and a rotational motion. Each of these motions were calculated to exhibit an almost identical velocity and acceleration profile to attempt to limit the effect of stimulus differences. The visual motion characteristics can be observed in Figures 4.2 and 4.3, these motion characteristics include gradual changes in acceleration and velocity throughout the duration of motion. Based on previous research, visual motion characteristics typically are maintained at a constant velocity. This constant velocity subsequently may be at a speed which is quick enough to gradually evoke a sense of self-motion over the duration of the visual stimuli. Research investigating the differences between 'real world' and 'virtual reality' visual motion has shown that postural responses are significantly depressed in "virtual reality motion" [170]. These researchers also observed that the visual motion detection threshold for "real world" motion was at $\sim 0.31°/s$, while "virtual reality motion" was $1.3°/s$ [170]. Indicating that results within a virtual environment may be suppressed or more difficult to achieve over a shorter/transient visual motion. The peak visual motion stimuli utilized by these researchers was $10°/s$ for 80 seconds [170]. The visual motion stimuli utilized within our study peaked at $\sim$5 m/s, however, this velocity change was curvilinear over the stimulation period exhibiting a rather rapid acceleration as the visual motion continued. To quickly explore if visual motion velocity and acceleration may have had an effect on onset of observed responses, an AP COP sway onset time was determined from all the subjects across all tasks, which was 438 $\pm$334 ms (Appendix A.1 Note: please read the caption to understand how this was calculated). This value happens to coincide with when the visual motion acceleration and velocity starts to get quicker (Figures 4.2 and 4.3). Indicating that the acceleration and velocity of the response may have played a role in the individual differences. It is possible that for some individuals they did not get the sense of self-motion at these slower speeds compared to other individuals, but once the velocity and acceleration reached some subjective threshold, the visual motion was already coming to an end. The sense of vection or visual self-motion perception can be delayed up to 10 seconds after the initiation of visual motion [194, 36], which could explain this lack of response across most individuals. However, this still does not fully explain why some individuals respond to these short transient stimuli while others do not.

Vection or self-motion perception has been observed to significantly increase postural responses in comparison to visual motion that does not evoke a sense of vection [200, 234, 110]. Indicating that vection or self-motion perception has a significant role in the produced postural responses to visual motion stimuli. Each of these studies observed that the first major response in most individuals occurred in the same direction of the visual motion, or in other words the postural responses produced attempted to oppose the direction of perceived self-motion [200, 234, 110]. Pervic and Mullen (1991) [200] proposed that this effect is likely due to the fact that this visual motion is what is commonly experienced during falls that occur in the opposite direction which may elicit vestibulospinal postural responses to maintain upright posture. These findings are most apparent in the largest responder, Subject 2 who exhibited what appears to be a consistent representation of this effect through each trial repeat (Appendix A.2). There is typically a postural response that opposes the virtual perturbation but then a correcting response occurs, which could be due to the proprioceptive and vestibular cues correcting this postural response to maintain vertical upright stance. This could indicate a role of sensory re-weighting that occurs within some individuals but not others, or at least not to the same extent.

The concept of sensory re-weighting is commonly acknowledged as a key factor in the efficient control of balance and posture. The role of visual information in the control of posture and balance has been explored with the use of tasks that specifically attempt to isolate sensory inputs and investigate behavioural responses. The utilization of visual motion with a fixed support, like what was presented in this study has been explored. This research found that visual motion presented alone when standing on a fixed surface resulted in the smallest amount of postural sway [15, 195]. The amount of sway increased dramatically when the platform became sway referenced or physical perturbations were utilized [15, 195]. This re-weighting towards proprioceptive and vestibular information suggests that these two systems have a large influence over the control of balance. Therefore, in the circumstance of this current study it is possible that many individuals were largely unaffected by the visual motion due to this re-weighting towards proprioceptive and vestibular cues. However, the individuals that did exhibit increased levels of postural sway could be exhibiting an increased reliance on visual cues, "visual dependence".

Maire et al, (2017) [155] define visual dependence as "the reduced ability to disregard visual cues in complex or conflicting visual environments". Evaluating visual dependence has been suggested to be done in several different ways which includes: the use of optokinetic stimulation when standing, the use of a rod-and-frame test, a posturography test or visual stimuli in virtual reality conditions [155]. This is interesting as in this study we implemented the use of visual motion within a virtual environment which could be exhibited in some individuals which are more visually dominant. In the realm of the rod-and-frame task, research has observed a range of individual differences in young healthy populations in the determination of true vertical [14, 121], exhibiting a normal distribution of individuals who were more dependent on visual cues than others. This is interesting as visual dependence is an attribute that has been commonly associated with older adults, as with age visual motion has a greater impact on postural responses than their younger adult counterparts [230, 34]. In the context of our study it is possible that our population of participants are exhibiting this normal range of individuals exhibiting visual dependence. It also possible to consider that that immersion and presence in the virtual environment was modulated by these individuals of greater visual dependence. Immersion is described as the capabilities of the technology to provide an inclusive, extensive, surrounding and vivid virtual environment [220]. While presence can be viewed as an outcome of immersion as it represents the sense of being engaged or being within the virtual environment [220]. It is possible that some individuals had a greater sense of presence within the virtual environments resulting in an increased dependence or weighting of visual feedback, but as we did not take measures of immersion or presence we can not know for certain.

