

Cybersickness: Linking Postural Control to User Discomfort in a Virtual Roller Coaster

by

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Author's Declaration

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

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Abstract

Cybersickness (CS) remains a major obstacle to the widespread use of Virtual Reality (VR), with leading explanations emphasizing sensory conflict, sensory reweighting, and postural instability. Prior research has shown that individuals who flexibly reweight visual, vestibular, and body cues report lower CS, particularly in interactive VR tasks where users can move freely. Whether this relationship generalizes to more passive, visually intense VR experiences is less clear. This thesis examined sensory cue reweighting and postural control as predictors of CS during an immersive roller coaster simulation. Nineteen younger adults completed the Oriented Character Recognition Task (OCHART) before and after VR exposure to estimate perceptual upright and quantify cue weightings. During VR exposure, postural movement was recorded using markerless motion capture, and participants reported symptoms using the Fast Motion Sickness (FMS) scale after each trial. Contrary to findings from interactive VR contexts, sensory reweighting was not significantly associated with CS in this passive roller coaster environment. In contrast, measures of postural control, particularly total path length, were robust predictors of sickness severity, with greater displacement linked to higher FMS scores. These findings suggest that in visually dominant VR tasks with limited bodily engagement, postural instability provides a more reliable marker of CS than sensory reweighting. This work clarifies that the predictive value of sensory reweighting is context-dependent, emerging more clearly in interactive than passive VR tasks. It further points toward movement-based strategies for mitigating discomfort in VR experiences where movement is restricted but visual conflict is high.

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Chapter 1

Introduction

1.1 Overview

Maintaining a stable perception of the world during head, eye, and body movements is essential for everyday functioning. As we walk, read, or drive, our brain constantly updates signals about orientation, balance, and position so that we can act safely and effectively. Without this stability, even simple tasks would feel confusing and disorienting. The ability to see an object's orientation as constant, even when the viewing angle changes, is called orientation constancy (Day & Wade, 1969; Stiles et al., 2015). This ability is part of many daily experiences—for example, recognizing a tilted book or keeping focus on a moving target.

Orientation constancy arises from the brain's integration of signals from multiple sensory systems. The visual, vestibular, and somatosensory systems each provide information about body position and movement, but these signals do not always agree (Reason, 1978). For example, vision might suggest motion when the body is still, or vestibular signals may conflict with visual signals during head turns. To maintain stability, the brain must compare these signals, decide which are most reliable, and sometimes adjust their importance (Landy et al., 1995).

In most natural settings, this process works well. But in VR, the challenge becomes much greater. VR often delivers strong visual motion cues without matching signals from the body or vestibular system. A roller coaster simulation, for instance, can make the eyes report rapid tilts and accelerations while the inner ear signals that the body is not moving. These mismatches increase sensory conflict and can lead to cybersickness—a form of motion sickness characterized by nausea, dizziness, and disorientation (McCauley & Sharkey, 1992).

For VR to be effective, orientation constancy must be preserved. When it is stable, conflicts between sensory systems are reduced, and users feel more comfortable and immersed. When it breaks down, sensory mismatches grow, making sickness more likely. As VR is increasingly used in areas such as healthcare, education, and entertainment, understanding how orientation constancy is maintained or disrupted in these settings is critical for improving user comfort and system design (Dilanchian et al., 2021; Martingano et al., 2022).

This thesis focuses on orientation constancy within the larger framework of multisensory integration and sensory reweighting. VR provides a unique way to study how the brain resolves conflicts between the senses. By examining how orientation constancy is challenged in VR and how individuals adapt through sensory cue reweighting, this thesis aims to advance both theoretical understanding of perception and practical strategies for mitigating CS.

1.2 Multisensory Integration

In the context of VR, multisensory integration is essential for a smooth, comfortable, and immersive experience, as participants receive rich, simultaneous sensory input that must be integrated to navigate and interact effectively in VR. Multisensory integration refers to the brain's ability to combine multiple sources of sensory signals to acquire more accurate and precise knowledge of a stimulus of interest. The brain combines inputs from different sensory modalities to shape our perception of the environment that we are in, typically from visual, auditory, vestibular, and somatosensory signal inputs (Martin, 2019; Wolfe et al., 2021). For instance, superior colliculus, located on the brainstem, is a station for multisensory integration. The superior colliculus is involved in visual processing and gaze control, but it has also been found to be responsible for auditory, somatosensory stimuli and transform these sensory signals into premotor commands (Stein, et al., 2020). This neural process is crucial for everyday activities like maintaining balance, navigation in the environment, recognizing objects etc. For instance, numerous sensory modalities are unified to form a better understanding of the space when we navigate through a new environment; the visual system scans the space and locates the direction we should be headed; the vestibular system is active constantly to maintain balance while exploring; the auditory system monitors the noise in the environment; and the olfactory system can enhance sensory experience, particularly when distinctive scents are present, and olfaction can enrich spatial experiences by supporting memory through its connections to the hippocampus, a key structure in memory consolidation (Herz, 2016; Wilson & Stevenson, 2003). Together, these systems help us interact seamlessly with our surroundings.

In VR, however, the integration demands are greater. Visual inputs often dominate, while vestibular and somatosensory cues may provide conflicting information. This conflict requires the brain to reweight sensory cues, adjusting the relative importance of each input. When reweighting is successful, perception remains stable and immersion is preserved. When reweighting fails, mismatches between senses grow stronger, often leading to CS. This link between multisensory

integration, cue reweighting, and CS underpins the thesis' focus on quantifying sensory contributions during VR exposure.

1.2.1 Vestibular System

The vestibular system is key to balance control, eye movement, spatial orientation, and the perception of motion. The vestibular system plays a particularly important role in VR (VR), where sensory mismatches between sensory inputs often lead to motion sickness and disrupt immersion. In our experiment, the relevance of the vestibular system lies in its ability to process and integrate sensory information that contributes to orientation constancy and stability in VR environments. The cochlea, located in the inner ear, is involved in auditory processing, while the vestibular organs-the otolith organs and semicircular canals-support balance and spatial orientation. The otolith organs detect linear acceleration, head tilt, and vibrations. Semicircular canals sense rotational movements of the head, the hair cells located in the ampulla decode the axis of rotation and velocity. The hair cells in these structures convert motion into neural signals, which are transmitted to the brain via the vestibulocochlear nerve (cranial nerve VIII). Importantly, this nerve carries both auditory and vestibular information: auditory signals project to the cochlear nuclei, while vestibular signals project to the vestibular nuclei in the brainstem. Thus, although they share a common nerve, the pathways diverge early, reflecting their distinct but complementary roles (Wolfe et al., 2021).

Vestibular signals travel through both ascending and descending pathways, contributing to spatial orientation, balance, and postural control. Once in the brain, vestibular information is processed first in the vestibular nuclei of the brainstem. These nuclei send signals along ascending pathways to the thalamus, insula, posterior parietal cortex, and area 3a, supporting perception of orientation, posture control, and environmental awareness. Descending pathways include the lateral vestibulospinal tract, which helps control posture through axial muscles, and the medial vestibulospinal tract, which stabilizes head and eye position during movement (Wolfe et al., 2021).

Unlike vision, the vestibular system does not project to a single specialized cortical region. Instead, vestibular information is distributed across a network of multimodal regions. From the vestibular nucleus, projections will reach many regions, some will reach the cerebellum, and some will reach the thalamus. A unique feature of vestibular processing is the absence of a dedicated “vestibular cortex; instead, vestibular input is distributed across a network of multisensory brain regions. One of the largest areas of this network is called parietal-insular vestibular cortex (PIVC). The input to this

region is not exclusively vestibular signals, it also receives visual input and position sense receptors from the neck. PIVC is located where the parietal and insular cortex meet. PIVC was shown to receive input from various regions of the brain and has been described as the core region for vestibular signal processing in the cortex (Lopez & Blanke, 2011).

The higher order processing of vestibular signals becomes multisensory very quickly once it reaches the cortex. Even though PIVC is a core vestibular organ in the brain according to Lopez et. al, 2011, many other cortices have detected vestibular responses as well: somatosensory cortex, area MST (Medial superior temporal), intraparietal sulcus, and hippocampus. The widespread and multimodal destinations of the vestibular signals explain the large influence of them on self-motion perception, spatial navigation, internal models of gravity, one's body perception and bodily self-consciousness (Lopez & Blanke, 2011)

Visual processing is closely linked to the vestibular system through reflexes such as the vestibulocochlear reflex (VOR), which stabilizes gaze during head movements. The VOR ensures visual focus on an object regardless of head movements or compensates for head movement to keep focusing on the object (Martin, 2019) (Wolfe et al., 2021). For instance, when the head is turned left horizontally, the eyes are moved to the right conjugately. This specific movement of the eyes requires activation of the left medial rectus and right lateral rectus muscles, which are activated by the motor neurons that fire due to the excitation of the vestibular neurons (Martin, 2019) (Wolfe et al., 2021). In VR, however, the VOR is often disrupted. Visual inputs from the headset suggest strong self-motion, while vestibular signals indicate stillness. This mismatch is a major trigger of CS (Di Girolamo et al., 2001). A wider field of view enhances immersion and presence in VR, but it also increases the likelihood of motion sickness due to amplified visual-vestibular conflict. Compared to daily life, in VR the visual-vestibular signal mismatch would only be amplified due to the wider peripheral view. The extra peripheral view in VR provides more motion cues to be taken in and have a greater sensory information mismatch, thus resulting in worse motion sickness (Martin, 2019) (Warchol et al., 2024).

The anatomical location of the vestibular nuclei helps explain why vestibular conflict so often produces nausea. In the brainstem, the vestibular nuclei lie adjacent to the nucleus tractus solitarius (NTS) and vagal nuclei, which regulate autonomic functions such as nausea and vomiting. They are also positioned near the cerebellum, which contributes to balance and motion coordination (Balaban, 2002; Yates et al., 1998). Although this proximity facilitates interaction, the mechanism is not purely

anatomical: it involves direct vestibulo-autonomic projections. Specifically, neurons in the medial and inferior vestibular nuclei send both monosynaptic and polysynaptic projections to the NTS, dorsal motor nucleus of the vagus, and parabrachial nucleus (Balaban & Yates, 2004). These structures integrate vestibular, visceral, and cardiovascular inputs and mediate autonomic responses such as nausea, vomiting, and changes in heart rate and blood pressure.

