THE EFFECT OF CIRCULAR VECTION ON THE SUBJECTIVE POSTURAL HORIZONTAL IN THE PITCH PLANE

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Abstract

Postural orientation assessments, including the subjective postural horizontal (SPH) test, has been demonstrated as a great tool for assessing otoliths contributions to postural orientation and balance (Beule et al., 2006). Previous work has shown that dynamic visual stimuli, in the form of circular vection (CV) in the roll plane, significantly affects the body position and horizontal orientation perception of the support surface (Cleworth et al., 2023). However, CV in the pitch plane has been shown to introduce a different form of the visual stimulus and elicit distinct postural strategies compared to the roll plane. Therefore, by altering the support surface and visual information, this study aims to examine the effect of applying pitch CV in VR, on the body response and perception of horizontal orientation of the support surface. Overall, pitch CV significantly affected SPH of the platform and body position. This thesis contributes to our understanding of the complex integration of the visual and vestibular systems during postural orientation tests and offers a potential avenue for testing postural orientation and balance deficits in clinical populations.

Dedication

I dedicate this work to Al-Mahdi, for whom new advancements and discoveries in science will serve as tools to achieve peace and justice.

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Table of Contents

List of Tables:

List of Figures

List of Abbreviations

AP – Antero-posterior

BOS – Base of Support

BW– Backward

COM – Centre of Mass

COP – Centre of Pressure

CV– Circular vection

CNS– Central nervous system

DW–Downwards

FW– Forward

HMD– Head mounted display

LED – Light emitting diode

LGN– Lateral geniculate nucleus

ML – Medio-lateral

RMS– Root mean square

SPH –Subjective postural horizontal

UP–Upwards

VEPR– Visually evoked postural response

VR– Virtual reality

VIMS- Visually induced motion sickness

Chapter 1: Introduction

1.1 Thesis Overview

Maintaining balance is an essential aspect of our daily lives as it enables us to interact safely with our environment. Despite the profound research about balance and the significant advancements in this field, there are still significant research gaps of the underlying mechanisms of balance control and the factors that could impact it. One such factor that warrants further investigation is vection, an illusion of self-movement when no movement has occurred (Palmisano et al., 2015). Although vection commonly occurs in daily situations when riding a train or driving a car, its role in balance and postural orientation assessments, as well as its interaction with other sensory cues remains poorly understood. Therefore, this thesis aims to address these knowledge gaps by examining the effects of circular vection in the pitch plane on body lean and the perception of the subjective postural horizontal during upright stance. This thesis is divided into 4 main chapters. Chapter 1 provides a literature review of balance and the sensory contributions of the visual, vestibular, and somatosensory systems to balance control, followed by a review of vection, the different characteristics of vection and induced postural responses, and the main assessments of balance and postural orientation. Chapter 2 outlines the methodology that was used to study the effect of vection on body lean and postural orientation. Chapter 3presents the findings of this study, followed by Chapter 4 where these findings are discussed in the context of the current literature.

1.2 Balance

The increased incidence of falls and injuries is a critical problem in aging populations particularly those with vestibular and proprioceptive loss. Other than physical injuries, falls could lead to other negative consequences such as avoiding activity and a reduced quality of life (Kosorok et al., 1992, Zijlstra et al., 2006). Therefore, given the serious consequences of falls, it is crucial to gain a good understanding of balance. Balance, stability, and postural control are three main terms that are often used interchangeably to describe the ability to maintain equilibrium (Pollock et al., 2000). Two main components are part of postural control: postural orientation and postural equilibrium. Postural orientation is defined as the control of body alignment with respect to gravity, the surrounding environments and support surfaces, as well as the internal references (Horak, 2006, Gaerlan, 2010). On the other hand, postural equilibrium involves the coordination of strategies used by the sensorimotor system to stabilize the center of mass (COM) of the body (Gaerlan, 2010). COM is defined as the point where the mass is equally distributed against the base of support (BOS); which is the area of support during both self and externally induced disturbances (Horak, 2006).

Balance can be further classified into static balance and dynamic balance (Dunsky et al., 2017). Static balance is defined as maintaining stability while standing in a fixed upright posture where the center of mass is over the base of support (Dunsky et al., 2017). Dynamic balance on the other hand, is maintaining stability while the body is in motion such as when walking or responding to perturbations (Dunsky et al., 2017). Several distinctions between static and dynamic balance have been found within older and younger adults. Older adults were shown to have a greater difficulty to maintain their balance when standing on one leg and during reaching tasks that involved maintaining balance at the same time (Adkin et al., 2000). These distinctions were a result of the decline in muscle strength and proprioceptive inputs that older adults experience with age (Adkin et al.,2000). Therefore, given these factors that might influence postural control, it is important to understand the contributions of sensory inputs in balance maintenance.

1.3 Sensory Contributions to Balance

Balance is maintained by the integration of multiple sensory inputs provided by three main systems; the visual, vestibular, and somatosensory systems (Luo et al., 2018). The following sections will discuss in more detail the roles of the three systems in maintaining balance and providing essential information to the central nervous system (CNS).

1.4 Visual System

When moving through the environment, vision provides vital information for sensing self motion (Rokszin et al., 2010). During forward motion, the outward flow of motion on the retina which is provided by the surroundings is known as optic flow (Rogers, 2021). This optical flow is when there is a movement between the viewer and their surroundings which causes changes in the images of the retina (Rogers, 2021). The eyes, which are the main sensory organ in the visual system, are the peripheral source for the detection of the visual stimulus and for processing physical features of the surrounding environment (Gibson, 1979). Light enters through the cornea of the eye which travels through the pupil, and then is focused through the lens (Armstrong et al., 2014). The cornea and lens are both responsible for projecting the inverted images. In addition to that, the retina has protein molecules known as rods and cone which are photoreceptors that also play a role in detecting light (Armstrong et al., 2014). Rods are responsible for perceiving vision and body motion when the surrounding environments are dimly lit (Armstrong et al., 2014). Cones on the other hand, are responsible for detecting colour in well-lit environments (Armstrong et al., 2014). Rods and cones are both responsible for emitting neural impulses to the brain as a response to when light is absorbed (Kandel et al., 2013). These impulses then pass through the optic nerve where they are converted into electrical signal safter undergoing a process defined as phototransduction cascade (Kandel et al., 2013). The axons of this optic nerve then pass through the lateral geniculate nucleus (LGN) (Kandel et al., 2013). The main site of this nucleus is the thalamus which is responsible for processing information to the occipital lobe where the primary visual cortex resides (Kandel et al., 2013). Two main pathways known as dorsal and ventral streams make up the visual system (Sheth et al., 2016). The dorsal stream is referred to as the "where" pathway as it is responsible for the identifying the orientations of objects (Sheth et al., 2016). The ventral stream on the other hand, is mainly known as the "what" pathway as it is responsible for identifying what the objects are (Sheth et al., 2016). Recognizing and identifying these objects and the surrounding environments visually is a crucial step, however it is only one of the first steps of the cortical processes. Ultimately, the additional regions of the brain including the frontal attentional networks, are crucial for creating a full representation of the environment and the orientation of the person in space while they maintain their balance (Kandel et al., 2013).

The sensory system is responsible for processing two kinds of sensory inputs, including incoming afferent information and outgoing efferent information (Kapoula & Thuan, 2006). The afferent system can be further divided into what is known as the focal system, which is responsible for perceiving the motion of the object (Gaerlan, 2010). It is also divided into the peripheral system which is crucial for perceiving self motion (Guerraz et al., 2008). Furthermore, a component of the afferent system known as the retinal slip is used by the CNS as feedback to regulate sway (Gaerlan, 2010). Therefore, this system provides crucial sensory information during motion perception and postural control.

1.5 Vestibular System

In addition to visual information, the vestibular system is a sensory organ located within the inner ear which mainly receives information about the motion and orientation of the individual. Three semicircular canals and otoliths organs are located on both sides of the head. Each organ has hair cells that reside in vestibules and are filled with fluids (Goldberg, 2012). The three canals are angled 90 degrees to one another which corresponds to the different types of movements each canal can detect including when the head nods up and down, side to side head shake, and when tilting the head left and right (Michael-Titus et al. 2014). The otolith organs on the other hand, are made up of two sacs: one known as the utricle and the saccule. This sac is stimulated by linear acceleration of the head and is mainly influenced by the gravity (Howard, 1982). The canals on the other hand, can be stimulated by angular head rotations around horizontal, vertical, and the anterior-posterior axes (Goldberg, 2012). Information from these vestibular organs is then transmitted to the brainstem by the vestibular nerve which is then relayed to other areas including the cerebellum and cerebral cortex which are responsible for the coordination of the movement (Khan et al., 2013). Moreover, the vestibular inputs are mainly processed by the vestibular nuclei which also receive visual and somatosensory information (Khan et al., 2013). Therefore, the vestibular system along with the visual system, provides vital information when maintaining balance.

1.6 Somatosensory System

In addition to the visual and vestibular systems, the somatosensory system is the main system that is responsible for body position sensation. It consists of multiple receptors that are defined as cutaneous and joint receptors. It also includes receptors known as the muscle spindles and the Golgi tendon organs (Calvert et al., 2004). The main role of the cutaneous receptors is to detect when a stimulus is external, while joint receptors are mechanoreceptors that are responsible for sensing tactile information from stimuli about touch and pressure (Calvert et al., 2004). Muscle length changes are detected by the muscle spindles receptors while the receptors of the Golgi tendons are responsible for detecting the changes in muscle tension (Calvert et al., 2004). Therefore, the somatosensory system plays a vital role in sensing and communicating the position of the body to the musculoskeletal system.

1.7 Sensory Integration and Re-weighting

Postural control is maintained through the communication and sensory information integration from three main sources; the visual, vestibular, and somatosensory systems (Luo et al., 2018). Although it is challenging to isolate the input coming from one system, all three systems work quite well together when maintaining postural control (Gaerlan, 2010). However, these systems are not always in agreement, inputs provided by one system sometimes conflicts with the input signaled by one of the other systems (Luo et al., 2018). According to the sensory reweighting hypothesis, the contribution of each of the three systems varies and is adjusted by the CNS depending on the reliability and availability of the sensory information in a particular situation (Nashner et al., 1978). Therefore, it is important to assess each of these systems individually in order to gain a better understanding of how they work together to maintain postural control. Although the contributions of the somatosensory system are crucial in postural control maintenance, for the purpose of this study, we will mainly be focusing on the roles and contributions of the vestibular and visual systems.

1.8 Vestibular Contributions to Balance

The vestibular system plays a vital role in postural control as it is mainly responsible for detecting the acceleration and orientation of the head (Goldberg, 2012). The vestibular system inputs are not as crucial for maintaining balance during simple tasks such as walking, as during these tasks accurate inputs are provided by the visual and somatosensory systems (Fujimotoa et al., 2010). However, accurate vestibular inputs are vital for maintaining postural control when tasks are more challenging (Fujimotoa et al., 2010). For instance, individuals that had deficits in their vestibular system reported higher levels of instability when they tried to maintain their balance during head motion and support surface perturbations (Allum et al. 2001; Carpenter et al. 2001; Beule et al., 2006).

Physically displacing the head by rotating an individual while they are sitting in a chair is one way to stimulate the vestibular system (Kirollos, 2019). Another method is by using dynamic perturbations of the support surface such as motion platforms. By perturbating the support surface, the role of the visual and vestibular systems in perceiving motion can be better understood (Kirollos et al., 2019). Moreover, other methods such as caloric and galvanic vestibular stimulation are often used to stimulate the vestibular system artificially (Goldberg, 2012). Both types of stimulations act directly on the vestibular nerve which as a result transduces a signal to the brain about the motion without physically moving the head (Goldberg, 2012). This helps in the facilitation of the vestibular system assessments while the head is stationary.