Despite these potential differences in immersion and presence there was no average statistical effect of the virtual height. Upon further reflection this could be due to the fact that this virtual height was not perceived as threatening. The height the participants were exposed to was only at the top of a set of stairs (as opposed to the top of a skyscraper as was used in Chapter 3), and while this may be more threatening than ground level it is not the same as being at a virtual ledge. The effect of restricted height (ledge) and unrestricted height (away from ledge) during quiet stance has been observed to result in individuals shifting away from the ledge a significant amount in comparison to when not right at a ledge [43]. Therefore, this would be a change that would likely benefit this design to determine if this was an underlying effect of the lack of responses at the group level.

4.6 Conclusion

In this study the effect of visual motion with differing visual characteristics (visual motion type, height and direction) on postural responses was investigated. The results exhibited that on average there was postural sway in response to the visual motion, primarily in the AP COP, with a statistical effect of duration on AP COP sway. Indicating that the duration of the visual motion may result in a greater sense of self-motion. Additionally, it was observed that there were some select individuals who produced markedly larger postural responses to this visual motion stimuli, again primarily within the AP COP. There was also a few individuals who also exhibited large head accelerations to the rotational stimuli. These findings suggest that this transient visual motion has the potential to perturb postural control for those individuals who rely more heavily upon visual information. Future research could look to further investigate how these shorter transient visual motion stimuli may be able to indicate individuals who are more visually dependent. Additionally, altering the characteristics of visual height to be perceived as more threatening could allow for a re-evaluation of how visual context may effect postural responses during visual motion.

Chapter 5

General Discussion

As bipedal organisms with a narrow base of support, humans live in a gravitational environment where falling down is highly likely, and if not rapidly counteracted will threaten our survival. In this dissertation I wanted to assess how the onset of postural instability is perceived and how methodological differences can affect this perception, how this perceptual onset can be affected by visual information, and how visual motion with differing characteristics affects postural responses. What was found was that perception of postural instability onset is sensitive to how postural pertubations are delivered (manual random delivery of SOAs versus repeated SOAs; shifted versus balanced distribution of SOAs). That visually threatening stimuli can improve the precision of perceptual responses in regards to postural perturbation onset. Finally, that transient visual motion appears to only effect a small number of individuals. Theses studies will be summarized below and I will discuss some of the main research themes across the studies and propose some future directions for this research.

5.1 Summary of Findings

In Chapter 2 the methodological design of a TOJ task was evaluated to determine how it may affect the perception of postural instability onset. This study was designed to challenge findings regarding an observed perceptual delay of postural instability [148, 149]. This first study explored the differences between a balanced and unbalanced stimulus onset asynchrony (SOA) design during a TOJ task. Additionally, this study implemented the use of the method of constant stimuli to repeat each of the SOAs an equal number of times and also implemented the use of a computer controlled releasing mechanism for more precise control of creating experimentally repeatable postural perturbations. Results from this study show that that there was not a significant difference of the point of subjective simultaneity (PSS) from true simultaneity (0 ms), indicating that the perception of postural instability onset is not slow. This result was found for both the equal SOA distribution and also for the unequal SOA distribution. There was also no statistical effect on the just noticeable difference (JND) between the conditions. These findings directly challenge prior observations in the same lab by Lupo and Barnett-Cowan (2017; 2018) [148, 149], which indicates that the methodological design of the TOJ task can directly impact the perceptual outcome measures. This study stresses both the importance of how the design of a study can influence results and also the importance of replicating, extending, and falsifying research to not complacently assume that prior research represents scientific truth[53, 199].

Chapter 3 assessed the effect of visual contextual information on the perception of postural instability onset. This study used a two stage experiment design, first comparing how the presence of visual information affects the perception of postural instability onset, and secondly how visual context, specifically perceived threat, affects perception of postural instability onset. It should be noted that the methodological design utilized in Chapter 2 was adopted across each of these two experiments in Chapter 3. There has been plenty of research exploring how the presence of visual feedback can affect posture and balance and how perceived threat can affect posture and balance. However, no research had explored how altering visual cues can impact the perceptual onset of multisensory events such as postural instability. The first experiment had two conditions, the first condition had the eyes closed (similar to Chapter 2) and the second condition had their eyes open. It was observed that the presence of visual information did not have a statistically significant effect on the PSS or the JND. The second experiment also presented two different conditions, the first condition had the eyes open (identical to experiment # 1 eyes open condition) and the presentation of perceived threat (virtual height) with the use of a VRHMD. This second experiment did not observe any statistical difference between the PSS, but there was an observed statistical difference between the JNDs. Specifically, the virtual height condition led to a reduced JND, indicating that participants were more precise in their estimates of postural instability onset in the presence of a virtual height. These findings suggest that individuals may rely more heavily on other sensory modalities such as proprioceptive feedback in the perception of postural instability onset as opposed to vision with respect to judging the onset time of instability, however, visual information gathered prior to the onset of the postural event improves the precision postural instability onset estimates.