Additionally, vestibular signals are relayed to cerebellar regions such as the nodulus and uvula, which modulate autonomic output indirectly through brainstem circuits. This dual engagement of vestibulo-autonomic and vestibulo-cerebellar pathways explains why abnormal vestibular input—such as that induced by VR sensory conflict—can elicit powerful autonomic symptoms. In this sense, the vestibular system exerts dual influences: one on perceptual and motor processing (supporting orientation and movement), and another on autonomic regulation (producing nausea and discomfort). These pathways are distinct yet functionally integrated, making the vestibular system a central contributor to the onset of cybersickness (CS).

In the context of this study, the vestibular system is not examined in isolation but as part of the broader process of sensory reweighting. The OCHART task provides a way to estimate how much weight participants place on vestibular, visual, and gravitational cues when judging orientation. Earlier work by Chung & Barnett-Cowan (2013) showed that individuals who were better able to adjust sensory weights after VR exposure reported less CS. More recently, Izadi (2023) suggested that vestibular input may become more heavily weighted during reweighting. By combining OCHART with motion capture, this thesis builds on these findings to test whether the degree of vestibular reweighting—and its relationship with movement patterns—can help explain why some individuals experience more CS than others.

Beyond its role in producing nausea, the vestibular system also interacts with posture and movement control, which are key variables in this study. Prior research shows that postural instability often precedes and predicts motion sickness, a phenomenon described as the postural instability theory of motion sickness (Riccio & Stoffregen, 1991; Palmisano et al., 2018). This suggests that individuals who move more or sway less steadily in VR may be more likely to develop CS. By collecting center of mass position and velocity measures with motion capture, this study links vestibular reweighting directly to movement patterns. While earlier work in the lab (Chung & Barnett-Cowan, 2013; Izadi, 2023) focused on how sensory weights change before and after VR

exposure, the present study examines whether ongoing changes in cue weighting and postural control during VR are associated with CS severity. This combination of perceptual and movement-based measures provides a more complete picture of why some individuals adapt successfully in VR while others become sick. In summary, the vestibular system's dual role in perceptual orientation and autonomic regulation makes it central to understanding sensory reweighting and the onset of CS in VR.

The vestibular system's strong influence on both perceptual orientation and autonomic responses makes it central to understanding why sensory conflict often produces CS. Yet most evidence on vestibular contributions comes from tasks where participants actively move or where gravitational cues dominate perception (Balaban, 2002; Chung & Barnett-Cowan, 2013). Less is known about how vestibular reweighting operates in visually dominant but physically passive VR contexts, such as roller coaster simulations, where visual motion is strong but vestibular input is minimal. This raises the question of whether vestibular flexibility protects against CS only in active conditions, or whether it can also buffer discomfort in immersive but passive VR.

1.2.2 Visual System

The visual system plays a central role in how we interact with the world and is often the dominant sense for orientation and navigation. In the context of CS, the problem arises when visual input and vestibular signals conflict. To understand this contribution, it is important to review how visual information is processed in the brain and how it supports orientation (Martin, J. D., 2019). Visual processing begins in the retina, where light is converted into neural signals. Ganglion cell axons converge at the optic disc to form the optic nerve, which transmits signals to the lateral geniculate nucleus (LGN) of the thalamus. From the LGN, visual signals are projected through the optic radiations to the primary visual cortex (V1) in the occipital lobe (Martin, 2019; Wolfe et al., 2021). This pathway, comprising millions of neurons, encodes essential features of the environment such as form, color, location, and motion (Wolfe et al., 2021).

The final destination of optic radiation, the primary visual cortex, is also called V1 and is located in the occipital lobe. Perceived visual information is then sent to secondary and higher-order processing areas of the brain to process more complex visual contexts. From the occipital lobe, visual information is processed along two main pathways: the ventral stream (including V4) for object recognition, and the dorsal stream (including V5/MT) for motion processing. V4 connects to the

temporal lobe forming the ventral stream of visual information processing, which carries specific features of objects and scenes, critical for our ability to recognize objects effectively regardless of their orientation. The ventral stream, projecting toward the temporal lobe, encodes object identity—allowing us to recognize shapes, letters, and scenes regardless of orientation (Goodale & Milner, 1992). This stream is particularly relevant to the OCHART task, where participants must identify ambiguous characters (“p” vs. “d”) and make judgments about their upright orientation. Object recognition in this case depends on the ventral “what” pathway, which distinguishes letters from other categories like faces or places (Grill-Spector & Weiner, 2014). V5 connects to the parietal lobe forming the dorsal stream, which carries spatial information, locating the stimulus, and guiding action/navigation (Martin, 2019). The dorsal stream, projecting toward the parietal lobe, encodes spatial location and guides movements in space (Goodale & Milner, 1992; Martin, 2019). Together, these pathways enable both recognition and navigation.

In VR, the ventral stream supports object recognition, and any lag or inconsistency in the virtual content can disrupt perception, contributing to sensory mismatch and CS; the dorsal stream contributes to understanding virtual position and coordinating movements in virtual space, inaccurate feedback of the virtual content regarding this information leads to spatial disorientation, creating sensory mismatch with the vestibular system and leading to CS.

In addition to recognition and navigation, the visual system contributes to postural control. A specific mechanism here is ocular torsion, in which the eyes rotate slightly to compensate for head tilt, helping to stabilize the visual field. Controlled by the oblique eye muscles, ocular torsion is essential for daily activities such as reading, driving, and sports (Wibble, 2024). Although not directly manipulated in this study, ocular torsion is relevant because the side-lying posture during OCHART likely induces it. Along with the vestibulo-ocular reflex (VOR), ocular torsion helps stabilize gaze and maintain orientation. Both are crucial in VR, where stable vision reduces sensory conflict and enhances immersion (Schoppik et al., 2017). In addition, Schoppik and colleagues pointed out effective ocular torsion, as well as integrating vestibular with visual cues are important to prevent motion sickness and enhance the sense of presence in the VR environment (Schoppik, D. et al., 2017).

Vision also provides higher-level orientation cues. Environmental references, such as the ground plane or horizon, help determine “which way is up” (Barnett-Cowan & Harris, 2009). Under natural conditions, visual, vestibular, and somatosensory cues are usually aligned, allowing effortless

orientation. In VR, however, this congruence can break down. Artificial environments often present strong but misleading orientation cues that conflict with gravitational and bodily signals, producing perceptual illusions that lead to CS (Barnett-Cowan & Harris, 2009).

Importantly, the OCHART task does not only test perceptual recognition of letters. It also requires decision-making and executive control. After identifying whether the ambiguous character appears more like a “p” or a “d,” participants must select and report their choice with a button press. This engages frontal executive regions such as the prefrontal cortex and supplementary motor area, which coordinate perceptual judgments with action selection (Miller & Cohen, 2001; Aron et al., 2004). Thus, OCHART performance reflects not only visual recognition in the ventral stream but also the integration of perception, decision-making, and motor response.

This is particularly relevant to the VR simulation used in this study, which includes polarity cues that bias orientation perception. These manipulations force the brain to rely heavily on visual input, even when it conflicts with vestibular or proprioceptive feedback. By doing so, they amplify the kind of sensory mismatch that the OCHART task is designed to capture.

The visual system provides powerful cues for orientation and is often dominant in environments with structured visual references such as human-made interiors (Barnett-Cowan & Harris, 2009). In VR, however, highly dynamic visual scenes can overwhelm other sensory inputs, producing mismatches with vestibular and proprioceptive feedback (Palmisano et al., 2020). Prior studies show that when visual cues dominate reweighting, individuals are more prone to CS unless they can flexibly adjust to the conflict (Chung & Barnett-Cowan, 2023). Still, most of this evidence comes from free-moving exploration tasks. Whether visual reweighting predicts CS during passive, visually intense simulations—where vision drives the experience almost entirely—remains unclear.

In summary, vision is the primary modality for spatial perception, object recognition, and orientation. Its processing streams support both identification and navigation, but in VR, they are also the main source of sensory conflict. Moreover, tasks like OCHART highlight how visual recognition is intertwined with executive control, reflecting the broader processes of sensory integration and decision-making. For this reason, studying how visual signals are integrated and reweighted relative to other senses is critical for understanding why some individuals adapt successfully to VR while others experience sickness. In summary, the visual system often dominates orientation perception, but in VR, conflicting visual and vestibular cues can overwhelm reweighting processes and trigger CS.

1.2.3 Somatosensory System

The somatosensory system is another key contributor to orientation and balance, working alongside the visual and vestibular systems. It includes multiple modalities, such as touch, proprioception, temperature, pain, itch, and visceral sensation. Each modality has distinct receptors and fiber types that transmit signals at varying speeds. For example, proprioception—also called kinesthesia—relies on fast, myelinated alpha and beta fibers, whereas itch signals are transmitted more slowly along unmyelinated fibers (Martin, 2019).

Proprioception is particularly important for this thesis. It provides the sense of limb position and movement in relation to gravity and the body axis (Lacquaniti et al., 1997). Proprioception allows individuals to sense limb position and movement even in the absence of visual input (Allum et al., 1998). When combined with touch and visual input, proprioception forms a strong foundation for motor control and spatial orientation (Sozzi et al., 2021). These signals are critical during locomotion, supporting coordination and maintaining postural stability (Ritzmann & Gollhofer, 2017).

The underlying pathways reflect this importance. Proprioceptive and tactile inputs travel mainly through the dorsal column–medial lemniscus (DCML) pathway, which carries information to the thalamus and then to the primary somatosensory cortex (S1) in the post-central gyrus. S1 contains the well-known sensory homunculus, where the body is represented in a somatotopic map. Finer sensations, such as those from the hands and face, occupy larger cortical areas (Martin, 2019). S1 lies adjacent to the primary motor cortex (M1), separated by the central sulcus, with extensive interconnections supporting sensorimotor integration. Studies in primates show extensive reciprocal connections between M1 and subdivisions of S1, such as areas 3a, 1, 2, and S2 (Proulx et al., 2022). This organization highlights how proprioceptive input supports not only perception but also motor planning and execution.

Somatosensory feedback also plays a central role in balance. For example, receptors in the soles of the feet contribute to postural control, and tactile stimulation of these receptors has been shown to improve balance and spatial orientation (Lackner & DiZio, 2005). In everyday life, tactile and proprioceptive signals work together with vestibular and visual input to stabilize posture. In VR, somatosensory signals may be absent or misaligned with visual and vestibular input, making sensory integration more challenging. This mismatch can increase the risk of CS. By contrast, studies show

that adding tactile or proprioceptive feedback in VR improves orientation, enhances immersion, and reduces sickness by minimizing sensory conflict (Gao, 2022).