Despite the significant role of the vestibular system, one main limitation of the vestibular system is the otolith organs can only detect acceleration (Howard, 1982). This is due to the inertial properties of the mechanoreceptors which limits the system's ability to differentiate between a static position and moving at a velocity that is constant (Lishman et al., 1973; Kirollos, 2023). So in this case, the brain must do an additional integration in order to determine the position which may lead to errors (Mayne, 1974). Despite this limitation, the role of the vestibular systemin perceiving motion is crucial as demonstrated in individuals with deficits in their vestibular system (Kirollos, 2019). Vestibular deficits patients are not able to perceive self motion at all or as well as healthy individuals and they usually report higher perception thresholds (Guedry et al.,1963).

1.9 Visual Contributions to Balance

The role of the visual system during postural control tasks is vital as it is essential for providing stabilizing cues. The visual contributions to balance can be assessed in several ways by the alteration of the sensory information that the individual receives (Gaerlan, 2010). One method is by the comparison of the presence of visual inputs versus when visual information is absent. It has been demonstrated that when visual information is present during eyes opened tasks, body sway is reduced by approximately 40-50% compared to the when visual information is absent during eyes closed tasks (Diener et al., 1984). Moreover, absence of visual cues is correlated with decreased performance and an increase in trunk sway during balancing tasks (Allum et al.,2001, Gaerlan, 2010). This demonstrates the vital role that the visual system plays in stabilizing balance during upright tasks.

Despite the primary roles of the visual system when maintaining balance, it has been demonstrated that balance can be maintained in situations when vision is absent such as when placed in dark environments (Uchiyama et al., 2009). When placed in a darkened environment, the typical response is a reduction in the body oscillation, however what is interesting is that participants were focusing on a light emitting diode (Guerraz et al., 2008, Gaerlan, 2010). This shows how important the visual information is for increasing postural stability. Other characteristics of the visual environment including the size of the depth of perception, and the motion of the visual environment have also been demonstrated to influence the contributions of vision when maintaining balance (Gaerlan et al., 2012). Moreover, the role of vision in postural control is essential for accurately assessing the distance and for recognizing objects in the visual environment (Lord et al., 2001). For instance, low contrast binocular vision and reduction in peripheral vision were shown to be correlated with higher incidents of falls (Lord et al., 2001).

Another way to assess the visual contributions to balance is by the exposure to perturbations in the visual environment. The typical response to the exposure to a moving visual environment, is the stabilization of the body's position and leaning in the same direction as the direction the visual scene is moving in (Tanahashi et al., 2007). Perturbations of the visual environment can be controlled and altered through projectors, moving room environments, and virtual reality devices (Lestienne et al., 1977; Bronstein, 1986; Engel et al., 2020). Two main theories were proposed to explain the contributions of vision when maintaining postural control. The inflow theory suggests that extraocular muscles such as the muscle spindles, are responsible for providing information about where the eye is in the orbit (Guerraz et al., 2008, Gaerlan, 2010). In contrast, according to the outflow theory, the neural outflows including signals about the eye movement, sends information to the CNS which responds by maintaining visual consistency throughout (Guerraz et al., 2008). Therefore, the information provided by vision is critical as it provides feedback and reference frames with respect to the visual environment during balance tasks.

1.10 Somatosensory Contributions to Balance

The somatosensory system plays a vital role when maintaining balance during upright stance. It consists of two main systems including the tactile and proprioceptive systems (McKeon et al.,2017). Tactile system involves receptors in the skin and sensations such as touch, pressure, and vibration (Bray et al., 1999). Cutaneous mechanoreceptors located in the feet, are responsible for providing tactile sensations to the CNS and play a critical role when controlling balance during upright stance. It has been found that the change in pressure under the feet is related to the change in upright position (McKeon et al., 2017). The contributions of the somatosensory system to balance have been assessed through multiple ways that influence the tactile information including the anesthetization of the receptors, altering the supporting surface, and by cooling the cutaneous mechanoreceptors of the plantar to reduce its sensibility (Meyer et al. 2004; Wu et al., 1997; McKeon et al., 2017). Other studies applied vibration to the skin of the foot and found that these vibrations induced an involuntary whole-body tilt and adaptive responses to maintain stability (Kavounoudias et al., 1997). These alterations to the afferent tactile information and the resulting responses further emphasize the role of the somatosensory system when maintaining balance. Proprioceptive system on the other hand, involves the sense of joint motion and position including changes in muscle length and joint angles (Bray et al. 1999). This system includes receptors such as the muscle spindles and Golgi tendon organs. Other receptors of the proprioceptive system are located in the lower legs and feet and are sensitive to rotations of the ankle (Fitzpatrick et al., 1994). It has been found that feedback from lower leg proprioceptive receptors is critical for automatic corrective balance responses (Kavounoudias, et al., 1997). When information from tactile and proprioceptive systems is not signaled to the CNS, or during cases where there is a loss of sensation by the somatosensory system such as that experienced by neuropathy patients, this causes a decline in balance control and an increased risk of falling (Van Deursen et al., 1999). Patients with disorders in their peripheral nervous system such as diabetic neuropathy experience deficits in their somatosensory sensation from distal regions of their legs and a loss of position and vibration sensation (Van Deursen et al., 1999). Therefore, the somatosensory system through tactile and proprioception information, is crucial for maintaining balance.

1.11 Visual-Vestibular Integration

Despite the important roles of each of the visual and vestibular systems during postural control tasks, these systems have a few limitations. Pervious sections highlighted the factors that could influence the information coming from the visual system including the characteristics of the visual scene and the motion and environment of the scene (Redlick et al., 2001). One limitation includes the limited ability of optic flow to only provide information about the person and the motion of the surrounding environment. On the other hand, signals provided by the vestibular system, specifically those coming from the otoliths, are limited as the source of the head acceleration is uncertain; these accelerations could be a result from tasks such as walking that are self generated, or even by acceleration induced by the gravity (Redlick et al., 2001). Integrating the cues provided by both visual and vestibular systems could provide a solution to these limitations. The visual and vestibular systems work well together to determine the orientation of the body relative to the reference frame and environment. (Patla et al., 1998). When the vestibular system detects movement, in response the eyes move and then the visual images are stabilized on the retina by a reflex known as the vesitibulo-ocular reflex (Somisetty, 2019). Despite how well these two systems work together, a conflict may arise between the inputs of the visual and vestibular systems when the visual environment the individual is exposed to is perturbated. This could result in the illusion of movement, a concept known as vection.

1.12 Vection

The term vection is defined as the illusion of motion when no movement has occurred (Palmisano et al., 2015, Kooijman et al., 2023). It is often categorized as two types referred to as circular vection and linear vection. Circular vection is a circular motion sensation as a result of the visual field rotation in either the roll, pitch, or yaw planes which are rotations around the x, y, and z axes, respectively (Palmisano et al., 2015). In contrast, linear vection is the translation of the visual scene away from or towards the individual, creating in the individual exposed to this scene translation a sense of moving forward and backward relative to the scene stimulus (Palmisano et al., 2015). Linear vection can be induced through monitors and screens (Palmisano et al., 2015). A classic example of this type of vection is when an individual is sitting in a stationary train while another train passes by. Even though the train they are on is stationary, this creates the illusory sensation that the train they are sitting in is moving as well (Kooijman et al., 2023). Numerous studies have investigated the underlying mechanisms of this phenomenon and have shown that the velocity and direction of the motion is carried by optic flow patterns (Warren et al., 1976). These optic flow patterns are processed by a specialized group of cells which may play a role in the sensation of vection (Nakayama et al.,1974). It has been suggested that these specialized group of cells are motion sensitive cells that are located in the visual system and play a role in structuring the visual field (Nakayama et al., 1974). The sensation of movement when no movement has occurred is mainly detected by the visual system (Wright, 2009). This creates an internal conflict between the sensory inputs provided by the visual system and that sensed by the two other systems (Wright, 2009). The following section will discuss the underlying mechanisms and one of the main characteristics of vection, known as vection onset.

1.12.1 Vection Onset

Perturbation to the visual scene in the form of visual motion, causes vection that is in the opposite direction that the visual scene is moving in (Guerraz e al., 2008). Vection onset is defined as the period of time between the beginning of the optic flow pattern and when vection is perceived (Ni et al., 2022). Various factors play a role on the varying values of vection onset including the visual stimuli's characteristics, rate of rotation, and familiarity with the stimulus through previous exposure to a similar stimulus (Keshavarz et al., 2015). Moreover, it is crucial to discuss because a high latency experience could result in negative effects such as motion sickness and disorientation (Keshavarz et al., 2015; Keshavaraz et al., 2019). Vection onset has also been shown to be positively correlated with increased rate of rotation in circular vection studies (Guedry et al., 1974). Furthermore, vection onset has also been demonstrated to be affected by the size of the display, with small display sizes resulting in a shorter vection onset compared to displays that are larger in size (Howard et al., 1966).

The traditional sensory conflict hypothesis states that the observed vection onset is the result of a conflict between the visual system processing self motion cues, and the vestibular system not detecting these cues (Keshavarz et al., 2015). This conflict is resolved once the speed is constant since as discussed earlier, one of the limitations of the vestibular system is that it cannot differentiate between constant speed and stationery. However, this hypothesis was challenged by a study that used an effect of a camera shake while exposing the participants to a visual display (Palmisano et al., 2000; Kirollos et al., 2019). The acceleration of the visual displays led to a shorter vection onset compared to when the display was moving at a constant speed (Palmisano et al., 2000; Kirollos et al., 2019). Moreover, the additional perturbations with the accelerating display resulted in a stronger vection effect (Palmisano et al., 2000). These results contradicted the hypothesis as it is expected that the combination of both perturbations should result in a conflict between both systems and as a result, a delay with a reduced vection effect (Kirollos et al., 2019). Therefore, due to contradictory results to the proposed hypothesis, an alternative explanation was required.

Another hypothesis that has been proposed to explain the conflict between both systems is the visual dominance hypothesis. This hypothesis states that when both systems are in conflict, the signals coming from the visual system are prioritized over the inputs coming from the vestibular system (Berthoz et al.,1975; Kirollos et al., 2023). However, studies have also challenged this hypothesis by demonstrating that it is unable to explain the reported vection onset times (Kirollos et al., 2023). If it is true that the conflict between the two systems is resolved by visual dominance, we then expect that vection would be immediately experienced when the individual is exposed to the visual display. However, no current findings support this as studies have shown vection onset times of several seconds (Kirollos et al.,2023). Therefore, this hypothesis also fails to account for the vection onset times that are typically observed.

In contrast to the hypotheses discussed above, it has been suggested that the vestibular system might also play an important role when the two systems are integrated (Harris et al., 2000). The vestibular system had a stronger effect on the perceived motion direction compared to the visual system (Harris et al., 2000). This was demonstrated by the stronger effect of the vestibular system on head perception during a task that included perturbations to the platform and dynamic visual scenes that were opposite to the direction of the platform perturbation (Butler et al. 2010; Kirollos et al., 2019). Considering all these proposed hypotheses, and the capabilities and limitations of each of the visual and vestibular systems, one system might be more dominant in certain studies depending on the task, however these two systems work so well when integrated. In fact, the capabilities of the two systems complement each other as the vestibular system can detect head acceleration in contrast to the visual system which mainly detects constant velocities (Kirollos et al., 2023). Overall, vection onset provides a better understanding of the complex integration between both systems, and the underlining mechanisms of self motion. A better understanding of these dynamics helps us explore the effects of circular vection and the resulting visually induced postural responses which will be discussed in the following section.

1.12.2 Vection and Visually Induced Postural Responses

Exposure to vection generates a sway response known as visually evoked postural response (VEPR) (Lestienne et al., 1977). This type of response typically occurs in the same direction as the direction of the visual scene rotation (Lestienne et al., 1977). VEPRs have been demonstrated to be influenced by several factors including the environment of the visual scene (Bronstein et al., 1997, Lavalle et al., 2022). This was investigated by Bronstein et al., (1997) by asking the participants to fixate their sight either directly on the background or through an object in the field which was a window. When the participants fixated directly on the background, their VERPs followed the same direction as the visual scene motion (Bronstein et al., 1997). This made it less challenging for the participants to stabilize their bodies when referencing it against an external reference. In contrast, when they fixated on the background through the window, this made it more challenging for them to stabilize and resulted in VERPS in the opposite direction of the background scene motion (Bronstein et al.,1997).