Chapter 4 explored how visual motion with differing visual characteristics and context (virtual height) alters postural responses. This study focused on some primary visual characteristics, the visual motion/perturbation type (rotation or linear), the visual motion context (ground or height), the visual motion direction (forward or backward) and there was one additional trial to explore how a longer visual motion may be different compared to a shorter visual motion. The postural responses were measured with force plates, accelerometers and electromyography (EMG) to quantify change in postural control. Here it was found that at the group mean level, there were no meaningful effects of the visual perturbation type, height or direction on postural control. However, a very important observation was made in this study, one largely ignored in the literature: there were very divergent individual postural responses found, with a large majority of individuals who did not respond to the visual perturbations at all, while others had quite pronounced changes in balance control. These results indicate that for those individuals who did not respond, these short transient visual perturbations did not have any effect on posture regardless of the visual context. This could be due to the brief stimulus period or perhaps a down weighting of visual information during these tasks to instead rely more heavily upon proprioceptive and vestibular feedback. With respect to the few individuals who did exhibit strong responses to these visual perturbations, their responses were so large that they approached a similar range observed in longer continuous visual motion. Given the literature on large individual differences in relying on visual information for spatial navigation and orientation perception, our results suggest that these individuals may be more visually dependent, resulting in them being more reliant on visual information. These results could also indicate that these individuals perceive vection (illusory self-motion) more quickly than the majority of individuals. This is interesting as these shorter visual motion stimuli could be utilized as a way to probe if an individual is more reliant on visual motion cues in the control of balance and posture.

As initially introduced, the theoretical framework this thesis was exploring was how sensory information can modulate both perception and action related to postural control 1.1. The collective results from my thesis began to provide greater insight into how perception may be involved in postural related tasks. Evocative visual cues presented within a VRHMD exhibited an effect on the precision of perceptual judgements related to postural instability onset and individual differences of postural sway in response to visual motion. Each of these designs exhibited the importance of how an individuals perception of sensory cues may affect their perception of instability onset and production of postural responses. Though the question still remains as to whether these perceptual changes could be directly correlated to behavioural outcome measures or if certain aspects of postural control are isolated from perception. A goal of this research was to eventually relate perceptual measures of postural instability onset to behavioural responses, though the pandemic limited the ability to conduct this study. However, some general ideas could be formed from the currently collected studies. There is evidence of the usefulness of VRHMD and virtual environments and how these environments can directly impact perception and can also subsequently lead to relatively broad individual differences. Hence, further exploring how VRHMD and virtual scenes can be utilized as a tool to probe both perception and action within individuals to gain a greater understanding of how these visual cues are utilized. Additionally, virtual visual cues can impact precision of perceptual responses and postural responses but these effects may occur indirectly. Meaning that the sensory feedback received from the visual system may impact perception which may result in alterations of later stages of postural control. These virtual visual scenes may also result in a modulation of the cortex resulting from changes in perception resulting in direct impacts on precision and postural behaviour. These avenues would still need to be explored further with the use of more specifically time locked measurements of behaviour and then relating these measures to perceptual measures. This would assist in determining if perception of postural events and sensory cues related to postural impact behaviour measures of postural control at later latencies.

5.2 Perceptual Tasks and Postural Instability Perception

This dissertation, which explored the perception of postural instability, started by re-evaluating how previous studies had conducted the use of a temporal order judgement (TOJ) task, with specific interest in the stimulus onset asynchronies (SOAs) distribution. There were some initial thoughts that perhaps the methodology employed was the reason why Lupo and Barnett-Cowan (2017; 2018) [148, 149] observed a delay in the perception of postural instability onset compared to an auditory reference stimulus. This concern about the methodology arose in part due to the fact that cortical responses to postural events occur at a rapid speed, 90-150 ms [244, 173, 224, 62] which is comparable to cortical responses to auditory events, 50-150 ms [188, 236, 132]. In my dissertation I repeatedly found that the perception of postural instability onset was not slower than an auditory reference stimulus when using a more controlled methodology. This finding stresses the importance of the effects that methodological design decisions can have on quantifying the perception of sensory information onset. The utilization of a technique that actively controls and limits potential variability between participants is critical in making conclusions about scientific findings. This controlled design is also important to allow future researchers to repeat or re-test a hypothesis as well.

Some factors to further consider for the design of the perceptual tasks in the perception of instability onset are related to the perceptual task utilized. Within this dissertation a temporal order judgement (TOJ) task was used in which participants chose whether postural instability or an auditory reference stimlus occurred first. There are two other types of tasks that have also been utilized to measure the perceived timing of sensory events, the reaction time (RT) test and the simultaneity judgement (SJ) task. The RT task requires participants to respond as quickly as they can once they detect a sensory stimulus, while the SJ task asks the participants to state whether the two presented stimuli were simultaneous or asynchronous. Each of these tasks attempt to quantify how individuals perceive the relative timing of sensory information, however there are well documented differences when comparing TOJ, SJ and RT tasks.

Rutschmann and Link (1964) [206] tried to determine if RT latencies could be used as a predictor of TOJ responses during an audio-visual task. What they observed was that auditory reaction times were ~ 45 ms quicker than the visual reaction times, but for TOJ responses in order for the two stimuli to be perceived as simultaneous the auditory stimulus needed to be presented ~ 43 ms prior to the visual stimulus [206] in order to be perceived as simultaneous. This was the opposite of what would be expected if reaction time responses were to be utilized as a predictor of TOJ responses. Additionally, it has been observed that factors such as the amplitude of the stimulus presented has a greater affect on the reaction time responses than TOJ responses [115, 116]. As discussed previously there is the theory referred to as "one system two decisions", which implies that motor and perceptual responses utilize the same internal processing pathways but at different decision making levels [41]. These researchers observed that the reaction times and TOJ responses differed together at the various SOAs but there was a great amount of variability in the TOJ responses in comparison to the RT responses [41]. These findings would imply that the RT and TOJ responses utilize the same pathways but are processed at different cortical levels, exhibiting that these tasks likely represent two modes of sensory perception.