For the present study, these points are especially relevant. In the process of sensory reweighting, the brain adjusts how much weight it gives to each available cue. While vision and vestibular input are obvious components, somatosensory cues form the body's anchor against gravity and are essential for stable orientation (Peterka, 2002; Lackner & DiZio, 2005). This means that the "body aspect" of sensory weighting includes both vestibular and somatosensory contributions. In tasks like OCHART, participants rely on these body-based cues, along with vision and gravity, to judge what feels upright (Pettorossi & Schieppati, 2014).

Somatosensory cues, particularly proprioception, provide a stable body-based reference for orientation and often anchor perception against gravity (Lackner & DiZio, 2005). In VR, however, these cues are reduced or disconnected from visual and vestibular inputs, especially in seated or passive experiences where movement is minimal. This raises the question of whether proprioceptive reweighting mitigates CS in passive VR, or whether its role becomes evident only during active movement.

Finally, it is important to emphasize that this thesis does not aim to expand the detailed neuroanatomy of the somatosensory system. Instead, the focus is on how somatosensory input contributes to perceptual decision-making. By examining how somatosensory weighting shifts during VR exposure, and how these shifts relate to susceptibility to CS, this study aims to clarify the body's role in orientation perception under conditions of sensory conflict. Somatosensory cues provide a gravitational anchor for the body, and when misaligned with visual or vestibular input in VR, they complicate reweighting and increase susceptibility to CS.

1.3 Virtual Reality

VR (VR) has evolved considerably over the past century, moving from early experimental systems to the immersive headsets widely available today. One of the earliest mature states of VR was introduced by Krueger with *Videoplace*, an interactive environment where users could engage in artistic activities virtually. Krueger, often referred to as the "father of VR," also introduced the concept of artificial reality, where user actions were recognized by the system and real-time feedback maintained a "sense of presence" in the virtual world (Krueger et al., 1985). Later developments in

simulation and training technologies, such as flight simulators and early head-mounted displays, further laid the groundwork for modern VR systems (Paro et al., 2022).

VR can be defined as a system that enables observation and interaction within a simulated environment, creating a strong sense of presence—the subjective experience of “being there” (Mihelj et al., 2013). Presence is strongly influenced by the richness and synchronization of sensory input. Visual, auditory, and haptic signals are the fundamental components of VR, and when these are realistic, synchronized, and rich, the sense of presence is enhanced (Mihelj et al., 2013). Today, VR is most commonly accessed through head-mounted displays (HMDs), often paired with handheld controllers that provide haptic feedback. These tools enable users to interact with virtual environments using visual, auditory, and haptic input, enhancing immersion (Servotte et al., 2020).

The balance between immersion and comfort is critical. Higher immersion usually increases presence, but it also heightens the risk of CS when visual, vestibular, and somatosensory cues do not align (Stanney et al., 2020). CS is widely recognized as one of the most significant barriers to broader VR adoption. Systematic reviews have highlighted its impact across domains: in education, where it can reduce learning efficiency (Caserman et al., 2021); in healthcare, where it can hinder rehabilitation and cognitive training (Cossio et al., 2025; Ramaseri Chandra et al., 2022); and in entertainment, where it directly limits user comfort and engagement (Weech et al., 2019).

VR holds particular promise in clinical and aging populations, including therapeutic applications and cognitive assessments. Studies show that VR-based interventions can enhance engagement, improve balance, and provide safe environments for rehabilitation (Lecavalier et al., 2020; Kim et al., 2021; Laessoe, 2023). However, older adults may face higher susceptibility to CS due to age-related changes in balance and sensory integration (Helou et al., 2023; Snoswell & Snoswell, 2019). These vulnerabilities underscore the importance of addressing CS if VR is to become a reliable tool in healthcare and aging research.

In summary, VR has advanced from early experimental systems to highly immersive platforms with applications in healthcare, education, and entertainment. However, the immersive nature of VR also introduces vulnerability: mismatched sensory signals often trigger CS, compromising user comfort. For VR to reach its full potential, it is essential to understand how sensory systems—particularly vision, vestibular input, and somatosensation—are integrated and reweighted to maintain orientation constancy. This understanding forms the foundation for the present thesis. VR provides a

powerful tool for studying sensory integration, but its tendency to create mismatched sensory inputs makes understanding reweighting processes essential for reducing CS.

As VR applications expand into education, healthcare, and entertainment, their intensity and level of immersion also vary. Free-moving exploratory VR (e.g., space navigation) offers opportunities for users to physically interact with the environment, potentially engaging flexible sensory reweighting to reduce discomfort. By contrast, passive but visually provocative VR content, such as roller coaster rides, removes the possibility of active control and relies almost entirely on visual stimulation to drive immersion. This contrast reveals a gap in current understanding: do sensory reweighting mechanisms that mitigate CS in active VR also function effectively in visually dominant, physically passive contexts?

1.4 Cybersickness

Virtual Reality (VR) has revolutionized healthcare, education, and entertainment, but for it to reach its full potential, it must overcome a persistent challenge: CS. CS is a type of motion sickness triggered by VR environments and is one of the primary barriers to widespread adoption. It manifests as nausea, disorientation, eyestrain, and general discomfort. The most widely accepted explanation is the sensory conflict theory, which posits that symptoms arise when visual, vestibular, and somatosensory cues provide conflicting information about self-motion. This conflict is especially pronounced in VR, where users see continuous visual motion but remain physically stationary (Lawson et al., 2021; Conner et al., 2022).

While sensory conflict theory remains a central framework for understanding CS, other perspectives highlight its multifactorial nature. Postural instability theory proposes that prolonged or unresolved instability in balance control precedes symptom onset (Riccio & Stoffregen, 1991), whereas poison theory views sickness as an evolutionarily conserved defense mechanism against sensory mismatches, triggering nausea and vomiting as if responding to ingested toxins (Stanney et al., 2020). Recent integrative models emphasize the efficiency of sensory reweighting—the brain’s capacity to flexibly adjust the weighting of visual, vestibular, and somatosensory inputs—as a key determinant of susceptibility (Gallagher & Ferrè, 2018; Weech et al., 2020; Chung & Barnett-Cowan, 2023).

Crucially, there is substantial individual variability in these underlying mechanisms. Differences in vestibular sensitivity, postural control strategies, multisensory integration efficiency, and even autonomic responsiveness may influence how each person responds to the same VR environment. For example, some individuals may rely more on vestibular input and experience strong autonomic activation, whereas others may effectively down-weight conflicting sensory cues and maintain stable posture. Genetic factors, age, sensory dominance, prior VR experience, and anxiety or interoceptive sensitivity may further modulate these responses. Thus, CS likely arises from interacting mechanisms whose relative contributions vary across individuals, which underscores the need for individualized models of CS susceptibility.

There is also growing evidence that experience with VR modifies sickness susceptibility. Longitudinal studies suggest that repeated VR exposure can reduce symptoms, as users adapt both behaviorally and physiologically. This adaptation may involve changes in sensory reweighting strategies over time, though the exact mechanisms remain under investigation (Keshavarz et al., 2019; Fulvio et al., 2021). These findings are important for understanding not only why individuals differ in their first VR sessions, but also how tolerance may evolve with repeated exposure.

Demographic factors further shape CS responses. Age is one of the most debated. Some studies report that older adults experience less CS, possibly because they move more tentatively in VR or because their sensory organs are less sensitive, reducing cue conflict (Dilanchian et al., 2021; Saredakis et al., 2020). Others, however, have shown that older adults exhibit greater postural instability and higher CS under prolonged exposure (Risi & Palmisano, 2019). The findings for younger adults are equally split—some tolerate VR well, while others show high susceptibility even after short exposures (Chung & Barnett-Cowan, 2023). These mixed results raise a central question for this thesis: when directly comparing younger and older adults, which group will show stronger CS, and how will this relate to differences in sensory reweighting?

Other individual differences are also relevant. Women are often reported to experience higher CS than men, potentially due to visual display settings not optimized for interpupillary distance (Howard & Van Zandt, 2021; Luong et al., 2022). Prior VR exposure also matters: increased familiarity generally reduces symptoms over time (Luong et al., 2022). Beyond demographics, exposure conditions strongly influence severity. Shorter VR sessions tend to produce fewer symptoms, while longer or more visually intense exposures exacerbate sickness (Lecavalier et al., 2020; Oh & Son,

2022). Rest intervals have been shown to reduce postural sway disturbances and provide partial relief (Clark, 2021).

Understanding sensory reweighting is therefore essential for grasping CS. Studies using measures such as subjective visual vertical (SVV) show that individuals whose perception of vertical shifts significantly after VR exposure are more likely to report higher CS, suggesting difficulties in smoothly reweighting sensory input (Chung & Barnett-Cowan, 2023). This provides a direct link to the OCHART task, which quantifies sensory weighting across vision, vestibular input, and gravity.

Theories of CS emphasize sensory conflict and postural instability as key drivers (Riccio & Stoffregen, 1991; Palmisano et al., 2020). While both frameworks point to the importance of sensory integration, most empirical evidence linking reweighting flexibility to reduced sickness comes from exploratory VR tasks where participants can move freely (Chung & Barnett-Cowan, 2013; Izadi, 2023). Whether these protective mechanisms extend to more passive VR experiences are unknown. Roller coaster simulations, which are visually intense but physically static, provide an ideal test case to examine this question, as they reliably induce sickness while minimizing active motor engagement.

Taken together, the literature shows that CS is influenced by sensory conflict, individual differences in reweighting ability, demographic factors, and exposure conditions. However, findings on age-related susceptibility remain inconsistent, especially when comparing younger and older adults. This thesis aims to address this gap by testing whether differences in sensory reweighting ability across age groups predict CS severity, and whether these differences also relate to movement strategies during VR exposure. Exploring the mechanisms of sensory reweighting is critical to explaining why some individuals develop CS in VR while others remain resilient.

1.5 Perceptual Upright

1.5.1 Subjective Visual Vertical

The Subjective Visual Vertical (SVV) describes how individuals perceive the vertical direction in their environment. It is usually measured by asking participants to align a line with what they believe to be “upright,” a task strongly guided by gravitational cues. SVV is therefore widely used to study how gravity and vestibular signals influence orientation (Dyde et al., 2006; Haji-Khamneh & Harris, 2010). Because the vestibular system provides information about head position relative to gravity, SVV reflects how strongly the brain relies on this input to establish a reference for verticality.