VEPRs are also significantly influenced by the intensity of the visual field (Fujimotoa et al., 2020). Early vection studies generated the illusion of vection using vertically stripped optokinetic drums which resulted in an illusion that is opposite to the stripes motion (Keshavarz et al., 2015, Kirollos et al., 2023). The intensity of circular vection visual field was stronger compared to that of linear vection (Mach,1870; Riecke et al., 2015). The effects of vection instensity on postural control strategies were also investigated in a study by Lestienne et al. 1977), where they reflected an image that moves back into the visual field of the participant. They found that the intensity of the visual field was strong as the direction of the participant's body sway matched the direction of the visual scene movement in the anterior and posterior direction (Lestienne et al. 1977). Furthermore, VEPR were found to be correlated with the amplitude, velocity, the direction of the visual flow, and the orientation at the head, knee, and hip segments (Keshner et al., 2004). This demonstrates the effect of the visual scene intensity and environment on VERPS.

Additionally, a correlation has been demonstrated between the velocity and the effect of vection on postural responses (Lestienne et al., 1997). Several studies have investigated the effect of velocity on the strength of vection and they found a positive relationship between faster optic flow displays and stronger vection and postural responses (Riecke, 2010; Kirollos et al., 2023). Therefore, these studies were vital in highlighting the possible ways to reproduce and study vection in a laboratory environment, and the optimal conditions to induce vection and VERPS.

1.12.3 Vection and Visual-Vestibular Integration

The inputs of the visual, vestibular, and somatosensory systems interact in a main area of the brain known as the vestibular nuclei (Lopez et al. 2012). Moreover, it is suggested that the sensory inputs provided by these three systems are integrated using the same neural processes (Haggerty et al., 2017). Body sway in response to vection during stable support surface tasks, has been shown to rely on a shared central mechanism (Wang et al., 2010). However, during unstable support surfaces, this instability and body sway response occurs earlier and in the opposite direction of vection response (Guerraz and Bronstein, 2008; Keshner et al., 2004). This difference suggests the separate control mechanisms are responsible for the perceptual and postural sway responses

Reviews from behavioral and neuroimaging studies demonstrated that there are areas where the inputs coming from both the visual and vestibular systems interact during vection (Palsimano et al., 2015; Kirollos, 2019). The two main areas are the brain stem and the cortical levels (Dichgans et al. 1975). The short latency of the visual information could also be connected to the early VEPRS. Furthermore, there is evidence that this connection could result in suppressing the signals coming from the vestibular system through the sub-cortical visual pathways (Miles,1998)

The integration between the inputs coming from the visual and vestibular systems was demonstrated in a study by Kim et al. (2015). The main task was to tilt the head left and right while being exposed to several visual stimuli through a VR headset (Kim et al., 2015; Kirollos, 2019). Conditions were classified into two types including passive and active motion. During the passive condition, the main task was to keep the head still while viewing the stimulus. They hypothesized that vection will have the largest effect during the active motion condition (Kim et al., 2015). Since during the active position, tilting the head would activate the vestibular system which as a result would reduce the conflict between the visual and vestibular systems and result in a stronger vection effect. However, surprisingly, no main difference was demonstrated between both conditions. The passive condition had a stronger vection effect in contrast to the active condition (Kim et al., 2015). Therefore, these outcomes provide valuable insights into the visual and vestibular systems integration, and the relationship between vection, the perceived motion, and postural stability.

1.12.4 Roll vs Pitch Circular Vection

Vection is classified into two types: roll vection and pitch vection. Illusions produced by the visual and vestibular systems induce body motion that is perceived in the roll side to side directions and pitch up and down directions (Keshavarz et al., 2017). Distinct differences in the latency onset and the magnitude of the perceived self motion were observed in studies that examined circular vection in roll and pitch directions (Riecke et al., 2015; Keshavarz et al., 2017). Similar outcomes were demonstrated in studies that used a virtual reality headset (Kitazawa et al., 2009). The observed differences in vection types may be further explained by the information provided by the visual and vestibular system and their effect on perceived self motion (Keshavarz et al., 2017). Furthermore, there are distinct differences between linear and circular vection optic flow (Feuereissen et al., 2013). Linear vection results in a forward self motion and exhibits images of the objects in the scene in the direction of travel (Gibson., 1966; Kirollos et al., 2019). On the other hand, during circular vection, the pattern of the optic flow results in an illusion of rotating that is opposite to the motion of the visual scene (Gibson, 1966; Kirollos et al., 2019).

The way the brain processes sensory information of self motion is affected by the integration of the sensory inputs in the vestibular nuclei (DeAngelis et al., 2012). The typical response to the exposure to visual motion is the sensation of tilting in the opposite direction (Keshavarz et al., 2015). During roll CV perturbations, the trunk tilts in the direction of the visual scene rotation and down weights the inputs of the somatosensory system from the legs, signalling that no tilt has occurred (Held et al., 1972). Moreover, CV in the roll plane demonstrated a stronger influence on stability in contrast to perturbations in the pitch plane (Carpenter et al., 2001). Furthermore, CV in the pitch plane elicits distinctly different postural strategies compared to stimuli in the roll plane (Allum et al., 2008). Roll plane rotations mainly activate upper body muscles such as the trunk and hip, compared to visual scene rotations in the pitch plane which activate lower leg muscles (Allum et al., 2008). Overall, these findings suggest that the direction of the rotating stimulus could influence the effect of CV. Rotations in the pitch plane elicit faster onset and weaker self motion illusions in comparison to rotations in the roll plane (Feuereissen et al., 2013). However, to fully understand the underlying factors that contribute to these differences, further research is needed.

1.13 Assessments of Balance

Balance is maintained through the integration of sensory information coming from the visual, vestibular, and somatosensory systems. Understanding the different ways balance can be measured is crucial to effectively assess these sensory integrations when in conflict such as during vection, and for identifying potential disorders that could impact balance maintenance. The following sections will discuss in more detail how balance can be measured and assessed through virtual reality, dynamic posturography, and postural orientation assessments.

1.13.1 Virtual Reality and Balance

Virtual reality (VR) has been demonstrated as a great tool for creating visual environments that are suitable for clinical use (Morel et al., 2015). VR is more commonly used nowadays in various domains due to its ability to create a controllable environment (Assländer et al., 2023). The visual scene is updated based on the head orientation of the individual and their movements (Morel et al., 2015). The usability of VR for research purposes has been assessed, and three main considerations were set including its reliability, validity, and safety (Soltani et al., 2021). A study by Riecke et al. (2006) demonstrated the effect of VR visual stimuli on the resulting postural sway. The visual stimulus through VR affects postural sway by the degree to which it replicates a real-life scene, and by the correlation between spatial presence and the VR induced vection (Riecke et al., 2006).

VR has also been demonstrated as a useful tool for exploring the multisensory components of postural control (Assländer et al., 2023). Using VR for studying balance and vection offers the advantage of isolating each of the sensory systems inputs (Morel et al., 2015). This can be done by manipulating and removing the visual system inputs while maintaining inputs coming from the vestibular and somatosensory systems (Gaerlan et al., 2010). Some of the early limitations of VR headsets including the size and weight of the HMD, and the resolution restricted the study of vection (Morel et al., 2015). However, these limitations have been solved by the new HMD advancements that are low in cost but have great resolution (Cipresso et al., 2018). Moreover, the use of VR by researchers to examine the visually induced vection has been on the rise as evidenced by various studies that have demonstrated the effectiveness of VR in inducing vection (Kim et al., 2015; Riecke et al., 2015; Keshavarz et al., 2017; Kirollos, 2019).

Investigating CV induced through VR and the variables that could affect its perception, this can help us better understand the complex relationship between inputs of the visual and vestibular systems during dynamic balance tasks.

1.13.2 Dynamic Posturography

Posturography is an assessment that is used to assess the ability of an individual to maintain upright postural control (Visser et al., 2008). Posturography can be further classified into two types; static posturography which is during quiet stance, or dynamic posturography where perturbations are applied to stance (Rosiak et al., 2022). During static posturography, the individual stands quietly on the ground, on a fixed platform, or on a force plate which captures the oscillations of the body through the embedded force detectors (Visser et al., 2008). On the other hand, dynamic posturography involves perturbations of the platform that allows for a controlled translation and rotation of the support surface while destabilizing balance (Winter et al., 1995).

Using force plates, postural control can be assessed by recorded ground reaction forces (Winter, 2011). Center of pressure (COP) displacements in the medio-lateral (ML) and antero-posterior (AP) directions which run along the frontal and sagittal planes respectively, are calculated from these recorded forces (Winter, 2011). The assessment of body sway and COP during balance tasks provides insights into the underlying mechanisms of how the body sustains postural control. Furthermore, root mean square (RMS) of the COP displacement and velocity are time domain measures that are often used to assess postural sway (Palmieri et al., 2002). For instance, higher RMS levels and lower velocity were shown in older participants resulting in decreased postural stability (Palmieri et al., 2002). Frequency domain analysis is another method used for understanding postural sway and the contributions of each of the systems during a balance task (Palmieri et al., 2002). This assessment helps researchers estimate the role of each system during different tasks by identifying a frequency range that includes the sensory systems and analyzing the power within this range for each system (Palmieri et al., 2002). Many studies have studied and attempted to define this range and found that the somatosensory system has a frequency between 0.3 and 1.0 Hz (Nashner et al., 1982), a much faster frequency range in contrast to the slower frequencies of the vestibular (0.5 Hz) (Nashner 1972), and visual systems (0.1 Hz) (Nashner et al., 1970). A definite range has not been set yet however this assessment has potential as a useful method for measuring postural sway and better understanding the role each system plays during these balance tasks.

The perturbations applied to the balance system could be coming from external or internal sources, with external perturbations that are usually applied without the knowledge of the participant to test the reactive responses of the sensory systems (Kirollos et al., 2023). These perturbations include several methods that include platforms that rotate and translate. Therefore, dynamic posturography assessments, kinetics and kinematics measurements, as well as body responses recordings, helps us gain a better understanding of the visual and vestibular systems interactions. We also gain more insight about the postural responses that result from the exposure to mechanical perturbations during balance control tasks- a topic which will be discussed in more detail in the following section.

1.14 Postural Responses to Mechanical Perturbations

Individuals use various strategies to remain upright when maintaining balance (Blenkinsop et al., 2017). One of the strategies is known as the hip strategy, where the body makes rotations around the joints of the hip (Blenkinsop et al., 2017). Conversely, the ankle strategy involves rotations around the joints of the ankle (Blenkinsop et al., 2017). It has been demonstrated that when an individual stands on a stable surface during a balance task, they usually use the ankle strategy to maintain their balance (Blenkinsop et al., 2017). However, when they are exposed to sudden perturbations, they usually tend to switch to the hip strategy (Blenkinsop et al., 2017). It has also been observed that the response to balance maintenance is affected by the direction in which the person is about to fall into (Blenkinsop et al., 2017). For example, during support surface perturbation in the posterior direction, the plantar and knee flexors and hip extensors of the ankle are activated as a result of the ankle strategy, in contrast to the hip strategy which activates the hip flexors and knee extensors (Blenkinsop et al., 2017). In addition to that, it was shown that the sensory inputs could affect the muscle activity that is controlled by the CNS by a concept known as the directional sensitivity of the sensory inputs and the resulting postural responses. (Carpenter et al.,2001; Allum et al.,2008). By exposing participants to multiple rotations of the support surface in different directions, findings revealed that the CNS independently controls motion in the roll and pitch planes (Carpenter et al.,2001; Allum et al.,2008). In other words, the body roll responses are primarily programmed by the CNS and then the pitch response is subsequently adjusted accordingly. This preference could be the result of biomechanical constraints, as the orientation of the lower legs muscles were found to be pitch-oriented, while the trunk muscles mostly roll-oriented, and mixed orientations in the knee and arm muscles (Carpenter et al., 2001). These results provide insight into the postural responses and strategies that the body uses when exposed to mechanical perturbations.