This also extends to the TOJ and SJ tasks. It has been found that the point of subjective simultaneity (PSS) values from a TOJ task are not correlated with the PSS values from an SJ task when presented with the same stimuli [241]. Vatakis et al, (2008) [245] confirmed this finding by observing no correlation between the PSS values of a TOJ and SJ task, as well as no correlation between the just noticeable difference (JND). This indicates that these tasks may also be measuring different aspects of temporal perception. Miyazaki et al, (2016) [171] utilized functional magnetic resonance imaging to determine whether cortical activity differs between TOJ and SJ tasks. The cortical regions that showed significantly greater activity in the TOJ task included the left ventral and bilateral dorsal premotor cortices, the left posterior parietal cortex and thalamus [171]. While the SJ task showed significantly increased activity in the insular cortex [171]. Which has led to the proposal that TOJ tasks involve more cortical processes than SJ tasks. This is interesting because it further stresses the importance of understanding the perceptual task you choose for your study and knowing what the inherent differences may be.

In regards to postural instability perception I believe, utilizing a controlled methodological design with older adults to re-test the findings from Lupo and Barnett-Cowan (2018) [149] would be of great interest. Using the revised methodology I have presented in this dissertation it could be more precisely determined whether older adults still perceive postural instability more slowly than younger adults with an equal SOA distribution or whether the methodological design affected those results as well. Based on the findings from this disseration, it is reasonable to predict that using the revised methodology will yield older adult PSS values that are closer to true simultaneity, however, whether the PSS values of older adults are still significantly different from those of younger adults needs reassessment. Such results could shed light on to the potential benefit of using perceptual tasks as a supplementary tool to assess balance and posture in clinical settings. Perceptual tasks paired together with behavioural testing could potentially provide a greater understanding of how perceptual measures may relate to motor behaviour. Subsequently, allowing for the formation of new methods to evaluate posture and perception in specific populations.

5.3 Visual Context During Balance and Posture

As seen from both the perceptual research and behavioural research in this dissertation the role of visual information appears to vary. Within a perceptual task the presence of visual information did not have any significant effect on the point of subjective simultaneity (PSS) or the just noticeable difference (JND). However, when the context of the visual cues placed participants at the edge of a virtual skyscraper there was a significant decrease of the JND (reduction in response variability). Comparatively, during the visual motion experiment that placed participants at the top of virtual stairs, there was no observed effect of this perceived threat on postural sway. The immediate comparison is that the visual scenes are dramatically different in these two studies. The postural risk associated with these visual scenes is quite different, being at the edge of the virtual skyscraper constrains potential postural adjustments while being at the stairs does not to the same extent. For example when at the top of a set of stairs one can take a step or grasp a hand rail to catch themselves, but they cannot do this when at a ledge. This naturally could influence how an individual perceives the threat of a virtual scene and results in both perceptual and behavioural changes. This has been explored during quiet stance, where individuals exhibited significant decreases in COP sway in the anterior-posterior direction at height with a step restriction (or a ledge) [43]. Measures of fear, anxiety or balance confidence would be a way to quantify how the visual scene is perceived by the individual [49]. Allowing for a greater understanding of how the visual scene is being perceived by individuals and how it related to posture and balance.

Other aspects to consider about the visual context is the potential fidelity of the visual scenes. In our studies we used off the shelf visual scenes supplied by Oculus in an attempt to get the most visually compelling scenes. Though even with a visually compelling scene it is possible that the individuals are not immersed or lack presence in the virtual reality. As briefly discussed, described as the capabilities of the technology to provide an inclusive, extensive, surrounding and vivid virtual environment [220]. Inclusive indicates the ability of the system to shut out the real world, extensive indicates the number of sensory modalities that are utilized in the VR environment, surrounding indicates whether the visual field is panoramic or if it is limited to a narrow field and vivid indicates the resolution and fidelity of the provided sensory information [220]. Conversely, presence can be viewed as an outcome of immersion as it represents the sense of being engaged or being within the virtual environment.