Even small tilts can bias SVV, with deviations of $\pm 5^\circ$ already producing measurable changes in perceived vertical (Clemens et al., 2011). This sensitivity highlights how finely tuned our system is to gravity, but it also exposes the limits of SVV as a tool: it is dominated by vestibular and gravitational input. While this makes SVV valuable for clinical assessment of vestibular disorders, it captures less of the influence of vision and body cues that are critical in VR. For this reason, SVV alone cannot fully explain why some individuals reweight sensory cues successfully and avoid CS, while others do not.

1.5.2 Perceptual Upright

Perceptual Upright (PU) expands beyond SVV by considering the orientation at which objects and faces are most easily recognized. Unlike SVV, which is gravity-heavy, PU reflects the integration of visual, vestibular, and body-based cues (Barnett-Cowan & Harris, 2009). This broader scope makes PU more sensitive to changes in sensory weighting, particularly in environments where traditional gravitational cues may conflict with visual or contextual information.

PU is typically measured with the Oriented Character Recognition Test (OCHART), which uses orientation-dependent letters (e.g., “p” vs. “d”) to assess what participants perceive as upright (Dyde et al., 2006). Research has shown that PU values are more widely “spread” than SVV because they are strongly influenced by contextual visual information—for example, a tilted room can bias the perceived upright (Harris et al., 2010). This makes PU particularly relevant for VR, where immersive scenes often provide rich but conflicting visual orientation cues.

Studies confirm that visual cues often dominate PU in structured environments, while vestibular and body orientation cues become more influential when visual structure is reduced (Barnett-Cowan & Harris, 2009; Haji-Khamneh & Harris, 2010). Proprioceptive input from muscles and joints also contributes, anchoring PU to the body axis (Clemens et al., 2011). In this way, PU reflects a balanced combination of sensory inputs, providing a more comprehensive measure of orientation than SVV.

1.5.3 PU, Sensory Reweighting, and CS

The adaptability of PU highlights its importance for understanding CS. Sensory reweighting—the brain’s ability to adjust the relative importance of visual, vestibular, and somatosensory inputs—appears to be a key mechanism determining susceptibility to sickness. Chung and Barnett-Cowan (2023) found that individuals who failed to reweight effectively between these cues were more prone

to CS, while those who adapted more smoothly experienced less discomfort. Similarly, Weech and colleagues (2020) showed that down-weighting conflicting sensory inputs in VR reduced CS symptoms, supporting the idea that PU shifts provide an indirect measure of reweighting capacity.

This raises an intriguing possibility: if PU values can be shifted through training or intervention, might this reduce CS? Gallagher (2019) suggested that repeated VR exposure can alter cue weighting over time, pointing to a form of adaptive neuroplasticity. Although it remains uncertain whether PU can be deliberately trained, the evidence suggests that sensory weighting is flexible, and PU provides a valuable tool for capturing these dynamics.

For the purposes of this thesis, PU offers a stronger framework than SVV. While SVV primarily reflects gravity and vestibular signals, PU distributes weighting more evenly across vision, body, and gravity, allowing changes in each modality to be measured. This makes it especially well-suited to studying sensory reweighting in VR, where visual cues often dominate and can misalign with vestibular or somatosensory feedback.

By collecting OCHART data before and after VR exposure, this study assesses how PU shifts during immersion, providing an indirect window into which sensory systems participants rely on most. If sensory weighting changes are linked to CS severity or to differences in movement patterns across age groups, this would advance our understanding of how orientation constancy is maintained—or disrupted—in VR. Since PU tasks reveal how visual, vestibular, and somatosensory cues are combined, they offer an important window into the reweighting processes that underlie CS.

PU, as measured by OCHART, provides a sensitive tool to estimate how visual, vestibular, and body cues are weighted when judging orientation (Dyde et al., 2006). Previous studies using OCHART have shown that flexible reweighting across cues is associated with lower CS (Chung & Barnett-Cowan, 2013; Izadi, 2023). However, these studies primarily tested cue weighting before and after exploratory VR exposure, not in the context of passive, visually intense VR. By applying OCHART in a roller coaster simulation, this study asks whether the same relationship between reweighting flexibility and CS holds when participants are immersed but physically static.

1.6 Oriented CHAracter Recognition (OCHART)

The Oriented Character Recognition (OCHART) task is a specialized method developed to measure perceptual upright (PU)—the orientation at which objects and scenes are most easily recognized as

upright. In this paradigm, participants are presented with orientation-dependent letters, such as “p” and “d,” rotated at different angles. Their task is to decide which character is being shown. Because the identity of these letters depends directly on orientation, the OCHART task provides a sensitive way to probe the perceptual upright (Dyde et al., 2006).

What makes OCHART especially valuable is that it captures how multiple sensory cues—visual, vestibular, and body orientation—contribute to upright perception. For example, when characters are presented in a tilted background, the visual context biases responses, revealing the strong influence of environmental cues on PU. By systematically varying letter orientation and background conditions, OCHART reveals how sensory weightings shift under different contexts, something SVV alone cannot capture.

Since its introduction, OCHART has been widely applied and refined. Barnett-Cowan and Harris (2009) showed that PU reflects different cue weighting depending on environmental context: in structured environments with strong verticals, visual cues dominate, whereas in less structured environments vestibular cues play a stronger role. Haji-Khamneh and Harris (2010) further validated these findings, emphasizing the flexible integration of sensory inputs. Later studies extended OCHART into VR contexts, where conflicting cues are common. For instance, Mihelj et al. (2014) highlighted that PU alignment is critical for minimizing disorientation and enhancing presence in VR, while Weech et al. (2019) demonstrated that disruptions in PU contribute directly to CS, and that successful sensory reweighting helps reduce symptoms.

More recent work has applied OCHART to explore group differences. For example, Chung & Barnett-Cowan (2023) and Izadi (2023) used OCHART pre- and post-VR exposure to show that individuals vary in their ability to reweight cues, and that this variation predicts CS susceptibility. McManus & Harris (2023) applied OCHART in conflict paradigms, showing that group-level differences in perceptual upright shifts can reflect broader sensory integration strategies. Such findings are particularly relevant for understanding differences between age groups, clinical populations, and those more or less prone to CS.

Although OCHART is a behavioral task, it engages a broad neural network that underpins perceptual decision-making. The early visual cortex (V1–V4) processes letter features, while the ventral temporal cortex (including the visual word form area) supports letter recognition—the “what” pathway (Dehaene & Cohen, 2011). Orientation cues are integrated with vestibular input that travels

from the vestibular nuclei through the thalamus to reach the parietal and insular cortices, including the parietal-insular vestibular cortex (PIVC) (Lopez & Blanke, 2011). Proprioceptive signals from the body converge in the somatosensory cortex, further shaping PU.

Crucially, OCHART also requires executive control: the participant must interpret ambiguous stimuli, make a categorical judgment (“p” vs. “d”), and execute a motor response (button press). This engages parietal and prefrontal regions implicated in perceptual decision-making (Gold & Shadlen, 2007; Heekeren et al., 2008). Thus, OCHART is not only a test of low-level perception but also a window into how multisensory information is integrated and acted upon.

OUCHART provides unique advantages over traditional SVV measures. SVV is dominated by gravity and vestibular input, whereas OCHART reveals how vision, vestibular, and somatosensory cues are weighted more evenly. This makes it especially powerful for detecting subtle reweighting shifts, such as those hypothesized to occur during VR exposure. By administering OCHART before and after VR, we can quantify whether participants’ sensory weights shift, and whether these shifts correlate with CS severity. Although the present study focuses on behavioral measures, OCHART stimuli are well suited for integration with neural recording methods (e.g., ERP/ERSP), which could provide complementary insights into the timing and dynamics of sensory reweighting. While such neural studies have not yet been reported, their potential underscores the value of OCHART as a flexible experimental tool for probing multisensory processing.

This approach directly addresses gaps in prior work. Earlier studies by Chung & Barnett-Cowan (2023) and Izadi (2023) measured PU before and after VR, showing that greater flexibility in reweighting predicted lower CS. However, they did not capture what happens during VR exposure. The current study advances this line of work by combining OCHART with motion capture to track not only pre/post PU changes but also participants’ real-time movement patterns in VR. This dual approach allows us to test whether movement strategies and sensory reweighting jointly explain differences in CS across younger and older adults.

In summary, OCHART is a robust tool for probing perceptual upright and sensory integration. Its ability to reveal how multiple cues are weighed makes it especially relevant to VR research, where mismatched signals often drive discomfort. By applying OCHART in a pre/post VR design, this thesis aims to uncover whether age-related differences in sensory reweighting explain variability in CS, and how these differences are expressed in participants’ movements during immersion (Dyde et

al., 2006; Barnett-Cowan & Harris, 2009; Weech et al., 2019; Chung & Barnett-Cowan, 2023).

OCHART provides a unique way to quantify sensory cue weightings, making it a valuable method for testing how reweighting relates to CS.

1.7 Sensory Reweighting

After reviewing multisensory integration and the role of sensory conflicts in CS, it is important to consider the adaptive mechanism the nervous system uses to cope with such mismatches: sensory reweighting. Humans rely on three main sources of sensory information for balance and orientation—vision, vestibular input, and somatosensory/proprioceptive feedback. Under normal conditions, these cues align to support a stable percept of the world. However, when one source becomes unreliable, the brain dynamically adjusts the relative weight it assigns to each input, a process known as sensory reweighting (Barnett-Cowan & Harris, 2009; Barnett-Cowan et al., 2010).

Sensory reweighting can be thought of as the brain’s ability to adjust the “gain” on different inputs depending on reliability. In well-lit environments with strong visual structure, vision tends to dominate. In darkness or when visual cues are misleading, vestibular, and proprioceptive inputs take on greater importance (Barnett-Cowan & Harris, 2009). Neurophysiologically, this reflects both bottom-up processes (sensory gain adjustments at the level of the signal) and top-down influences (attentional control, expectations, and executive modulation). Work by Barnett-Cowan and colleagues has emphasized how reweighting emerges from distributed circuits involving vestibular brainstem nuclei, cerebellar control of posture, and parietal and insular cortices, with executive contributions from frontal regions when decisions must be made under conflicting cues (Barnett-Cowan et al., 2010; Chung & Barnett-Cowan, 2023).

Reweighting is evident in daily activities. On stable ground, vision is a strong anchor; in darkness, vestibular and proprioceptive signals dominate; and on unstable terrain, proprioceptive feedback from muscles and joints is emphasized over other cues. This flexibility allows humans to adapt to diverse contexts such as walking in dim light, adjusting balance on a moving bus, or compensating for tilted surfaces (Barnett-Cowan & Harris, 2009; Lackner & DiZio, 2005).