1.15 Postural Orientation Assessments

There are two common postural orientation assessments known as subjective visual vertical (SVV) and subjective postural vertical tests (Cleworth et al., 2023). These tests are mainly used to assess the effect of CV on perceptions of the visual and vestibular systems (Cleworth et al., 2023). During these tests, subjects are usually seated with their body tilted away from the vertical and are asked to adjust their SVV during different inclinations (De Vrijer et al., 2008; Ward et al., 2017). As the angle at which the body is tilted at increases, it has been correlated with an increase in the perceived vertical offset when referenced relative to the real vertical (Ward et al., 2017). The increase in body tilt angle has also been correlated with an increase in perceived vertical offset variance (Ward et al., 2017). This increase in variance has been found to be correlated with utricular deficits particularly those that have no ocular vestibular evoked myogenic potentials (Ocular VEMP) (Burgin et al., 2018). Limited changes were found when examining the SVV estimates of those with unilateral vestibular deficits unless they had one utricle that remained unstimulated (Clarke et al., 2001). These tests are great tools for the assessment of multisensory integration, however they have a number of drawbacks as they do not test otolith contributions to balance and are usually assessed outside the balance tasks (Cleworth et al., 2023). To account for these drawbacks, then came the subjective postural horizontal (SPH) test which assesses an individual's ability to subjectively perceive their own body's horizontal orientation in space (Beule et al., 2006). The main task during this test is to use a handheld controller to return the tilted platform to the perceived horizontal position. The SPH test has been demonstrated as a useful tool for assessing the contributions of the otoliths to postural control during a dynamic balance task (Beule et al., 2006). Healthy participants performed significantly different than those participants who had a complete unilateral loss due to vestibular neurectomy (Beule et al., 2006).

1.16 Current Knowledge Gap

Assessments of static balance are inadequate for assessing the postural responses and multisensory inputs during tasks that include stimulus perturbations, and as diagnostic tools for the assessments of subjects with otolith impairments. In contrast, dynamic perturbations are great tools for assessing each of the individual roles of the systems and how they affect the way the body responds and the strategies that are used. As previously discussed, the SPH test has been demonstrated as a viable tool for assessing the contributions of the otoliths to postural orientation during a balance task (Beule et al., 2006). However, it is still unclear how the combination of the SPH test with additional perturbations in the visual environment influences postural orientation and body responses, highlighting a gap in our understanding about the role of the visual system in postural orientation tests (Cleworth et al., 2023). To further investigate the role the visual system plays during these tests and its effect on the perception of the SPH, CV is applied to dynamically perturbate the visual environment (Cleworth et al., 2023). A study conducted by Cleworth et al. (2023), demonstrated that the effect of CV in the roll plane was significant during this balance task as the body responses and the SPH of the support surface were both biased by the additional perturbations of the visual environment. The effect of additional visual cues adds evidence to the proposed hypothesis of weighted multisensory integration during dynamic balance tasks (Cleworth et al., 2023). However, the effect of CV has been demonstrated to be influenced by direction of the stimulus. Applying CV in the pitch plane has been shown to introduce a different form of the visual stimulus and elicit distinct postural strategies compared to the stimulus in the roll plane (Carpenter et al., 2001). Nevertheless, the different effect of CV in the pitch versus roll planes on body orientation tests such as the SPH, remain unclear. To the best of our knowledge, there are no studies that have looked at how the SPH test is influenced by CV in the pitch plane, which illustrates a gap in research that requires further investigation.

1.17 Thesis Purpose and Hypothesis

The primary objective of this thesis is to develop a better understanding of how postural control during an upright dynamic balancing task, is affected by the inputs provided by each of the visual and vestibular systems. Specifically, this thesis aims to examine the effect of applying additional dynamic visual perturbation in the form of pitch CV in VR, on the body response and the perception of the horizontal orientation of the support surface. It was hypothesized that participants' body position and the SPH of the support surface will be biased in the direction of the CV perturbation. Additionally, it was hypothesized that when the visual signals elicited by CV in the pitch plane are congruent with the tilt of the support surface platform, this will lead to larger leans in the body compared to the condition without CV perturbation.

Chapter 2: Methods

2.1 Participant characteristics:

Twenty-two healthy young adults were recruited from York University and the surrounding community to participate in this study. Inclusion criteria included those who were between 18-40 years old and had normal or corrected to normal vision. Participants who self reported they have neurological or orthopedic impairments, symptoms of perceived dizziness and vertigo, or were taking any medications that are known to influence balance, were excluded from participating in this study. No independent variable was used for the biological construct in this study as research have shown no significant difference between males and females when they perceive visual motion (Vanston et al., 2017). Due to a few technical difficulties during data collection, a total of two participants were excluded in the data analysis. As a result, the sample size included the rest of the 20 participants (mean age (± SD): 24.1 (± 2.74) years, 11 female). This study was approved by the Human Participants Review Subcommittee of York University's Ethics Review Board (#e2019-367), and all participants signed a written informed consent prior to their participation in this study.

2.2 Experimental procedure

During each trial, participants were asked to stand barefoot on a custom-built rotating platform with arms resting naturally by their side while facing forward (Figure 1A). The platform rotated upwards (UP) or downwards (DW) 3° at 1°/s which was controlled by custom written software written in Spike 2 (Cambridge Electronic Design, Cambridge, England). To ensure the participants were safe while standing on the tilting platform, all participants had to wear a safety harness that was securely hooked to the ceiling during all conditions, and a spotter stood behind the participants to assist in case they fell off the platform.

In a pervious study we tested the comparative effects of different visual stimuli including the effect of a dots vs tunnel scene (Hamam & Cleworth, 2023). We found that the dots stimulus was most effective at inducing direction-modulated postural sway as evidenced by an increase in Head and COP mean position (Hamam & Cleworth, ISPGR 2023). That same custom-built random dot pattern visual stimulus scene which was coded using Vizard python programming (Worldviz, Santa Barbara, California, USA), was used in this study and displayed to the participants through a VR head-mounted display (HMD) (VIVE Pro 2, HTC Corporation) (Figure 1A) The scene rotated in the pitch direction either UP or DW at 60°/s for 30 seconds to create the illusion of CV. The HMD exposed Through the HMD; participants were exposed to a VR environment with a 110° field of view.

Participants were asked to face forwards and keep their feet in place while standing quietly on the platform, and to focus on the scene within the virtual environment for the duration of each of the seven experimental trials. While standing upright on the platform for 30s, participants were exposed to A) the visual scene rotating UP or DW at 60°/s (Figure 2), B) the platform rotating at 15 seconds 3° UP or DW at 1°/s (Figure 3), C) a combination of both the visual scene and platform rotating, D) or neither rotating. During conditions B & C, participants were asked to perform the SPH task. The CV scene rotated for the whole 30 seconds during the visual scene only and the combined visual scene and platform rotation trials. The platform was stationary during the first 15 seconds of each trial, but it rotated for 3 seconds and then was controlled for the last 15 seconds during the platform only rotation and combined trials. The four experimental trials make up a total of seven different conditions that the participants underwent in a pseudorandom order. Participants were given the option to take a break between trials whenever needed, however all participants were asked to take a break after the second set of trials.

2.3 Data collection and processing:

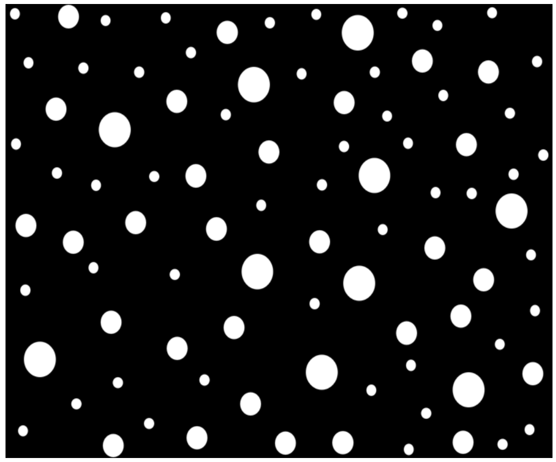
The primary outcome measure to assess balance behaviour for each trial was kinematic data. Pitch angular displacement of the head, trunk, thigh, and platform were calculated from 3D data obtained by a motion analysis system that samples light emitting body markers at 100 Hz (Optotrak, NDI). The markers were placed bilaterally on the zygomatic, mastoid, the acromion processes of the trunk, greater trochanter, lateral epicondyle of femur, fibular head, lateral malleolus of ankle, 5th metatarsal, and two on the platform (Figure2). The angles were bias corrected in the pitch plane by subtracting each data point from the initial value at the beginning of each recording. Trials were removed from further analysis if the markers were out of view for longer than 0.5s.

Segmental angular displacements were calculated over three main time intervals: Pre-tilt, Post-tilt, and Post-SPH (Figure 3). From 13.5-15 seconds, before the beginning of the SPH task, was defined as the pre-tilt window, the time interval from which the effect of CV on body lean before platform rotation was assessed. The time interval of 18-18.5s, after the SPH task started, was defined as the post-tilt window, the time interval from which the effect of the platform rotation om body lean was assessed. Lastly, 27.5 to 30 seconds was defined as the post-SPH window, the time interval from which the effect of CV and platform rotation on the position of the body was assessed. The resulting measures from each of the time interval windows were averaged for each participant within each condition across the trials to compare the three window intervals and the effect of direction.

2.3.1 Data analysis:

Following data collection and checking that the variables are normally distributed, 2x3 repeated measures analysis of variance (ANOVA) tests were conducted to compare the effect of the different conditions (CV, platform tilt, CV and platform tilt) and direction (UP and DW) forthe mean of the absolute angle displacements . Shapiro-Wilk tests, histograms, and log transformations were used to evaluate normality and were applied where assumptions of normality were violated. Outliers were detected using Z-scores, where a z-score of greater or less than 3 indicated the presence of an outlier. To confirm whether these values were true outliers and to identify if this data represents a normal standing behaviour, the time series data was plotted in MATLAB (Mathworks, USA). All outlying values were replaced with 3 standard deviations from the mean (Field, 2009). Greenhouse-Geisser corrections were used to adjust the sphericity of the data if did not meet Mauchley's test of sphericity. An α-level of 0.05 was set as a statistical significance. Lastly, the significance of the differences between the conditions were analyzed using post-hoc parametric analysis, and Bonferroni corrections were used to correct for multiple comparisons.

(A)



(B)

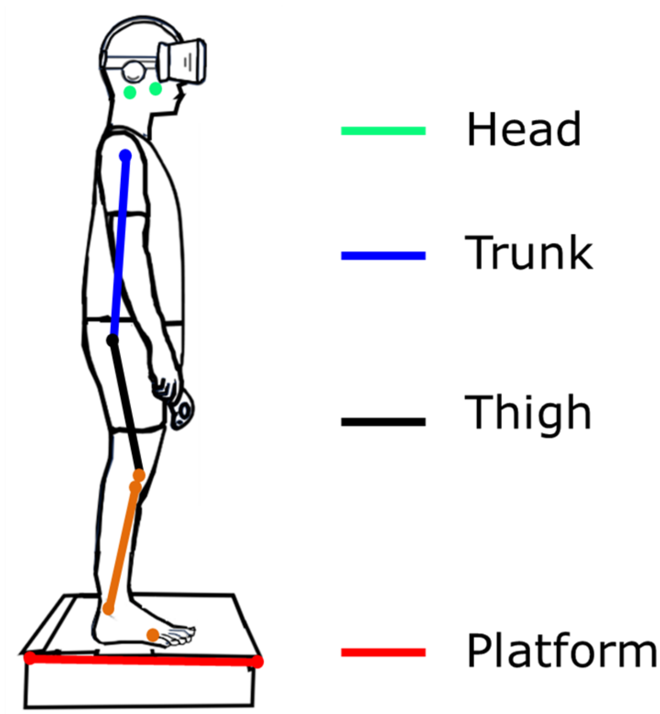


Figure 1. Experimental setup

(A) Participants' view inside the virtual environment; **(B)** Participant standing on the tilting platform while wearing the VR HMD. Each color represents the landmarks of the light emitting body markers that were placed on each segment to calculate segmental angular displacements.