This study utilized an Oculus CV1 which provides a resolution of 1920 x 1080, a refresh rate of 90 Hz and a 100-degree horizontal field of view and 90-degree vertical field of view. Each of these metrics are able to provide a relatively high resolution image, but the resolution of VRHMDs have since been developed to reach 1440 $\times$ 1600 and even 3664 x 1920 in the Quest 2. Despite these improvements in visual quality that would undoubtedly improve immersion, the system utilized in this dissertation was more than capable of providing a high resolution image. However, it is important to understand the differences in the field of view differences between real world and VR scenes presented within a VRHMD. Despite the fact that the VR environment provides a 100-degree horizontal field of view and a 90-degree vertical field of view, this does not replicate the amount of peripheral visual feedback received in the real world. Peripheral vision is known to be critical in visual motion detection and self-motion detection, with peripheral visual motion cues exhibiting an increased amount of postural stability in comparison to central visual motion cues [31]. Humans are believed to have about 180-degree horizontal and vertical field of view [166], which is a drastic difference to what is provided within current VRHMDs. Therefore, differences in field of view between virtual environments and real world environments need to be considered when discussing the potential excitability of the peripheral visual field. It is possible that within the context of VRHMD this relatively limited field of view may result in individuals receiving less visual context or less visual motion due to reduced field of view when compared to real world scenes. Within our studies the participants' head movements were 1:1 in the virtual environment to give the sense of an extensive environment, but participants were not able to physically move themselves around the environment. This has been shown to be a large limiting factor to feeling present within a virtual environment, even more so than the realism of the environment [251, 107, 65]. This makes sense because if you physically move your body and it is not directly translated within the virtual environment this would result in a disassociation between the individual and the virtual environment. Chapter 3 utilized VR in combination with a physical perturbation, so there was likely less of a dissociation between the virtual world and real world. However, the visual motion presented in Chapter 4 by design only stimulated the visual system, though I did attempt to replicate physical motion characteristics that may be experienced in the real world. Although this visual motion was modelled to replicate physical motion characteristics which included gravitational effects to create a more gradual curvilinear stimuli. This in theory would create a stimulus that is more immersive due to its more naturalistic motion profile. It is also important to consider that if 'real world cues' are not blocked out, this may lead to disassociation from virtual reality. Limiting external auditory cues or light that may stream in from gaps in the headset could be factors to consider. Auditory cues have been observed to significantly impact immersion in a VR environment, even ambient noise can improve presence and realism while also decreasing distractions [124]. Within Chapter 3 participants were exposed to white noise via noise cancelling headphones so this likely assisted with immersion, but this was not the case for Chapter 4. Therefore, this could have been another factor that limited the participants ability to become immersed within Chapter 4.

These considerations of the visual context when utilizing VR are important when trying to produce an evocative and immersive environment. Especially when the use of VR is trying to replicate what could be experienced in the real world. Therefore, attempting to quantify how evocative and immersive a VR should likely be paired with the use of questionnaires to determine how each individual is perceiving the produced virtual experience.

5.4 Individual Differences Across the Research

Individual differences were a common theme across my research. Within each of my studies, there was an observed range of responses which is not uncommon within research but a result that I always finding interesting. Within the realm of the perceptual research it is not uncommon to see a relatively wide range of responses. This naturally could exhibit the variability of how individuals perceive sensory events or could indicate how other psychological factors at the time may influence perception. My research was not designed at the onset to address the problem of individual differences but as I had earlier discussed in Chapter 3, factors such as fatigue, arousal, attention and anxiety could all be potential contributors to these differences. With the observed increased precision of the perceptual responses when at a virtual height, it appears to indicate that an individual's psychological state can directly impact these results. As I stated we didn't directly ask how the individuals felt when at the virtual height, but with previous research finding altered measures of fear of falling, anxiety and arousal at virtual height [219, 50, 49, 261, 39] it could be assumed this occurred in our study as well. However, these types of psychological measures should be collected and quantified in the future. I also believe utilizing a research design that is directly attempting to modulate individuals psychological state (i.e. fatiguing individuals prior to collection, or exposing them to fearful stimuli) and testing sensory perception could help provide insight into how these effects alter responses. Despite these possible confounding variables that could account for individual differences, future investigation on sensory weighting as a plausible hypothesis to explain individual differences in postural control are strongly encouraged.

One of the most interesting effects within this dissertation was in regards to the range of individual differences observed within Chapter 4. I have discussed the potential effects of these individual differences within Chapter 4 such as: how the speed of the visual motion may affect individuals' perception of self-motion, how visual dependence may cause certain individuals to exhibit larger effects of the visual motion, and how these differences in sensory re-weigthing across individuals may be explain the observed variability. However, because of this wide range of variability between individuals it is difficult to make an overall conclusion about how this type of transient visual motion affects postural responses. When calculating the mean responses across the individuals, which is the traditional approach used by most researchers, no meaningful significant effects were observed across the various condition types. To some researchers this would indicate that this paradigm does not have any meaningful effect on the population as a whole. However, I believe that seeing a few individuals respond to this type of stimuli so strongly, compared to a larger majority who had little response, makes these results even more interesting, as now there appears to be a case of 'responders' and 'non-responders' to visual perturbations. Here the responses in some of these individuals occurs over a very short period of time, which does not appear to have been explored at length in the literature. This is valuable, as it exhibits that visual motion cues can be utilized at a more rapid speed in certain individuals and result in postural responses which could be important when trying to measure the determinants of balance control across the general population.

As discussed through the various studies of this thesis it is important to address sample sizes and the potential effects on observed results. For each of the studies there was a relatively low amount of power across the primary measures, with the power ($1 - \beta = 0.64$) being largest when comparing the EO and VR JND values. Each of these studies exhibited a large variation of individual responses which limited the statistical effect and with the addition of more participants there would be improved power. However, this improved power may not have resulted in observed statistical effects as there are likely some limitations to the chosen outcomes measures and the potential effects of the conditions that were compared. I believe that within the perceptual research the repeatability of the study design and lack of statistical change with the PSS exhbits a potential limitation of this measurement despite the lower power across the studies. Though I do believe that further exploration of the JND differences within VR environments is of interest and could merit increase participants for the future. Regarding the final study the large individual differences would need to be first addressed prior to committing further time to collect more participants. I believe that an improved understanding of what causes certain individuals to respond more than others in response to visual motion needs to be first established. Then subsequently fine tuning the outcome measures of interest, as the current measures over the larger stimulus windows provide limited temporal understanding of postural changes.