VR presents a unique challenge for sensory reweighting. The headset provides compelling visual motion cues, while the vestibular system signals that the body is relatively stationary. Successful adaptation requires down-weighting unreliable visual input and relying more on vestibular and proprioceptive cues. Individuals who flexibly reweight in this way report less CS, while those who

rigidly depend on vision experience higher levels of discomfort (Weech et al., 2019; Chung & Barnett-Cowan, 2023).

Evidence also suggests that sensory reweighting is plastic and trainable. Longitudinal VR studies show that repeated exposure reduces reliance on visual cues and improves multisensory balance control (Barbanchon et al., 2024). Rehabilitation studies similarly report that VR-based training can facilitate reweighting, leading to improved postural stability in clinical populations (Lubetzky et al., 2023). This supports the idea that reweighting is not only a short-term adaptive mechanism but also capable of long-term recalibration.

For this thesis, sensory reweighting provides the theoretical foundation linking perceptual upright (PU), balance control, and CS. OCHART allows us to measure how visual, vestibular, and body cues are weighted before and after VR exposure, offering an indirect index of reweighting capacity. Combined with motion capture data, this approach will clarify how reweighting is expressed both in perceptual measures and in participants' movement strategies. Ultimately, this study aims to test whether age-related differences in sensory reweighting explain variability in CS severity and movement adaptation during VR exposure.

Sensory reweighting provides a promising framework for understanding CS, but its role may depend on context. In free-moving VR, flexible reweighting appears to reduce discomfort by allowing individuals to down-weight unreliable cues (Chung & Barnett-Cowan, 2013). In passive VR, where visual motion dominates, the role of reweighting may be smaller—or operate differently—since vestibular and proprioceptive inputs provide little reliable information to balance the overwhelming visual flow. This raises the possibility that CS in passive VR may be better explained by postural instability than by cue reweighting.

In summary, sensory reweighting is a flexible, multisensory process supported by both bottom-up sensory recalibration and top-down executive control. Its central role in resolving conflicts across vision, vestibular, and somatosensory inputs makes it key to understanding CS and critical for explaining differences in adaptation between younger and older adults. By focusing on how the brain dynamically adjusts sensory priorities, we can better understand both the causes of CS and the pathways for potential mitigation.

1.8 Musculoskeletal Movement and Motion Capture

In addition to perceptual measures like PU or SVV, the way people move in VR (VR) gives important clues about balance, sensory reweighting, and susceptibility to CS. Dilanchian et al. (2021) suggested that older adults may report fewer CS symptoms not because they are free from sensory conflict, but because they move more cautiously in VR, limiting head and body motion. Younger adults, by contrast, tend to move more freely and vigorously, which may increase sensory mismatches and discomfort. This raises a key question: do age groups adopt different movement strategies in VR, and how are these strategies linked to CS?

Motion capture is a useful tool for addressing this question. By tracking displacement and center of mass (CoM) velocity, it can measure postural sway and movement patterns with high precision. This is important because the postural instability theory argues that instability in body sway not only reflects balance control but also predicts the onset of motion sickness (Stoffregen & Smart, 1998). Studies in VR support this idea: individuals who show larger sway variability are more likely to experience CS (Arcioni et al., 2019; Palmisano et al., 2020). For example, Becerra et al. (2021) found that increases in both linear and angular CoM displacement were linked to higher CS scores. On the other hand, people who limit their movement often report fewer symptoms, though sometimes at the cost of immersion (Bailey et al., 2022).

Aging further shapes this relationship. Older adults generally show greater baseline sway, slower corrective responses, and reduced proprioceptive sensitivity compared to younger adults (Soares et al., 2020; Liang et al., 2022). At the same time, they may deliberately reduce their movements in VR as a strategy to avoid discomfort (Dilanchian et al., 2021). This creates a complex picture: older adults may be more unstable physiologically, but also more restrained behaviorally. Whether this restraint protects them or reflects limits in sensory reweighting remains unclear. Motion capture can help answer this by revealing how older and younger adults differ in their movement styles and whether these patterns are linked to CS (Soares et al., 2020; Palmisano et al., 2020).

The movements captured in VR are the final result of many systems in the brain working together. Descending motor pathways, such as the vestibulospinal tracts, help stabilize posture: the lateral tract adjusts trunk and limb muscles, while the medial tract coordinates head and eye positions (Lopez & Blanke, 2011). These signals are shaped by the vestibular nuclei, which integrate sensory input about balance and connect closely with both the cerebellum and brainstem areas that regulate nausea. The

cerebellum fine-tunes movement by comparing expected and actual sensory feedback, while higher areas such as premotor and frontal cortices contribute to planning and decision-making (Barmack, 2003). For example, in a task like OCHART, participants not only perceive a letter but must also make a decision and press a button—an action that reflects both perceptual processing and motor execution.

Seen this way, musculoskeletal movement is not just an outcome of motor commands—it is also a window into sensory integration. How people move in VR reflects how the brain weights visual, vestibular, and somatosensory cues to keep orientation stable. Reduced or exaggerated sway may indicate different reweighting strategies, providing a behavioral measure to complement perceptual tasks like PU.

Movement patterns offer another lens to understand CS. Postural instability theory predicts that greater sway signals difficulty integrating sensory cues, which in turn precedes CS (Riccio & Stoffregen, 1991). Prior studies link sway to sickness across a variety of VR tasks (Kennedy & Stanney, 1996; Palmisano et al., 2020), but it is not clear whether these links hold in passive contexts where participants are instructed to remain still. By measuring postural sway with motion capture during a roller coaster simulation, this study tests whether movement still predicts CS when active control is minimized.

In this study, motion capture is used alongside perceptual measures and self-reported sickness scores. This allows us to test whether differences in movement strategies between older and younger adults are linked to CS and to shifts in sensory weighting. Importantly, we record movement continuously during VR exposure, rather than only before and after. This makes it possible to track real-time adaptations—whether participants restrain movement as symptoms develop, exaggerate movement when immersed, or show distinct age-related patterns. In this way, motion capture provides a bridge between sensory integration in the brain and observable behavior in VR, laying a strong foundation for testing how musculoskeletal control contributes to CS across the lifespan. Measuring postural sway and movement patterns during VR exposure connects sensory reweighting directly to behavioral outcomes, offering critical insight into how CS develops.

1.9 Purpose and Hypothesis

The earlier sections showed how orientation constancy depends on combining signals from vision, vestibular, and somatosensory systems. When these signals do not match, as often happens in VR

(VR), people can feel disoriented and develop CS. We also discussed how perceptual measures like perceptual upright (PU), tasks such as OCHART, and behavioral measures like postural sway help us study how people balance these signals. Together, these approaches give us tools to understand how people adapt to VR and why some are more prone to CS than others.

Prior research suggests that individuals who flexibly reweight visual, vestibular, and body cues experience less CS, particularly in free-moving VR tasks where users actively navigate through space (Chung & Barnett-Cowan, 2013; Izadi, 2023). Yet it is unclear whether this protective role of sensory reweighting extends to more passive, visually intense VR contexts, such as roller coasters, where strong visual motion occurs without corresponding vestibular or motor feedback. At the same time, theories of postural instability suggest that CS may be reflected not only in perceptual reweighting but also in changes in movement patterns and balance control (Riccio & Stoffregen, 1991; Palmisano et al., 2020). This thesis therefore examines whether sensory cue reweighting and postural control can predict CS during an immersive roller coaster simulation, with the goal of clarifying how these mechanisms interact in visually provocative but physically passive VR environments.

Understanding how sensory reweighting, movement, and age interact in VR is critical for explaining individual differences in CS. Sensory reweighting reflects the brain's ability to dynamically shift reliance among visual, vestibular, and somatosensory cues when conflicts arise (Harris et al., 2010; Gallagher et al., 2019). Movement patterns, particularly postural sway, provide behavioral evidence of how these reweighting processes manifest in balance control and have been repeatedly linked to CS severity (Stoffregen & Riccio, 1991; Palmisano et al., 2020). Age further shapes both processes: older adults often show reduced sensory sensitivity and altered motor control, leading to differences in how cues are integrated and how movements are expressed (Saredakis et al., 2020; Dilanchian et al., 2021). By studying these three factors together, VR research can move beyond isolated explanations to a more complete account of why CS varies across individuals, ultimately guiding the design of immersive systems that are both safer and more inclusive across the lifespan.

In summary, the vestibular, visual, and somatosensory systems all contribute to orientation constancy, but their relative influence can shift depending on context. In VR, these shifts are especially important because mismatches among sensory cues often lead to CS. Prior studies have shown that individuals who flexibly reweight sensory cues experience less CS, particularly in

exploratory VR tasks where physical movement is possible (Chung & Barnett-Cowan, 2013; Izadi, 2023). What remains unclear is whether this protective effect generalizes to more passive VR contexts, such as roller coaster simulations, where vision dominates and the body is largely static. At the same time, postural instability has been consistently linked to CS across a range of settings (Riccio & Stoffregen, 1991; Palmisano et al., 2020). This suggests that in passive VR, postural sway may be a more reliable predictor of CS than sensory cue reweighting. By combining OCHART-based measures of perceptual upright with motion capture recordings of postural movement, the present study aims to directly compare these two mechanisms and test which better predicts CS during visually intense but physically passive VR.

The purpose of this study is to examine how sensory reweighting and movement relate to CS during VR exposure. In other words, we ask whether people who can shift their reliance between different senses experience less CS, and whether their body movements reflect differences in how sick they feel. By combining perceptual tasks, motion capture, and self-reported sickness scores, the study looks at how the sensory and motor systems work together in immersive environments. From this background, two hypotheses are proposed:

H1: Individuals who show greater changes in sensory weighting will report fewer CS symptoms.

H2: There will be a positive correlation between movement behavior (displacement and velocity of the center of mass measured by motion capture) and self-reported CS severity.

By testing these hypotheses, this study aims to explain more clearly why some people get sick in VR while others do not. CS is a major barrier to using VR in healthcare, education, and rehabilitation. If the findings support these predictions, they will show that both sensory reweighting and movement strategies are important factors in sickness. This would not only improve our understanding of the underlying mechanisms but also suggest practical ways to reduce CS—such as training people to adjust their sensory weighting or guiding them in how to move during VR.

Chapter 2

Materials and Methodology

2.1 Participants

A total of 25 younger adults (18 females, 7 males; $M = 23.76$ years, $SD = 2.83$) were recruited from the University of Waterloo. Due to data loss and instability in OCHART responses, six participants could not be fully analyzed, leaving a final younger adult sample of 19 with complete data. Most volunteered, while one received monetary compensation (CAD \$10/hour).