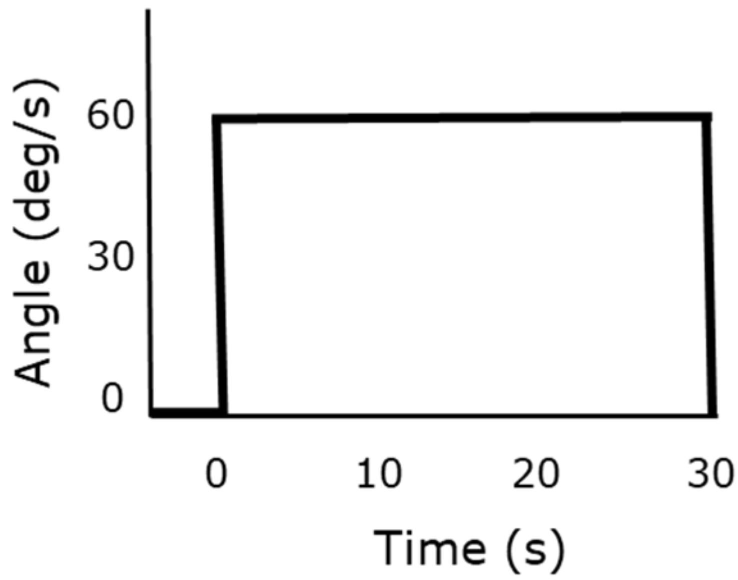


Figure 2: Visual scene setup, rotating UP or DW at 60°/s for the entire 30s trials.

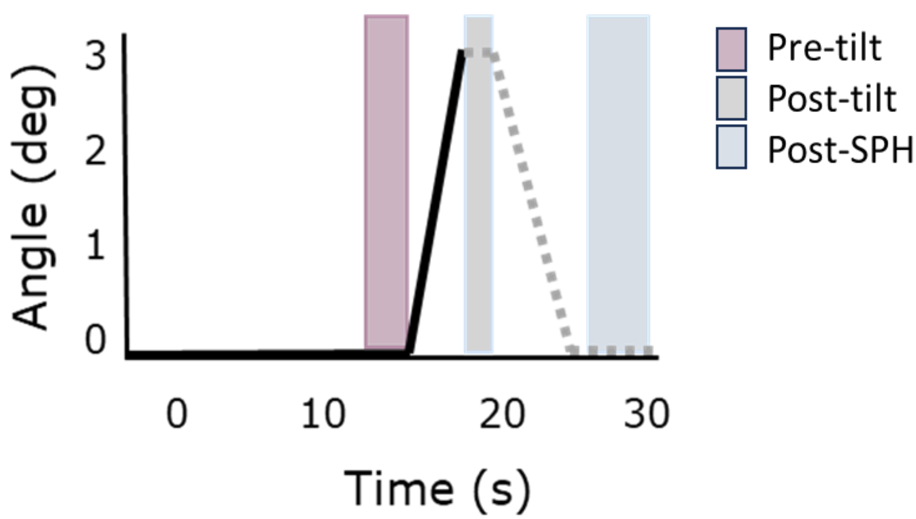


Figure 3: Platform setup, rotating at 15s 3° UP or DW at 1°/s. The dotted line represents the platform position corrected by the subject. The colored bars represent the three-time interval windows. The pretilt window right before the platform tilted is highlighted in purple, post-tilt window is highlighted in grey, and post-SPH window after platform was leveled at SPH is highlighted in light blue.

Chapter 3: Results

3.1 General results

Body lean was significantly affected by the visual scene and platform perturbations. Looking at the effects these perturbations had on specific body segments, it was demonstrated the position of the body and the SPH of the platform were significantly affected as shown by the increased angular displacements. Moreover, a further increase in body lean was demonstrated when visual and platform rotations were combined. The following sections will discuss in more detail the effects of these visual and platform rotations on specific segments and their responses during the three-time interval windows.

3.2 Pre-tilt Effects on Body Lean:

Prior to platform movement, CV had a significant effect on body lean during the pre-tilt window. The body lean was biased by CV in both directions and resulted in a lean in the same direction as the visual scene rotation (Figures 4 & 7). The biased body position varied for each of the body segments throughout each condition (Figure 8).

Head

There was a main effect of condition on head displacement, where the platform only (PO) condition was significantly less than CV and combined conditions (p's <0.001; Table 1). There was no difference between CV and combined conditions. However, there was a main effect of direction on head displacement, where the head displaced more in the DW compared to rotations (p= 0.009; Table 1, Figure 8). There was no interaction between condition and direction for head displacement (p=0.120; Table 1).

Trunk

There was a significant condition by direction interaction for the trunk displacement (p=0.034; Table, Figure 8). Independent of direction, PO was significantly less than CV and combined conditions, yet there was no difference between CV and combined conditions (Table 1). Furthermore, the DW conditions were larger than the UP conditions during CV and combined conditions only (Table 1, Figure 8). There was no difference between DW and UP for PO conditions (p=0.292; Table 1).

Thigh

There was a main effect of condition on thigh displacement, where the PO condition was significantly less than CV and combined conditions (p's <0.009; Table 1, Figure 8). In addition to that, there was no difference between CV and combined conditions (p=1; Table 1). There was no main effect of direction or interaction between condition and direction for thigh displacement (Table 1).

Platform

There was a main effect of condition on platform displacement, where the PO condition was significantly less than CV and combined conditions (p's<0.018; Table 1, Figure 8). However, there was no difference between CV and combined conditions (p=0.923; Table 1). Similar to the thigh, there was no main effect of direction or interaction between condition and direction for platform displacement (Table 1).

In summary, CV had a significant effect on body lean notably when the participants were exposed to CV in the DW direction (Figure 6). The distribution of the body lean across all segments varied with the greatest body lean exhibited by the head, followed by the trunk, and the least for the thigh (Figures 7 & 10, Table 1). Moreover, body lean increased during the first 10 seconds of the CV only trials (Figure 6). The strong effect of dynamic CV perturbations on body responses was observed through the significant difference between the PO and CV only trials, and the trials where the platform was stationary to that of the combined trials.

3.3 Post-tilt Effects on Body Lean:

The significant effects of platform rotation on body position were demonstrated during the post-tilt window. Body lean was further increased when the CV and platform rotations were combined and greater than the body lean that was induced by PO and CV only conditions (Figure 7 & 10).

Head

There was a significant condition by direction interaction for the head displacement ($p<0.001$; Table 2). Independent of direction, CV and PO conditions were significantly less than combined condition, yet there was no difference between CV and PO conditions ($p=1$; Table 2). Furthermore, the DW conditions were larger than the UP conditions during CV, PO, and combined conditions (Table 2, Figure 8).

Trunk

There was a significant condition by direction interaction for the trunk displacement ($p<0.001$; Table2). Independent of direction, PO and CV conditions were significantly less than the combined condition (Table 2, Figure 8). In addition to that, there was a difference between CV and PO conditions ($p=0.005$; Table 2). Furthermore, the DW conditions were larger than the UP conditions during CV, PO, and combined conditions (Table 2, Figure 8).

Thigh

There was a significant condition by direction interaction for the thigh displacement ($p<0.001$; Table2). Independent of direction, PO and CV conditions were significantly less than combined condition (Table 2). There was also a difference between CV and PO conditions ($p<0.001$; Table 2). Furthermore, the UP conditions were larger than the DW conditions during combined conditions only (Table 2, Figure 8).

Platform

There was a significant condition by direction interaction for the platform displacement ($p<0.001$; Table2). Independent of direction, PO and CV conditions were less than the combined condition (Table 2). Moreover, there was a difference between CV and PO conditions ($p<0.001$; Table 2). Furthermore, the DW conditions were larger than the UP conditions during PO, and combined conditions (Table 2, Figure 8).

In summary, a similar effect of CV to that of the pre-tilt window was induced on body lean during the CV only trials (Figure 6). During PO trials, participants leaned in the direction of the platform rotation (Figure 5). When CV and platform rotations were combined, this resulted in a further displacement in each of the segments (Figure 8). Rotations in the DW directions resulted in the greatest displacement of the head, in contrast to UP rotations which led to the greatest displacements in the thigh, followed by the trunk, and least displacement for the head.

3.4 Post-SPH Effects on Body Lean:

The post-SPH window when the participants brought back the platform to where they perceived as the horizontal, demonstrated the influence of CV on the SPH. The effect of CV on body lean was still evident during this window. Participants leaned in the same direction as the stimulus rotation (Figure 6).

Head

There was a main effect of condition on head displacement, where the PO condition was significantly less than CV and combined conditions (p's <0.001; Table 3, Figure 8). There was also a significant difference between CV and combined conditions, with higher head displacements during the CV only conditions compared to the PO conditions (Table 3). Furthermore, there was a main effect of direction on head displacement, where the head displaced more during CV and combined DW rotations compared to UP rotations (p= 0.032; Table 3). There was no difference between DW and UP for PO conditions (Table 3). In addition to that, no interaction between condition and direction for head displacement was shown (p=0.092; Table 3).

Trunk

There was a significant condition by direction interaction for the trunk displacement (p<0.011; Table3). Independent of direction, PO and CV conditions were significantly less than combined condition, however there was no difference between CV and combined conditions (p=0.062; Table 3). Moreover, there was a main effect of direction on trunk displacement, where the trunk displaced more during CV and combined DW rotations compared to the UP rotations (Table 3, Figures 8 & 10). On the other hand, there was no difference between DW and UP for PO conditions (Table 3).

Thigh

There was a main effect of condition on thigh displacement, where the PO condition was significantly less than CV and combined conditions (p's <0.001; Table 3, Figure 8). No main difference between CV and combined conditions was shown (p=0.013; Table 3). On the other hand, there was no difference between CV and PO conditions (p=0.084; Table 3), and no main effect of direction on thigh displacement (p= 0.456; Table 3). Moreover, no significant interaction between condition and direction for thigh displacement was shown (p=0.168; Table 3).

Platform

There was a main effect of condition on platform displacement, where the PO and CV conditions were significantly less than the combined condition (p's<0.001; Table 3). There was a difference between CV and PO conditions (p<0.001; Table 3). Moreover, there was no main effect of direction or interaction between condition and direction for platform displacement (p=0.361; Table 3).

In summary, CV had a significant effect on body lean and orientation. Figures 8 and 10 show the body lean at the end after the participants returned the platform to their perceived horizontal. During the combined trials, there was an increase in head and trunk during the DW rotations, and an increase in thigh and platform displacements during the UP rotations compared to that induced by PO and CV only conditions (Figure 7 and 10). The platform position during the combined condition was greater and significantly different than the PO condition (Figure 8, Table 3). Participants returned the platform to their perceived horizontal position and body position was corrected to near horizontal position in the UP condition when compared to the DW condition (Figure 7). Moreover, there was a difference between the observed body position at 13.5-15 seconds and that at 27.5-30 seconds which illustrates a significant difference in SPH values compared to the PO condition (Table 1 &2).