Trying to understand these differences could be important with the increased utilization of VR as a tool for rehabilitative strategies, this includes the utilization of virtual visual motion [239, 58, 80, 19]. Baram et al, (2002) [19] observed that when visual motion cues are provided in isolation (without body cues to update the motion) to individuals with Parkinson's disease, most, but not all, struggled to control gait in these conditions. Indicating that even in clinical populations there appears to be circumstances where visual motion cues can have differing effects on the control of posture. Therefore, trying to determine how vision and visual motion cues are utilized in this subset of the general population could lead to an improved screening methodology for this differential sensory dependence. This subsequently could lead to improved clinical and rehabilitative designs that are tailored to an individual and their specific sensory needs related to the control of posture and balance.

5.5 Future directions

For future research, I believe that investigating how older adults perceive the onset of postural instability with a controlled stimulus onset asynchrony (SOA) distribution will be important to address. This dissertation repeatedly showed that the utilization of a controlled SOA distribution during a TOJ task does not result in a perceptual delay of postural instability onset within young adults. Thus, as Lupo Barnett-Cowan (2018) [149] found that the perceptual delay of postural instability doubled in older adults in comparison to younger adults, it is important to determine what the perceived timing of postural perturbations is for older adults using this revised methodology. If a delay is still observed this could lead to determining if perception of postural events is related to behavioural postural responses in older adults. There could be potential of using this as a complementary measure when monitoring postural deficits or improvements in older adults or clinical populations.

It would also be interesting to quantify how differing perceptual tasks affect the perception of postural instability onset. I believe the most interesting comparison would be to compare the simultaneity judgement (SJ) task with the TOJ task. This would provide some more context as to how differing perceptual tasks that are thought to utilize differing cortical structures may result in differential perceptual results. Do to the nature of the postural event and how multiple sensory modalities are activated it would be interesting to determine if these differences observed in the TOJ and SJ tasks persist for a complex multisensory event such as balance control. This use of the SJ task could also be applied when presenting individuals with more visually threatening visual stimuli. To determine if this reduction of the variability of their responses follows a similar trend for that evoked in the TOJ task.

Finally, I believe that investigating the effects of visual context, such as perceived height can be more thoroughly explored. I believe the study design utilized in my dissertation can be improved in many ways. First the visual height could be presented at a ledge on a skyscraper, which would give the impression of having more limited postural mobility in the anterior direction, as compared to the Tuscany room that I used. Additionally, the environment used could be made to be more immersive perhaps with the addition of auditory ambient sounds such as wind and street noise [124] to give a stronger impression of being at a height. Subsequently, this research would likely focus more on the rotational motions, since rotational motions are more comparable to how falls are experienced in the real world. It would still be beneficial I believe to utilize differing visual motion lengths. This would attempt to capture individuals that may posturally respond to short visual motion stimuli compared to those that may only respond to longer visual motion stimuli. Such an approach would be able to provide more insight into how individuals may be utilizing visual motion with these different motion characteristics.

5.6 Conclusion

In this dissertation, the perception of postural instability was investigated when utilizing a controlled methodological design during a temporal order judgement (TOJ) task. The results showed that the methodological design appears to have an impact on the perceived timing of the postural instability onset. With a equally distributed stimulus onset asynchrony (SOA) design resulting in a reduction in this perceived delay in comparison to previous research. Additionally the effect of visual feedback and visual context (virtual height) was explored to determine if visual information can influence the perceptual onset of postural instability. The presence of visual information did not have any significant impact of the perception of postural instability onset and neither did the virtual height. However, there was a significant effect on the just noticeable difference (JND) or the variability of the responses during the virtual height condition. Indicating that the variability of the participants responses decreased when the individuals were exposed to the virtual height. This could indicate that some psychological effects such as increased arousal, increased fear, increased anxiety and reduced confidence in balance may have impacted the responses of the individuals. Finally, the effects of visual motion with differing visual characteristics (motion type, direction and height) on postural response was explored. There were no observed effects of the visual motion with differing characteristics at the group level but there were some observed individual differences. This exhibited how visual motion stimuli or sensory modalities may be utilized differently across the general population. With these findings, exploring how perceptual measures may relate to postural behaviour could provide greater insight into postural and balance control in older adults and clinical populations. These findings also indicate how virtual reality (VR) can be a powerful tool when investigating visual contributions to perception and behavioural responses to posture and balance. Though, the findings also exhibit how individuals can be very different in the utilization of sensory cues and the importance of exploring these differences.