Recruitment also targeted older adults (65+ years) through the Waterloo Research in Aging Participant Pool (WRAP). Although eight initially enrolled, the majority withdrew due to discomfort with the VR environment, resulting in only two partially completed datasets. Given this high dropout rate, the age threshold was lowered to 45+ years, but no additional participants were recruited despite further efforts. All older adult participants were compensated (CAD \$10/hour).

Thus, the final sample consisted primarily of younger adults, with insufficient data from older adults to support statistical comparison between age groups. This limitation reflects a broader challenge in CS research, where older participants are often underrepresented due to higher withdrawal rates in demanding VR tasks (see Saredakis et al., 2020). To maintain transparency, detailed dropout counts and reasons are documented in Appendix A.

Across groups, all participants reported no history of neurological, vestibular, or auditory disorders, and all had normal or corrected-to-normal vision. None reported acute illness, fatigue, or stress at the time of testing. The study received ethics clearance from the University of Waterloo Research Ethics Board, and all participants provided informed consent.

2.2 Apparatus and Stimuli

2.2.1 Oriented CHAracter Recognition Task

OUCHART uses the letters p and d, which change identity depending on orientation. Characters are rotated through various angles, and participants decide whether the letter shown is a p or a d. The point at which participants are equally likely to identify the letter as either (p or d) defines the

perceptual upright, or the “50/50 point.” Unlike SVV, which is heavily gravity-dependent (gravity = 1.0; vision $\approx$ 0.1; body $\approx$ 0.2), OCHART reflects more balanced weightings (body $\approx$ 2.6; vision $\approx$ 1.2; gravity = 1.0). These relative weightings were originally derived by fitting a linear vector sum model of visual, body, and gravitational cues to psychophysical data (Dyde, Jenkin, & Harris, 2006). Gravity is set to 1.0 for normalization, and body and vision weights are expressed relative to this, indicating their proportional influence on upright perception.

In this study, participants viewed the letter p across 24 orientations spaced 15° apart. These were presented against seven backgrounds: one neutral gray and six visually enriched rooms rotated in 60° increments (Figure 2.1). Across the task, this yielded 1,344 trials per condition, representing all combinations of letter orientation and background orientation with eight repetitions per combination. Trial order was fully randomized. On each trial, the stimulus was presented for 500 ms, after which the letter disappeared and a uniform gray background (matched to the gray in the visual backgrounds) remained on the screen while participants made their response (p or d) via a game controller. The next trial began immediately after a response, resulting in a response-contingent ISI with no fixed interval. This design allowed for precise control of stimulus duration while maintaining a continuous and efficient trial flow.

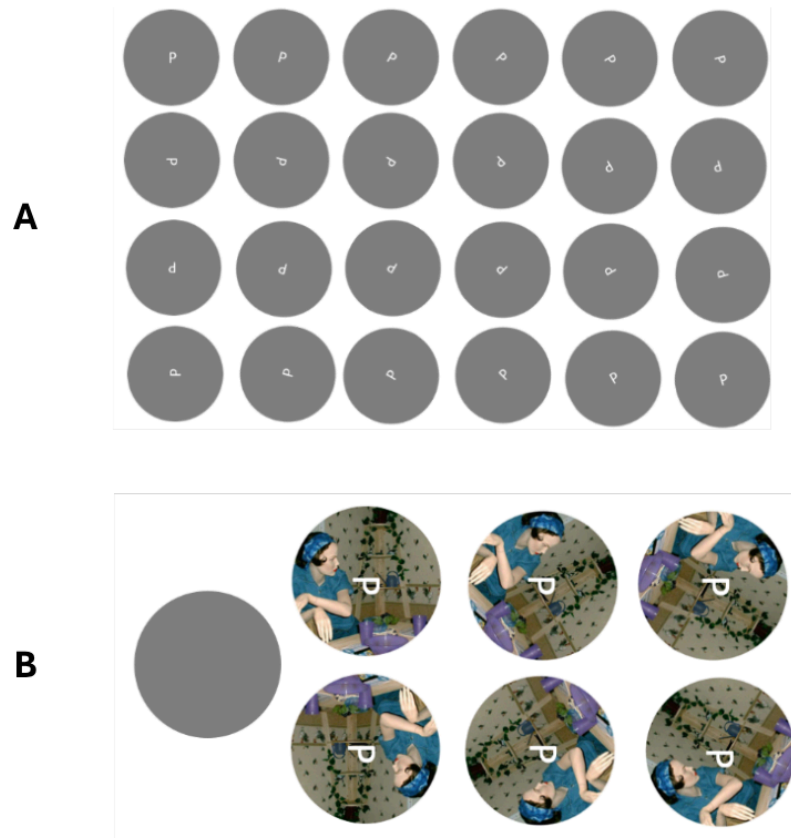


Figure 2.1: Stimuli used in the Oriented Character Recognition Task (OCHART).

A: Letter orientations of the character stimuli (“p”/“d”) used in the task, presented in 15-degree increments in all 24 letter orientations. **B:** All visual backgrounds used in the task, including the plain gray background and the rotated room in 60-degree increments.

2.2.2 Fast Motion Sickness Scale (FMS)

CS severity was assessed using the Fast Motion Sickness Scale (FMS), a simple self-report tool ranging from 0 (“no sickness”) to 20 (“severe sickness requiring termination”). After each trial, participants rated their level of discomfort (Keshavarz & Hecht, 2011), providing a continuous, trial-by-trial measure of how symptoms developed across the VR exposure. This design allowed us to track both acute symptom escalation and cumulative changes across multiple exposures.

One limitation of using the FMS is that severe symptoms may lead to participant dropout, which reduces the completeness of longitudinal data. In this study, attrition occurred in some cases; for

clarity, the number of affected trials is summarized briefly here, with detailed counts provided in the Appendix. Despite this limitation, the FMS remains one of the most sensitive and practical measures of CS for repeated assessments within a single session.

Beyond methodological considerations, the use of the FMS is central to addressing an important research gap concerning age differences in CS susceptibility. While it is well established that individuals vary widely in their tolerance for VR (Saredakis et al., 2020; Howard & Van Zandt, 2021; Luong et al., 2022), the literature on how age influences these patterns remains mixed. Some studies suggest that older adults may report fewer symptoms, potentially due to slower movement patterns or reduced visual–vestibular sensitivity (Dilanchian et al., 2021; Saredakis et al., 2020). Others, however, point to greater vulnerability in older participants, particularly in visually demanding VR tasks where balance and sensory integration are taxed (Risi & Palmisano, 2019). This heightened vulnerability may be linked to age-related neural changes affecting sensory processing and integration, such as reduced vestibular hair cell function and brainstem processing efficiency, slower multisensory integration, and diminished cerebellar and parietal contributions to postural control. These changes can increase the lag or noise in resolving visual–vestibular conflicts, making VR exposure more destabilizing. This inconsistency highlights the need for trial-by-trial symptom tracking across different age groups to clarify whether aging confers resilience or risk in VR contexts.

By combining the FMS with motion capture and perceptual measures, the present study provides a framework to explore not only the within-session development of CS but also how susceptibility may vary across individuals of different ages. This focus on age differences is critical for both theory and application: theoretically, it can refine models of sensory reweighting and postural control across the lifespan, while practically, it can inform the design of VR systems that remain accessible and tolerable for diverse populations.

2.2.3 Qualisys Markerless Motion Capture

To analyze body movement and postural control, the study used the Qualisys Track Manager (QTM) motion capture system. Eight synchronized RGB cameras recorded participants' movements (Figure 2.2). Data were processed using Theia, a computer vision software that estimates 3D body poses and overlays a skeletal model. Processed data were then imported into Visual3D for biomechanical analysis (Figure 2.3).

This pipeline allowed us to extract measures such as center of mass (CoM), CoM velocity, and path length, which served as indicators of balance and movement style. These metrics were then compared against perceptual (OCHART) and subjective (FMS) measures, enabling us to test whether postural control and movement patterns relate to CS severity and sensory reweighting (Kanko et al., 2021; Salehi et al., 2024).

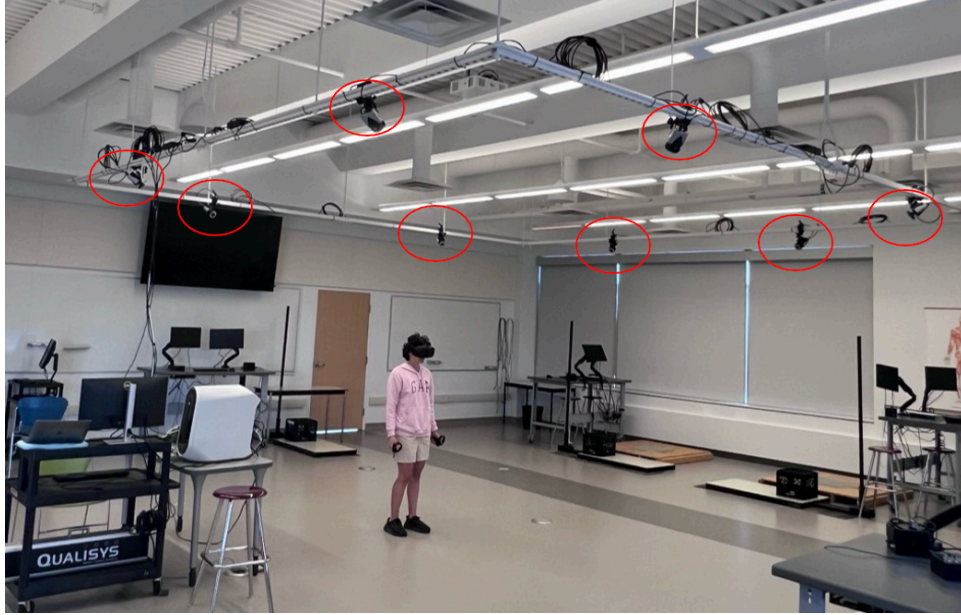


Figure 2.2: Motion capture laboratory setup with VR integration.

Example participant wearing a VR headset stands in the capture volume while 8 Qualisys motion capture cameras (highlighted in red) are positioned around the ceiling to track movement. This configuration enabled precise recording of whole-body kinematics during immersive VR exposure.