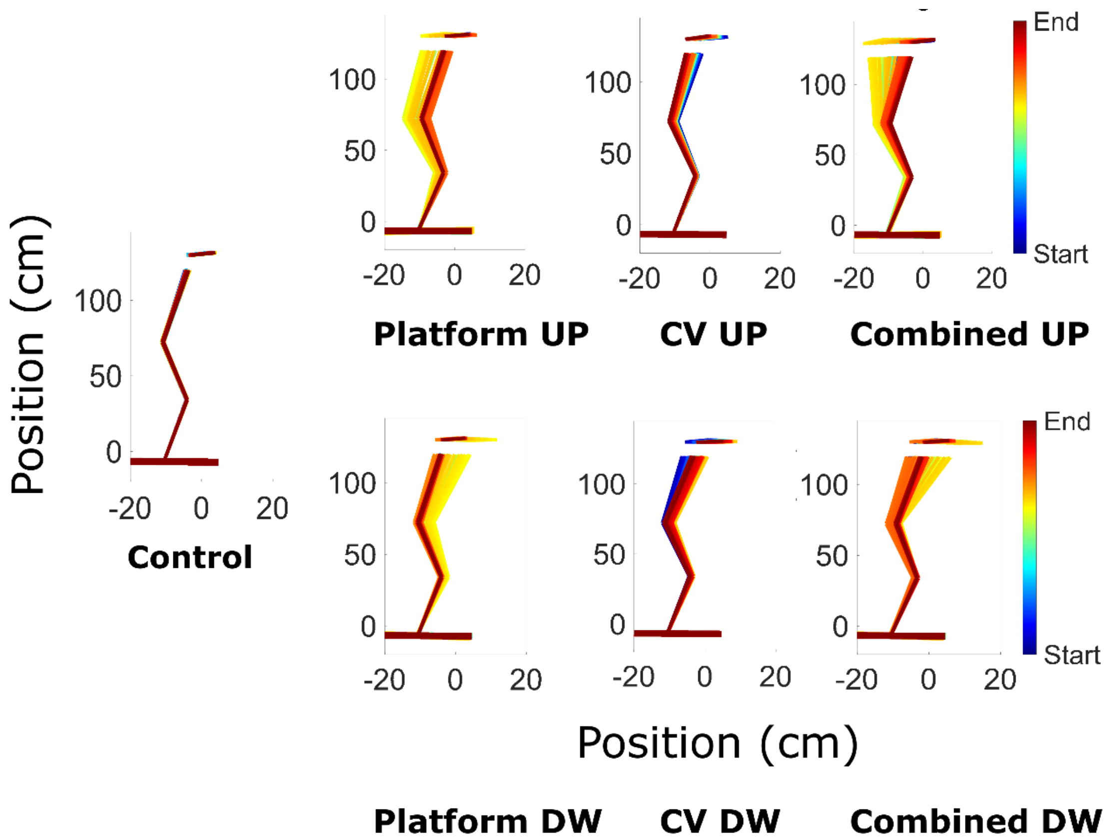


Figure 4: Illustration of the effect of CV on Body motion across all seven conditions. Stick figures show the typical subject response in position (cm)of the head, trunk, thigh, and platform displacements from start (blue) to end (red).

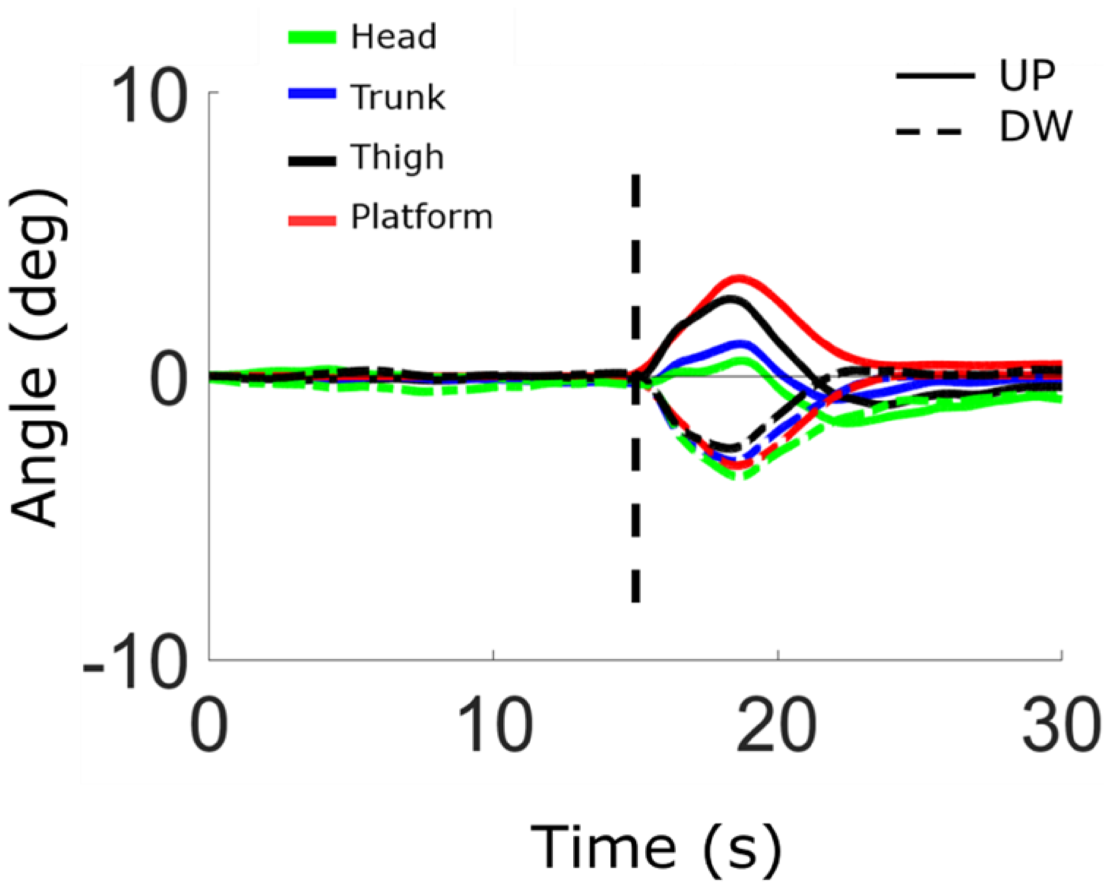


Figure 5: The Independent Effect of Platform Only Condition. This figure shows the Angle (degrees) displacement of the head (green), trunk (blue), pelvis (black), and platform (red) in both UP (solid line) and DW direction (dashed line) over Time (s). The vertical line represents the time (15 seconds) at which the platform started tilting.

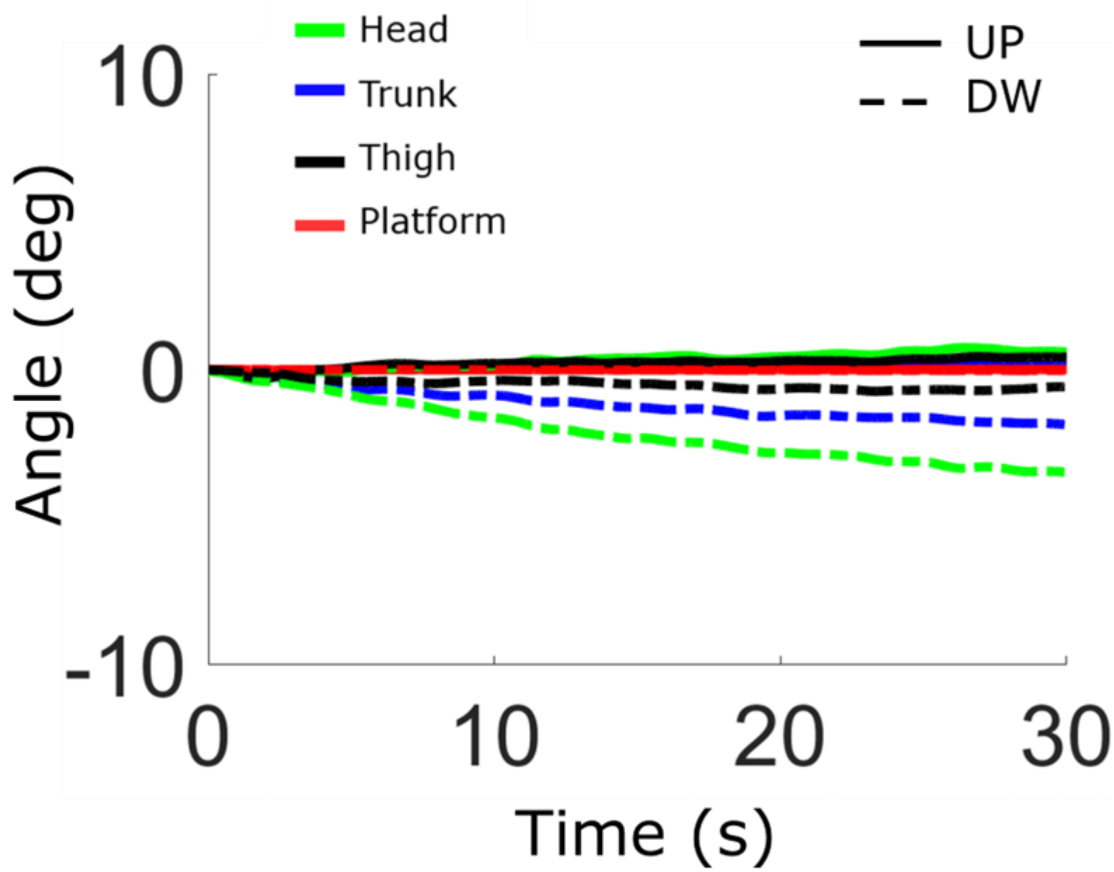


Figure 6: The Independent Effect of CV Only Condition. This figure shows the Angle (degrees) displacement of the head (green), trunk (blue), pelvis (black), and platform (red) in both UP (solid line) and DW direction (dashed line) over time (s).

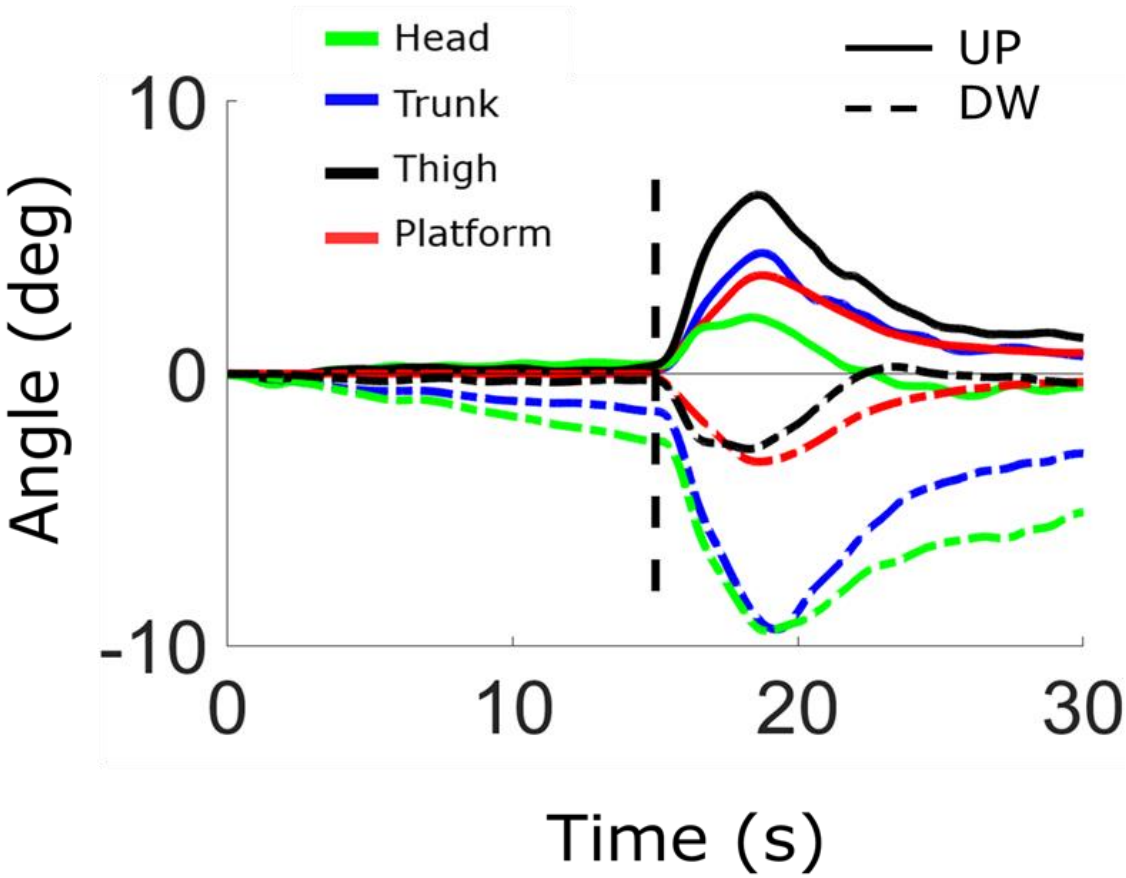


Figure 7: The Combined Effect of CV and SPH. This figure shows the Angle (degrees) displacement of the head (green), trunk (blue), pelvis (black), and platform (red) in both UP (solid line) and DW direction (dashed line) over time (s). The vertical line represents the time (15 seconds) at which the platform started tilting.