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Appendix A

Chapter 4 Supplemental Figures

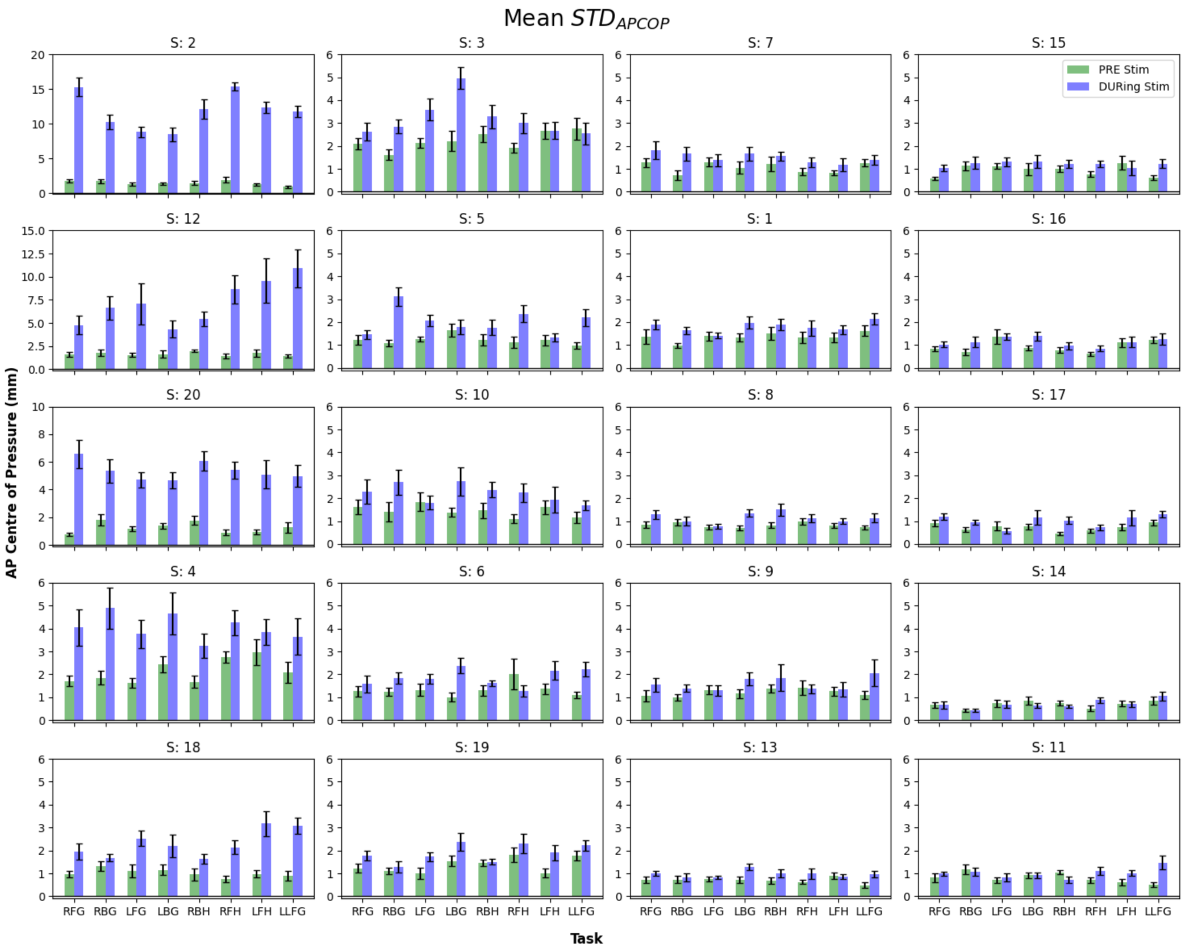

Figure A.1: Absolute mean values of AP STD for each participant in both the pre-stimulus and during-stimulus windows across all task conditions. This image depicts the values utilized to calculate the difference scores utilized within Chapter 4. The average sway variability can be observed independently over each window and exhibit how some individuals have greater baseline sway than others - hence the benefit of the difference score to normalize this pre-stimulus sway to their during-stimulus sway. **NOTE**: Subject 2, Subject 12 and Subject 20 have differing y-axis scales than other individuals to accommodate for the larger values.

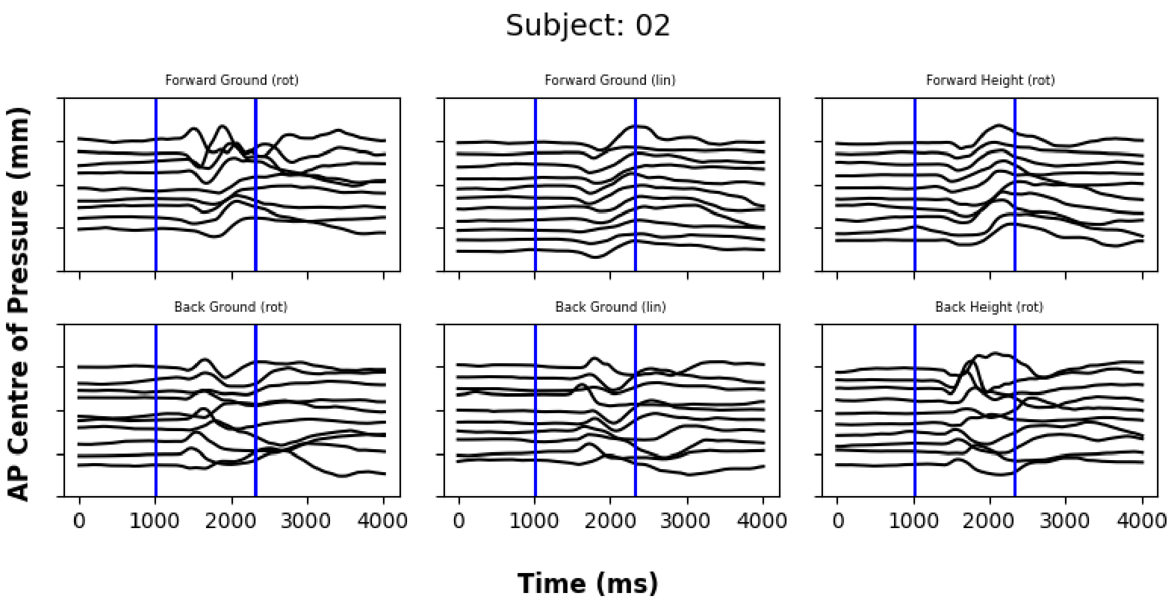

Figure A.2: A raster plot exhibiting the individual time series plots of the AP COP sway during six task conditions within Subject 2. This image is meant to visualize the relative consistency of the response and the apparent directionality of the response to the forward and backward visual motion.