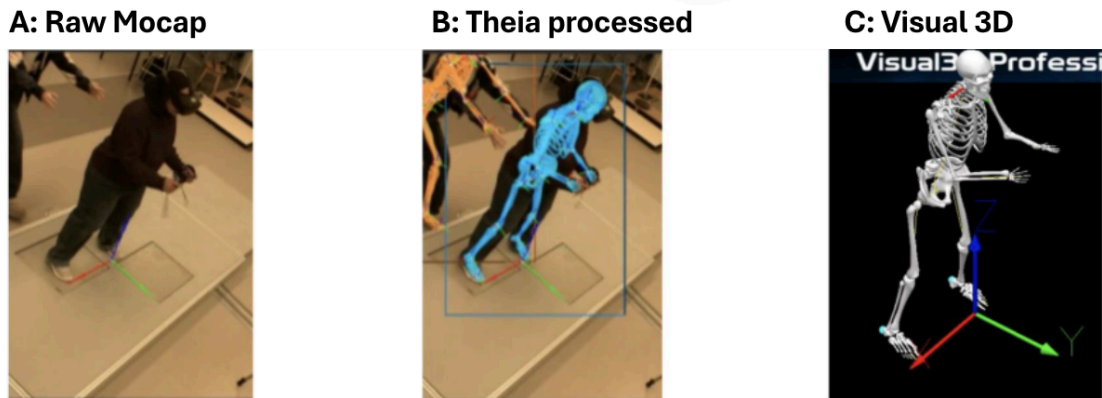


Figure 2.3: Motion capture data processing pipeline.

A: Raw motion capture (mocap) video collected during a trial, organized by trial number and camera ID. **B:** Theia processed data, including intelligent joint detection and labeling, multi-subject tracking, and automatic model creation. **C:** Biomechanical model generated in Visual 3D, which provides an extensive toolbox for biomechanical analysis. Parameters for subsequent analyses were extracted from this environment.

2.2.4 Oculus Headset – Epic Roller Coasters

VR exposure was delivered using the Oculus Quest 1 headset, which has OLED screens (1440×1600 resolution per eye) running at 72 Hz (Oculus, 2019). The chosen VR application was *Epic Roller Coasters*, selected because of its strong ability to induce CS. This game simulates fast roller coaster rides with sharp turns, drops, and loops, producing intense visual–vestibular mismatches.

The Oculus platform classifies *Epic Roller Coasters* as “intense,” reflecting the high likelihood of discomfort (Meta, 2019). This made it a suitable tool for studying individual differences in CS, as milder VR experiences may not reliably elicit symptoms.

All trials used the “Tropical Island” track (Figure 2.4), which features rapid direction changes, steep drops, and richly detailed scenery. These features increase immersion and presence but also maximize the likelihood of sensory conflict, making the track an ideal choice for probing how perceptual and motor systems adapt under challenging VR conditions.



Figure 2.4: VR roller coaster environment used to induce CS.

Screenshot from the *Epic Roller Coasters* VR application used to induce CS. The simulation includes rapid motion, sudden turns, and loops, creating strong visual–vestibular conflict to reliably provoke CS symptoms in participants.

2.3 Procedure

Each participant first completed a baseline OCHART task while seated upright. To ensure that visual input came only from the task itself, participants positioned their faces as close as comfortably possible to the laptop screen. They then repeated the OCHART task while lying in a right-side-down body orientation, using the same instructions. This manipulation allowed us to compare how visual, gravitational, and proprioceptive cues contribute to judgments of upright. Depending on the participant, each OCHART session lasted between 15 and 45 minutes.

After completing the baseline OCHART tasks, participants moved to the center of the motion capture area, where they were fitted with the Oculus headset. They then completed the VR roller coaster task (Tropical Island track, 2 minutes 30 seconds per ride). Before the ride began, participants were instructed to keep their feet planted and remain as still as possible, maintaining a natural upright stance. They were told that if they felt unstable, they could move or sway to maintain balance but should avoid stepping unless absolutely necessary for safety. This standardized instruction minimized voluntary movement while still allowing natural postural adjustments. Verbal instructions signaled

the start of each trial, and motion capture recordings were initiated at the same time. The markerless system was pre-set to record the full duration of each ride.

Each participant completed eight VR trials. After every trial, they verbally reported their peak sickness score using the Fast Motion Sickness (FMS) scale, with the prompt: “From 0 to 20, what was your peak sickness score during this ride?” Immediately afterward, they completed another OCHART task in the right-side-down orientation (Figure 2.5). This design made it possible to track changes in perceptual upright across repeated VR exposures and to relate these changes to both body movement and sickness severity.

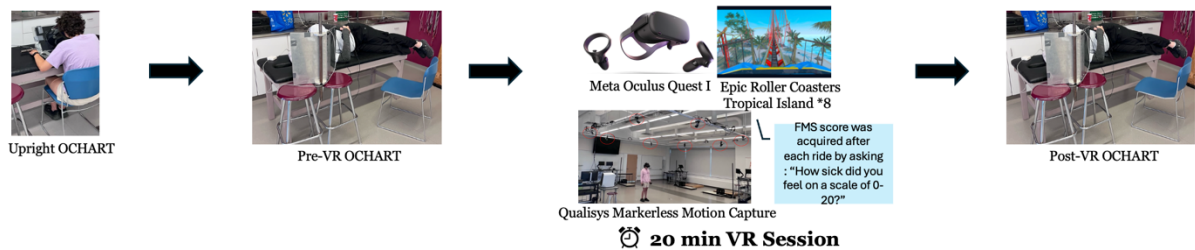


Figure 2.5: Experimental protocol flowchart.

Participants first completed the upright Oriented Character Recognition Task (OCHART), followed by a pre-VR OCHART in a right-side-down body position. They then underwent a 20-minute VR session using the *Epic Roller Coasters* application on the Oculus Quest I headset, with whole-body kinematics recorded via Qualisys markerless motion capture. After each ride, participants reported CS severity using the Fast Motion Sickness (FMS) scale. The session concluded with a post-VR OCHART to assess changes in perceptual upright.

2.4 Data Analysis

2.4.1 OCHART analysis

Responses from the OCHART task were first plotted as the percentage of “p” responses against character orientation. The resulting psychometric function followed a sigmoidal shape: at upright orientations (0° or 360°), responses were almost always “p,” while at inverted orientations (180°), responses shifted toward “d.” Between these extremes, the curve transitioned gradually from “p” to “d.”

The key points of interest were where responses were split evenly between “p” and “d” (50% each). These are known as the Points of Subjective Equality (PSE). Each psychometric curve

produced two such transition points. These were averaged and then adjusted by 180° to calculate the perceptual upright (PU), following the method outlined by Dyde et al. (2006). PU therefore represents the orientation at which the participant perceives ambiguous letters as equally likely to be upright or inverted, providing an estimate of their internal sense of upright.

This procedure was repeated separately for each background condition. By analyzing PU across different room orientations, as well as across pre- and post-VR exposures, we obtained a detailed set of values that revealed how upright perception shifted under varying sensory contexts.

2.4.2 Vector Sum Model

To move beyond raw PU values and quantify the contributions of vision, body orientation, and gravity, data were analyzed with a vector sum model. This model is based on the idea that the brain treats each sensory input as a directional signal for “up,” and combines them as if they were vectors (Dyde et al., 2006; Barnett-Cowan et al., 2010).

- Gravity was set as a fixed reference (weight = 1.0), always pointing toward physical vertical.
- Vision was represented by the orientation of the visual background (e.g., a rotated room).
- Body orientation was represented by the posture of the participant (e.g., upright or side-lying).

Unlike gravity, the weights for vision and body were unknown. These weights reflect the relative reliance participants placed on each cue when judging upright.

Each cue was represented as a unit vector pointing in its respective direction, scaled by its weight. The three vectors were then summed to produce a resultant vector, whose direction corresponded to the predicted PU. To estimate the weights, the model compared these predicted PU values to the actual measured PUs from the OCHART task. A least-squares fitting method was used to minimize the error between predicted and observed values (Figure 2.6).

This procedure yielded the best-fitting weights for vision and body relative to gravity. For example, a vision weight greater than 1.0 would suggest that the participant relied more on visual cues than on gravity, while a body weight smaller than 1.0 would suggest weaker reliance on proprioceptive input.

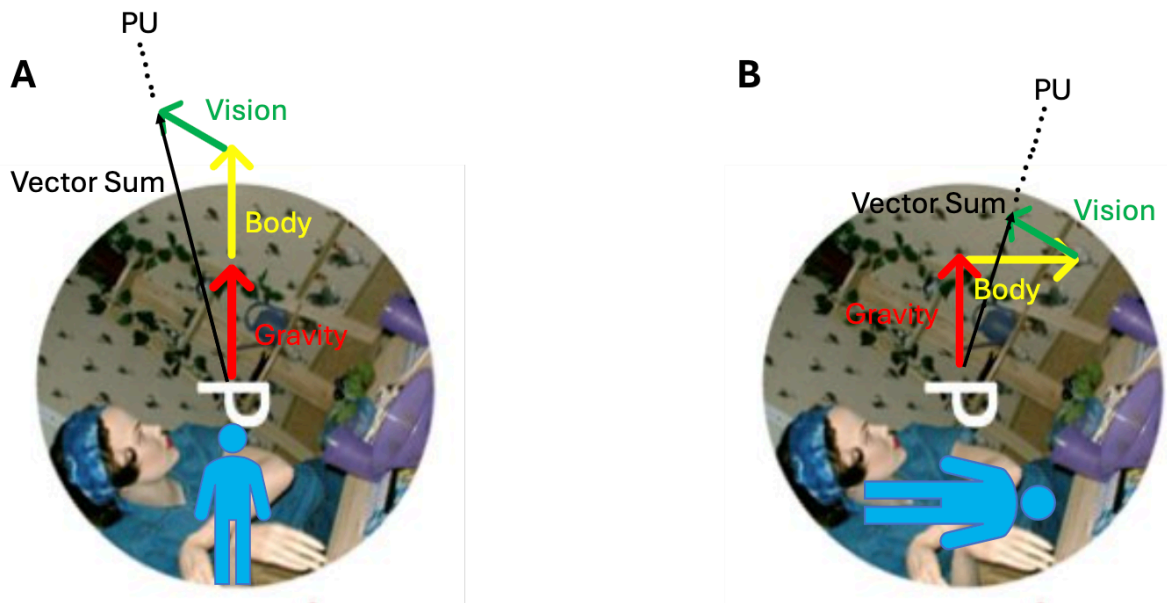


Figure 2.6: Illustration of the vector sum model of perceptual upright (PU).

A: When the participant is upright, gravity (red) is fixed at physical vertical (weight = 1.0), while body orientation (yellow) and vision (green) provide additional directional cues. Each cue is represented as a unit vector scaled by its weight, and the weighted vectors are combined to produce a resultant vector whose direction corresponds to the predicted PU (black). **B:** When the participant is supine, the contribution of body orientation shifts relative to gravity, while vision remains aligned with the rotated background. The same vector summation process applies, with differences in weighting across cues determining the predicted PU.