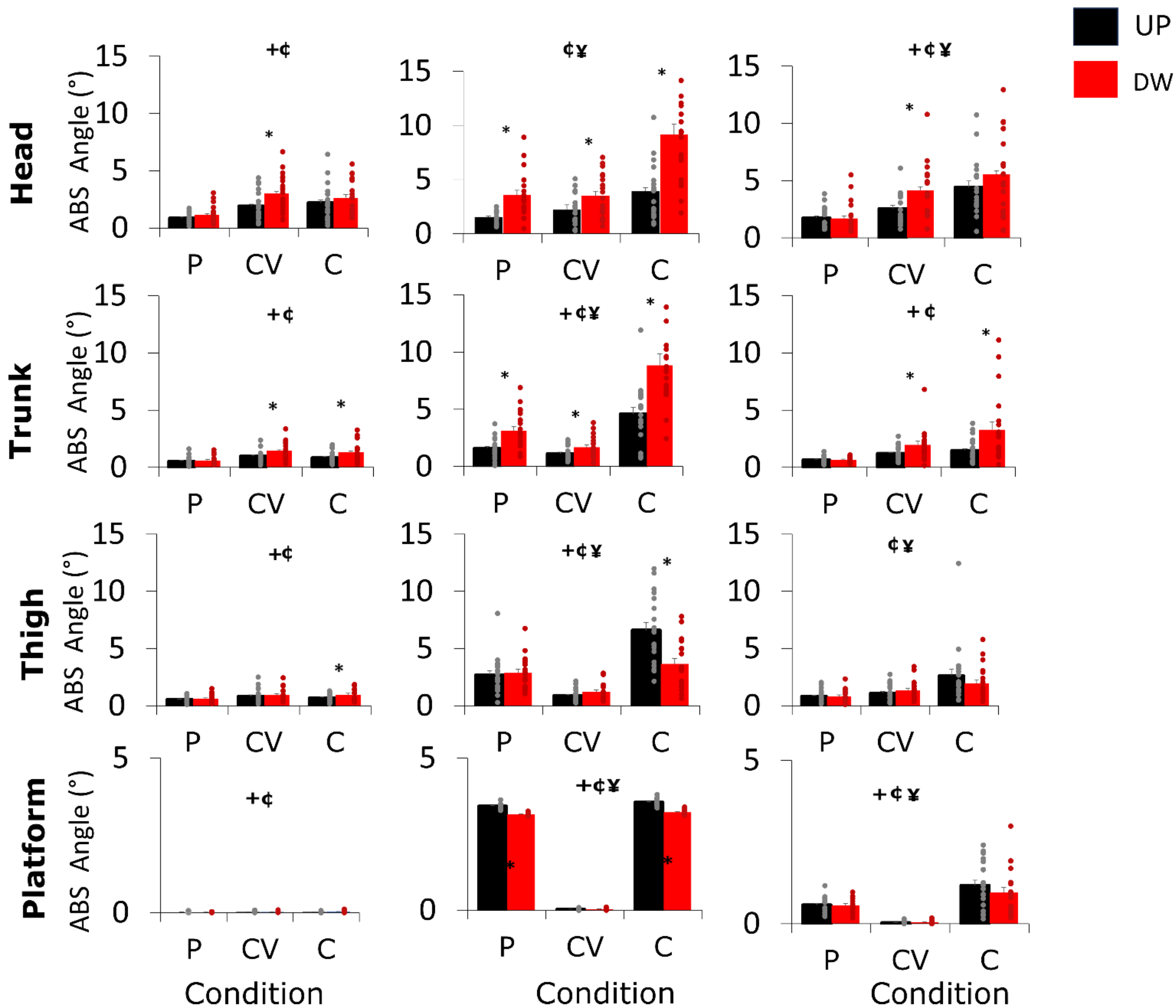


Figure 8: Population average responses during pre-tilt (on the left), post-tilt (middle), and post-SPH (on the right) time interval windows of each of the three conditions; platform only (P), circular vection only (CV), and combined (C) conditions in both upwards (UP) condition in black and downwards (DW) condition in red. The dots represent the individual data in UP condition in grey and DW condition in red. The mean of the absolute angles (°) displacements is represented by the height of the columns, and the vertical bars on the columns represent the standard error of the mean (SEM). The * indicates UP & DW are different; + P different than CV; ¥ CV different than C; and ¢ P different than C.

Table 1. Angle displacements (mean ± sem) of the three body segments and platform at the pre-tilt time interval window (13.5-15s) for the 3 conditions. Column 8 lists the results from the RM-ANOVA (main effect of condition only), probability (p) and F values for the significance of the main effects. Column 9 lists the results from the RM-ANOVA (main effect of direction only), and column 10 lists the main effect of condition by direction interaction. The displayed degrees of freedom values were corrected using the Greenhouse-Giesser method and rounded to the nearest integer. Significant results are highlighted with bold font.

Time 13.5-15s	Platform Only Up	Platform Only Down	CV Up	CV Down	Combined Up	Combined Down	Condition	Direction	Condition* Direction
Head	0.86 ±0.85	1.13 ±0.27	1.91 ±0.32	3.01 ±0.28	2.19 ±0.35	2.64 ±0.26	**p<0.001** F(2,36)=22.15	**p=0.009** F(1,19)=8.34	p=0.120 F(2,33)=2.25
Trunk	0.52 ±0.30	0.61 ±0.21	0.97 ±0.24	1.44 ±0.21	0.83 ±0.25	1.32 ±0.28	**p<0.001** F(2,35)=19.11	**p=0.003** F(1,19)=11.30	**p=0.034** F(2,32)=3.71
Thigh	0.52 ±0.23	0.60 ±0.25	0.82 ±0.28	0.94 ±0.30	0.69 ±0.23	0.96 ±0.25	**p<0.001** F(2,34)=18.54	p=0.068 F(1,19)=3.74	p=0.590 F(2,32)=0.54
Platform	0.01 ±0.52	0.01 ±0.45	0.02 ±0.38	0.02 ±0.29	0.02 ±0.40	0.03 ±0.37	**p=0.002** F(2,34)=12.40	p=0.661 F(1,19)=0.20	p=0.216 F(2, 36)=1.60

Table 2. Angle displacements (mean ± sem) of the three body segments and platform at the post-tilt time interval window (18-18.5s) for the 3 conditions. Column 8 lists the results from the RM-ANOVA (main effect of condition only), probability (p) and F values for the significance of the main effects. Column 9 lists the results from the RM-ANOVA (main effect of direction only), and column 10 lists the main effect of condition by direction interaction. The displayed degrees of freedom values were corrected using the Greenhouse-Giesser method and rounded to the nearest integer. Significant results are highlighted with bold font**.**

Time 18-18.5s	**Platform Only Up**	**Platform Only Down**	**CV Up**	**CV Down**	**Combined Up**	**Combined Down**	**Condition**	**Direction**	**Condition* Direction**
Head	1.53 ±0.16	3.56 ±0.27	2.21 ±0.33	3.48 ±0.27	3.92 ±0.28	9.16 ±0.24	**p=<0.001** F(2, 31)=21.55	**p<0.001** F(1,19)=20.47	**p<0.001** F(1,24)=19.59
Trunk	1.56 ±0.36	3.11 ±0.49	1.11 ±0.27	1.67 ±0.34	4.58 ±0.64	8.83 ±0.66	**p<0.001** F(1,24)=18.15	**p<0.001** F(1,19)=14.25	**p<0.001** F(1,23)=16.35
Thigh	2.69 ±0.46	2.87 ±0.38	0.89 ±0.26	1.21 ±0.30	6.60 ±0.56	3.65 ±0.55	**p<0.001** F(1,27)=14.24	**p=0.049** F(1,19)=4.41	**p<0.001** F(2,29)=17.59
Platform	3.42 ±0.01	3.16 ±0.01	0.02 ±0.44	0.03 ±0.32	3.54 ±0.01	3.22 ±0.01	**p<0.001** F(2,33)=15.48	**p<0.001** F(1,19)=14.56	**p<0.001** F(2,30)=16.03

Table 3. Angle displacements (mean ± sem) of the three body segments and platform at the post-SPH time interval window (27.5-30s) for the 3 conditions. Column 8 lists the results from the RM-ANOVA (main effect of condition only), probability (p) and F values for the significance of the main effects. Columns 9 lists the results from the RM-ANOVA (main effect of direction only), and column 10 lists the main effect of condition by direction interaction. The displayed degrees of freedom values were corrected using the Greenhouse-Giesser method and rounded to the nearest integer. Significant results are highlighted with bold font.

Time 27.5-30s	**Platform Only Up**	**Platform Only Down**	**CV Up**	**CV Down**	**Combined Up**	**Combined Down**	**Condition**	**Direction**	**Condition* Direction**
Head	1.72 ±0.22	1.70 ±0.28	2.55 ±0.22	4.17 ±0.26	4.42 ±0.27	5.57 ±0.36	**p<0.001** F(2,31)=20.55	**p=0.032** F(1,19)=5.38	P=0.092 F(1,26)=2.54
Trunk	0.65 ±0.17	0.66 ±0.14	1.21 ±0.26	1.96 ±0.42	1.48 ±0.40	3.29 ±0.73	**p<0.001** F(1,23)=15.53	**p=0.004** F(1,19)=10.98	**p=0.011** F(1,27)=5.13
Thigh	0.80 ±0.29	0.83 ±0.27	1.10 ±0.34	1.33 ±0.25	2.61 ±0.31	1.94 ±0.33	**p<0.001** F(1,24)=11.89	p=0.456 F(1,19)=0.58	p=0.168 F(1,23)=1.87
Platform	0.57 ±0.19	0.56 ±0.21	0.03 ±0.44	0.04 ±0.33	1.17 ±0.33	0.95 ±0.33	**p<0.001** F(1,23)=15.27	p=0.361 F(1,19)=0.88	p=0.359 F(1,22)=1.05

Chapter 4: Discussion:

4.1 Overview

The main objective of this study was to examine the effect of dynamic CV rotations on the postural responses and the SPH of the platform. The body leaned in the same direction as the CV stimulus and pitch angular displacement notably increased when the participants were exposed to CV in the DW direction. Figure 6 illustrates the body lean distribution across specific segments, with the greatest body lean exhibited by the head, followed by the trunk, and the least was for the thigh. Moreover, body lean increased during the first 10 seconds of the CV only trials, but then remained constant for the last 20 seconds of the trials (Figure 6). During combined conditions, when both CV stimulus and the platform rotated in the DW direction, upper-body tilt responded in a "proximal-distal" postural control as the head had the largest angle displacement when compared to the smaller angle displacement in the thigh. However, during UP combined rotations, the thigh had the greatest angle displacement followed by the trunk, and least for the head demonstrating more of a "distal-proximal postural control. The strong influence of CV rotations on postural responses was demonstrated during PO versus CV only trials. CV induced a further displacement of the segments in response to the platform rotation (Figure 7). Overall, these results demonstrate how dynamic visual perturbations can significantly affect body response and orientation.