Table A.1: This data represents the averaged AP COP onset time across all subjects for all tasks.

Averaged AP COP Onset Time	
Mean	438 ms
Std	334 ms
N	20

NOTE: The averaged onset time was first calculated for each subject across all tasks, then these subject averages were averaged across all subjects to get this mean AP COP onset time. The criteria for data to be included in this analysis were as follows: a 99% confidence band was calculated from the pre-stimulus window, this band was then applied to the during-stimulus window, if the AP COP data ¿3 SD for at least 100 ms that data point was included in the participant average. This means that some individuals may be contributing less AP COP onset times to this grand average - though all subjects had at least 1 task in which AP COP exceeded the 99% band in the during-stimulus window.

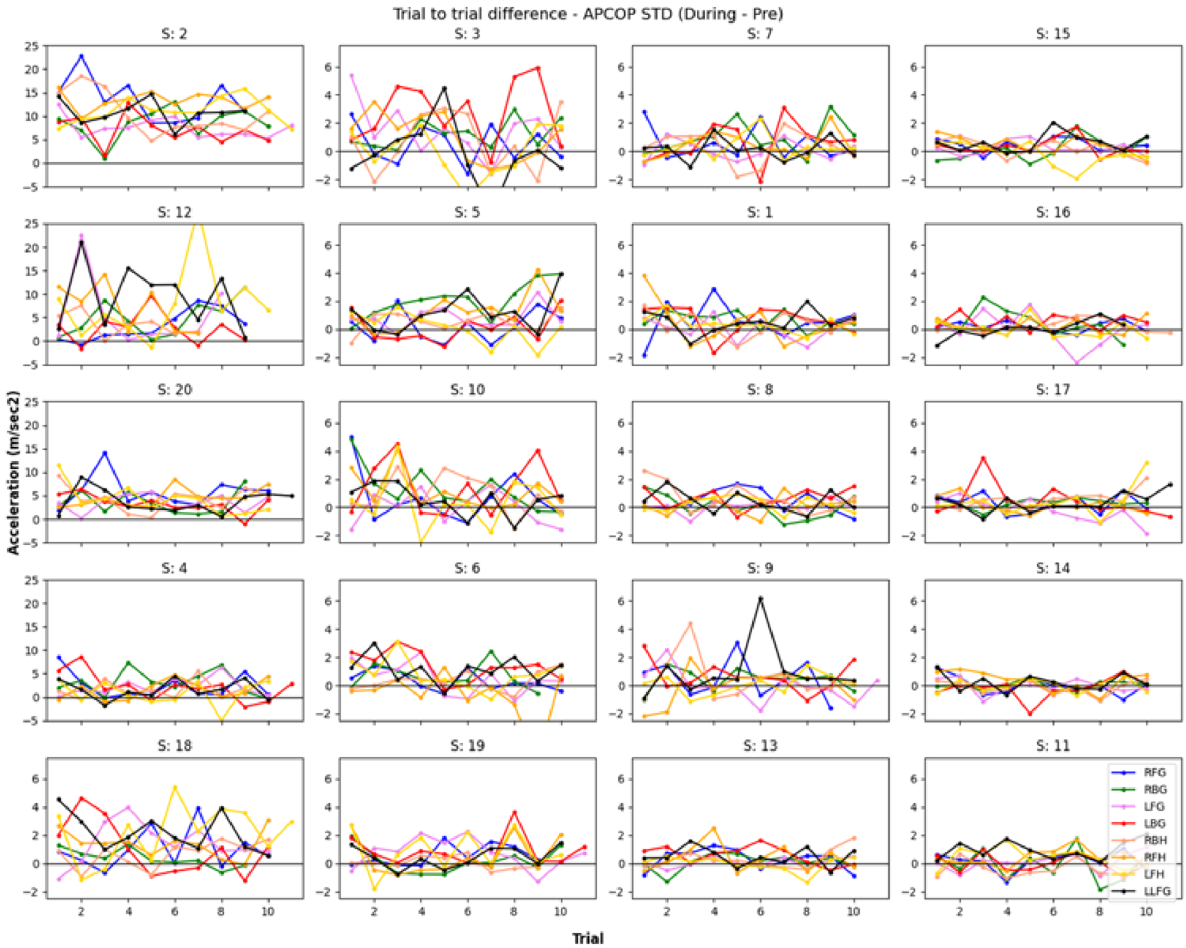

Figure A.3: Line graphs representing the $\Delta STD_{AP\ COP}$ for each individual trial over each condition for each participant. There were no statistically significant effects of first trial responses at the group level and no observable trend within each participant in regards to adaptation over time to the visual motion stimuli.