4.2 Direction Modulated Postural Sway

Postural sway is usually classified into two main types including forward and backward sway (Chen et al., 2014; Horiuchi et al., 2021). Previous literature of vection studies reported that the motion of a visual stimulus induces motion in the same direction as the rotation of the stimulus (Tanahashi et al., 2007, Van Asten et al., 1988, Guerraz et al., 2001). The results in this study were consistent with previous reports as the body lean was biased by both CV UP and DW perturbations and resulted in a lean in the same direction as the visual scene rotation. Several studies have tried to understand this postural lean when exposed to a visual perturbation, and found that when the participant experiences vection, their weighting of the sensory information is altered in an attempt to resolve the sensory conflict and maintain balance control (Tossavainen et al., 2006). The reaction is to usually lean in the same direction of the motion as the participant tries to compensate for this illusion of self-motion that is in the opposite direction in order to maintain balance (Tossavainen et al., 2006; Kirollos et al., 2019).

During this study, significant differences between forward and backward sway were observed which raises questions about the biomechanical constraint during postural control. To gain a better understanding of the mechanisms that underly these biomechanical constraints, the differences between these two sway types have been broadly investigated, and fundamental differences between different types of self-motion have been demonstrated (Young et al., 1975, Frigon et al., 1992; Geurraz et al., 2008). Through self-rotation caused by CV in the roll and pitch planes, these visual perturbations usually result in a sensation of a tilt with a smaller tilt component during the pitch CV compared to that of CV in the roll plane (Young et al., 1975, Watt et al., 1990). When exposed to pitch CV, DW rotations result in a forward self-rotation, and a backwards lean when exposed to UP scene rotation (Fushiki et al., 2000). Our results are consistent with these reports as the participants leaned backwards during pitch UP rotations and forward during DW rotations of the scene. However, our results demonstrate that DW rotations had a stronger effect on body lean compared to CV UP as shown by the larger displacements of the head and trunk angles. This effect has been demonstrated during pitch forward compared to backwards sensation of tilting (Young et al., 1975; Vidal et al., 2006). The observed differences might be attributed to biomechanical constraints as it has been shown that the effect of CV perturbations is strongly dependent on the position of the head and the effect decreases for the head when it is pitched 25° forward (Young et al., 1975). The pitch stimulus was shown to produce a tilting sensation for a steady pitch angle, and it was stronger when rotating in pitch forward (Young et al., 1975; Vidal et al., 2006).

During platform rotations, the body responds to minimize the COM displacement and restore the posture's stability (Chen et al., 2014; Szturm et al., 1998). These rotations result in a rotation of the ankle joint and induce a body lean in the anterior direction during toes down rotations (Szturm et al., 1998). On the other hand, toes up rotations result in a body lean in the posterior direction (Szturm et al., 1998). Similar results were found in this study as the participants leaned in the same direction as the platform rotation. Moreover, the head, trunk, and thigh displaced more during platform DW rotations compared to platform UP rotations during post-tilt (Table 2). The reported differences between forward and backward postural lean might also be due to the limits of postural stability and the maximum angle to tilt at before completely losing balance (Huo et al., 2000). When standing upright, the center of the foot pressure is positioned in a way where it corresponds to 0% of the BOS at the heel edge, and 100% at the toe edge (Chen et al., 2014; Jonsson et al., 2003). This limited base of support in the backward direction explains why people often experience less stability when leaning in the backward direction compared to the forward direction (Chen et al., 2014; Jonsson et al., 2003). In summary, it is important to gain a deeper understanding of the differences between forward and backward sway to improve our understanding of the dynamic visual stimuli effects and the resulting postural control strategies.

4.3 Visual vs. Vestibular Systems:

Previous literature of vection has shown conflicting results when comparing the visually induced vection and the resulting postural sway (Previc et al., 1992; Tanahashi et al., 2007). Studies have tested postural sway during both stable and unstable support surfaces. It has been demonstrated that postural sway on stable surfaces and sway induced by vection are shared by a central mechanism (Tanahashi et al. 2007). On the other hand, studies with unstable surfaces such as a moving platform have shown that the instability in postural control was in the opposite direction of the visually induced postural sway (Keshner et al. 2004). Recent vection studies on the illusion of self-motion have shown that both visual and vestibular systems inputs interact in a shared area of the brain stem (Brandt et al. 2002; DeAngelis et al.,2012). The results of this study provide insight into the integration of the visual and vestibular systems during CV and postural orientation tests. The visually induced self-motion is believed to be a result of interaction between the inputs of both the visual and vestibular systems (Wang et al., 2010, DeAngelis et al., 2012). In this study, during the pretilt window when the platform was stable, CV induced a robust effect on postural sway and participants leaned in the direction of the visual stimuli rotations. The combination of CV and platform rotations resulted in an increased displacement of the body lean. Participants were able to return the positions of the body and platform closer to zero during PO condition, in contrast to the combined condition where the body position was off zero to a greater degree (Table 3, Figure 8). During combined DW rotations, participants compensated by a response that showed a significant overshoot of their original horizontal position (Figure 7).

The relationship between visually induced vection and the sensory conflict has been examined through various studies. This conflict is the result of a mismatch between what one of the sensory systems senses compared to that sensed by the other systems (Wright, 2009). Vection is one example of this conflict as the visual system senses this visually induced motion while the vestibular system does not (Kirollos et al., 2019). One of the main vestibular system organs, the otolith organs, are responsible for detecting motion that is in line with the acceleration of gravity. Therefore, when exposed to a visual stimulus rotating UP and DW during an upright balance task, this rotation is in line with the gravity's acceleration and hence is detected by the otolith organs (Kirollos et al., 2019). This results in a weaker conflict between the visual and vestibular systems (Giannopulu et al.,1998; Kirollos et al., 2019). During CV only trials, participants postural lean was mainly based on the visual scene rotation. This demonstrated the strong effect of vection when there is a weaker conflict between the visual and vestibular systems (Kirollos et al, 2019). However, it has been demonstrated that vection could have a stronger effect when the visual and vestibular systems are in conflict (Palmisano et al., 2000, Kirollos et al., 2019). The results in this study demonstrated this effect as the combined UP and DW perturbations resulted in greater displacements of the head, trunk, and thigh compared to the pre-tilt window where there was no conflict between the visual and vestibular systems (Table 2). Moreover, it has been shown that when the base of support is not referenced to the earth, this results in weighting the dynamics of the visual field more when identifying the orientation in space (Guerraz et al., 2001). The bias of CV on the direction of body lean implies that the identification of horizontal orientation is affected by the visual information. Therefore, individuals may rely more on their visual system inputs when faced with visually induced self-motion during a postural orientation task (Gaerlan et al., 2010). In addition to that, vection may have a stronger effect when there is a conflict between the visual and vestibular systems as demonstrated in previous literature and by the results of this study. This complex interplay between both visual and vestibular systems in postural control warrants further investigation to better understand the mechanisms that underly these interactions and the body responses during a postural orientation task.

4.4 Limitations and Recommendations for future research

Although the findings of his study have shown some valuable insights, this study has several limitations that need to be acknowledged. One limitation in this study is the group of participants that were recruited. This group is not representative of the whole population as the participants were healthy young adults that had no neurological or vestibular impairments. Including a more diverse group is vital for more generalizable results to older age groups and those with balance related challenges and impairments such as otolith deficits. Additionally, the study only included conditions when CV and platform rotations were congruent. Studies investigating the effect of visual perturbations in the roll direction and platform perturbations in the opposite direction, found reduced responses and a bimodal response effect by the lower body (Cleworth et al., 2023). Considering the differences between pitch and roll CV, testing this study with incongruent conditions could offer further insights into the effects of CV on postural orientation tests. Finally, future studies could also test the effect of different pitch CV speeds during SPH tests. A range of rotation speeds from 0 to 360 deg/s were tested for each of the roll, pitch, and yaw axes (Ujike et al., 2004). It was demonstrated that the highest vection score was around 30 to 60 deg/s. It was also shown that veciton and motion sickness scores were highest during the roll rotations, second for the pitch rotations, and the least for the rotations in the yaw axis (Ujike et al., 2004). One of the limitations of vection studies is the visually induced motion sickness (VIMS) which is similar to motion sickness (Cha et al., 2021). It has been demonstrated that a strong conflict between the visual and vestibular systems enhances VIMS (Keshavarz et al., 2015). Even though no VIMS was reported during this study, considering the complex relationship between vection and this sickness, and the conflict between the visual and vestibular systems during postural orientation tests, is important to consider in future pitch CV and SPH studies to reduce the likelihood of inducing VIMS while still causing sensations of motion.

4.5 Clinical Applications:

The findings of this study have important clinical applications. Continuous perturbations of the visual environment through CV in the pitch direction, and orientation tests such as the SPH are great tools for assessing the function of the visual and vestibular systems (Beule and Allum, 2006). These perturbations can also be used to assess the visual function and sensory integrations in populations at high risk of falls particularly older adults, and those with vestibular deficits such as otolith impairments who have shown to have an increased reliance on vision (Tossavainen et al., 2006). Studies with CV perturbations are also great methods for better understanding how the sensory systems process visually induced motions (Kirollos et al., 2019). For example, a study by Palmisano et al. (2015) found that vection can be used to control one's motion which is crucial when spatially orienting themselves in space (Keshavarz et al., 2017).

Moreover, visual perturbations through VR and platform rotations are effective tools that could help clinicians assess patients with vestibular deficiency (Tossavainen et al., 2006). For instance, the effects of visual and platform rotations were tested on patients with a vestibular deficit in a study by Black et al (1983). They found that under visual control conditions, those with compensated and uncompensated vestibular function loss responded normally to postural perturbations (Black et al., 1983). However, when both surrounding visual and platform were perturbated, all of the participants responded with an abnormal postural control response (Black et al., 1983. The results showed that these patients were dependent on their vestibular inputs but when they became unstable whenever they were asked to rely on cues coming from the vestibular system or were forced to select between the cues coming from the visual and vestibular system (Black et al., 1983; Tossavainen et al., 2006). This conflict was resolved as they favored the inputs from the visual system (Tossavainen et al., 2006, Black et al., 1983). Therefore, through these assessments, researchers and clinicians can identify patients with vestibular loss that have an increased reliance on vision, and can create interventions that are targeted towards specific populations with a better understanding of their sensory inputs and postural responses.

4.6 Conclusions:

In conclusion, the effect of applying additional dynamic visual perturbations in the form of pitch CV on body responses and the perception of postural orientation were investigated in this study. The role of the inputs provided by the visual and vestibular systems during upright dynamic balancing tasks were also assessed. The main outcomes were the distinct postural responses induced by CV and varying patterns of body lean and angular displacements across different body segments. In addition to that, when CV was combined with the rotating platform, this induced an increase in angular displacements of the body lean, and significantly influenced the perceived horizontal orientation of the platform. Similar to the SPH and CV the roll plane study, the outcomes of this study support the weighted multisensory integration hypothesis as the postural responses and SPH of the platform were both biased by the direction of the visual cues (Cleworth et al., 2023). The SPH test and visual perturbations may also be useful for evaluating vestibular deficiency in clinical patients especially those with deficits in their otolith function. Overall, this thesis contributes to our understanding of the complex integration and role of the visual and vestibular systems during postural orientation tests, and it offers a potential avenue for testing postural orientation and studying balance deficits in clinical populations.

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