2.4.3 Interpreting Weighting Changes

By applying the vector sum model separately before and after VR exposure, we were able to examine whether sensory weighting shifted as a result of immersion. Increases in visual weighting after VR would suggest greater reliance on visual cues, while decreases in body weighting could indicate reduced trust in proprioceptive input. Such changes would reflect the process of sensory reweighting in response to altered sensory conditions.

This approach has been validated in earlier work. Dyde et al. (2006) showed that OCHART provides a balanced measure of cue contributions, unlike SVV, which is heavily biased toward gravity. Barnett-Cowan et al. (2010) further demonstrated how visual weighting dominates in structured environments, while vestibular and body cues take on greater importance when visual

references are weak. By building on this framework, the current analysis allows us to test whether VR exposure alters the relative influence of sensory cues, and whether these changes are linked to CS and movement patterns.

2.4.4 Interpreting Weighting Changes

To ensure reliability, PU values were analyzed only when OCHART responses yielded stable psychometric functions. As noted in the Participants section, three participants were excluded because their responses were too variable to provide consistent PU estimates. Such instability can arise for multiple reasons: (i) attentional lapses or inconsistent engagement, (ii) misunderstanding of the p/d classification task, and (iii) genuinely unstable internal estimates of upright under sensory conflict. Critically, when instability appears even under the neutral gray background (where two smooth, inverse-sigmoidal transitions $\sim 180^\circ$ apart are expected), this pattern is most consistent with instruction/comprehension or attention issues rather than perceptual reweighting. In all retained datasets, fits were inspected to confirm smooth, monotonic transitions between upright and inverted responses, ensuring that PU estimates and vector-sum modeling were based on valid, interpretable data.

2.4.5 Statistical Analysis

All analyses were conducted in R (Version 2023.12.0). The main goal was to test whether changes in sensory cue weighting and postural movement predicted CS severity, measured with the Fast Motion Sickness (FMS) scale. A secondary goal was to examine whether swaying in different directions (anterior–posterior, AP, vs. medio–lateral, ML) contributed differently to CS.

Three participants did not show clear transitions between “p” and “d” judgments across orientations in the OCHART task. Without these structured perceptual shifts, the vector sum model could not generate realistic cue weights (producing extreme values, sometimes in the millions). Dyde et al. (2006) noted that reliable cue weighting requires consistent perceptual variation across conditions. For this reason, these participants were excluded from analyses involving Hypothesis 1. This left 22 participants for the sensory weighting analyses.

2.4.5.1 Hypothesis 1: Cue weighting and CS

To test whether sensory cue reweighting predicted CS severity, we ran a set of linear regression models. Both final and average FMS scores were used as outcomes. Three predictor sets were tested:

1. Total reweighting magnitude: the Euclidean distance of changes in vision, body, and gravity cue weights.
2. Direction of change: whether each cue increased or decreased after VR exposure.
3. Absolute size of change: the amount of change regardless of direction.

2.4.5.2 Hypothesis 2: Postural movement and CS

To test whether movement predicted CS, we used linear mixed-effects models with random intercepts for participants. Each movement parameter was entered separately as a fixed effect, with FMS scores as the dependent variable. Parameters included:

1. Mean velocity
2. RMS displacement
3. Total path length
4. Sway area

We also explored sway direction. Separate and combined models were run with AP and ML path lengths and RMS displacement as predictors. Correlations and variance inflation factors (VIFs) were used to check multicollinearity.

For regressions, residuals were checked for normality, linearity, and homoscedasticity. For mixed-effects models, random effects were inspected with Q–Q and residual–fitted plots. VIFs confirmed acceptable collinearity levels. Outliers were identified with Grubbs’ test (single points) and the extreme studentized deviate (ESD) method (multiple points). Models were rerun without these cases to check robustness. False discovery rate (FDR) correction was applied to related tests. For paired-sample t-tests, effect sizes were expressed as Cohen’s d_z . The significance level was set at $\alpha = .05$.

Chapter 3

Results

3.1.1 FMS

Figure X shows the progression of FMS scores across the eight VR trials for each participant (N = 25). Each colored line represents an individual's trajectory over time, while the dots on the right display average FMS across trials. As can be seen, participants exhibited divergent sickness trajectories. A subset of individuals started with low FMS and remained stable or low throughout the session (e.g., P6), suggesting minimal symptom accumulation. Others began at moderate levels and increased steadily over repeated exposures (e.g., P23), indicating a gradual build-up of discomfort. A few participants displayed abrupt increases mid-session (e.g., P7), consistent with delayed onset patterns of CS, while a smaller number showed decreases or downward fluctuations over trials (e.g., P14), potentially reflecting adaptation or habituation. This pattern underscores that cybersickness does not develop uniformly across individuals but follows distinct temporal trajectories, which may be linked to differences in sensory integration strategies, movement behavior, or prior VR tolerance.

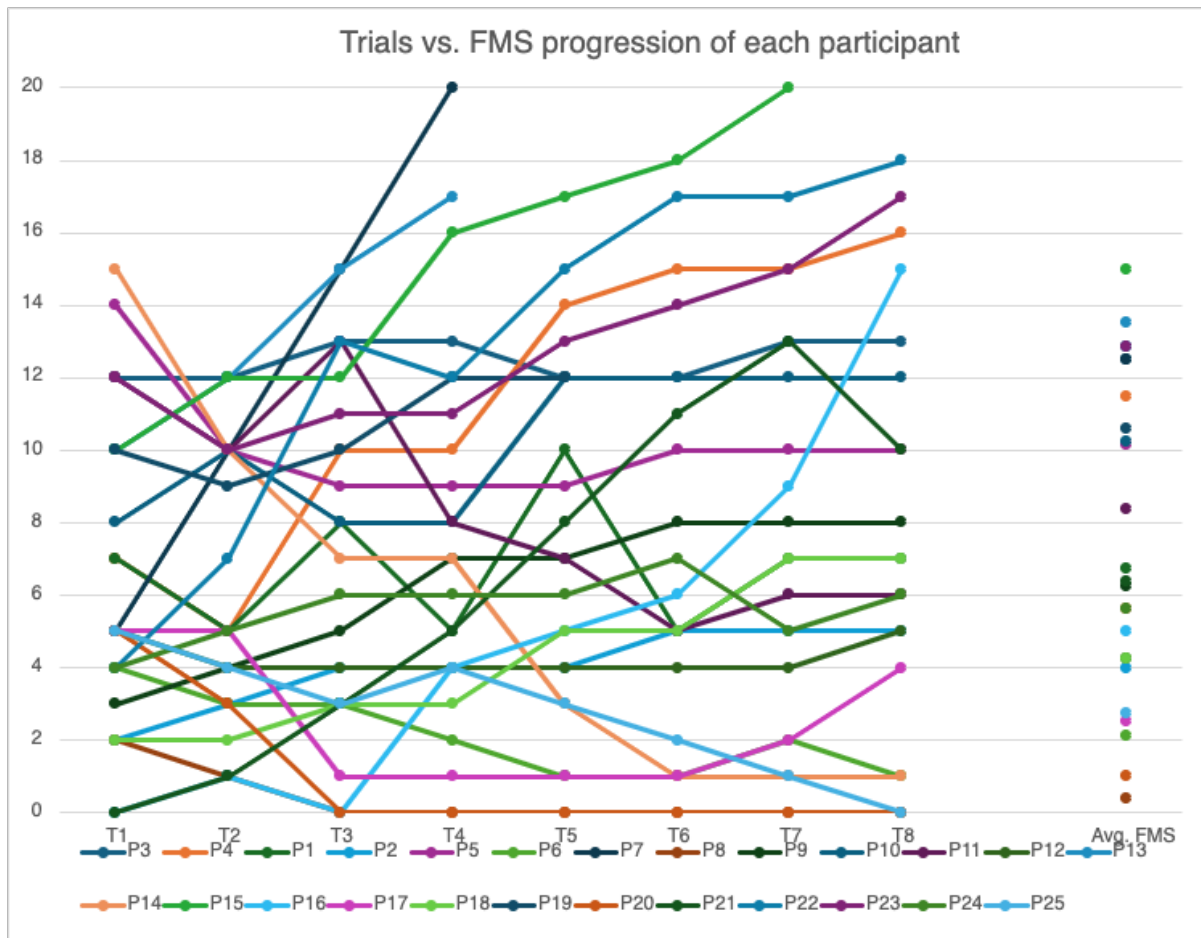


Figure 3.1: Trial-by-trial progression of cybersickness severity (FMS) across VR exposures.

This figure shows the progression of Fast Motion Sickness (FMS) scores across eight VR trials (T1–T8) for all participants ($N = 25$). The X-axis represents trial number, and the Y-axis represents FMS scores on a 0–20 scale. Each colored line corresponds to one participant’s trajectory of self-reported sickness over time. The dots on the right display each participant’s average FMS score across all trials.

3.1.2 Movement Analysis – Individual level

Before examining the relationship between movement parameters and FMS or OCHART outcomes, it is necessary to describe how participants moved during the VR task in isolation. Figures 3.1–3.11 illustrate representative examples of postural control patterns, contrasting a participant who exhibited

the minimum total path length (minimal sway) with one who exhibited the maximum total path length among participants completing all eight trials.

As shown in Figures 3.1, 3.3–3.5, the minimal sway participant demonstrated highly constrained postural adjustments. In the two-dimensional A–P vs. M–L displacement plots (Figure 3.1), the 95% confidence ellipses were small and tightly clustered, reflecting limited variability across trials. Similarly, time-series traces of mediolateral (X) and anteroposterior (Y) displacement (Figures 3.3–3.4) were relatively flat, with minimal fluctuations across the 150-s recording period. The vertical (Z) displacement (Figure 3.5) was nearly invariant across trials. These patterns suggest a conservative control strategy under VR sensory challenge, in which sway amplitude is reduced to maintain stability.

By contrast, the maximal sway participant (Figures 3.2, 3.6–3.8) exhibited broad and irregular trajectories with much larger 95% confidence ellipses, indicating greater variability across trials. Time-series traces revealed pronounced fluctuations in both the X and Y axes (Figures 3.6–3.7), while the Z axis (Figure 3.8) remained comparatively stable. Notably, variability appeared to increase across successive trials, suggesting that repeated VR exposure may have compounded postural instability or that this participant was unable to converge to a stable strategy.

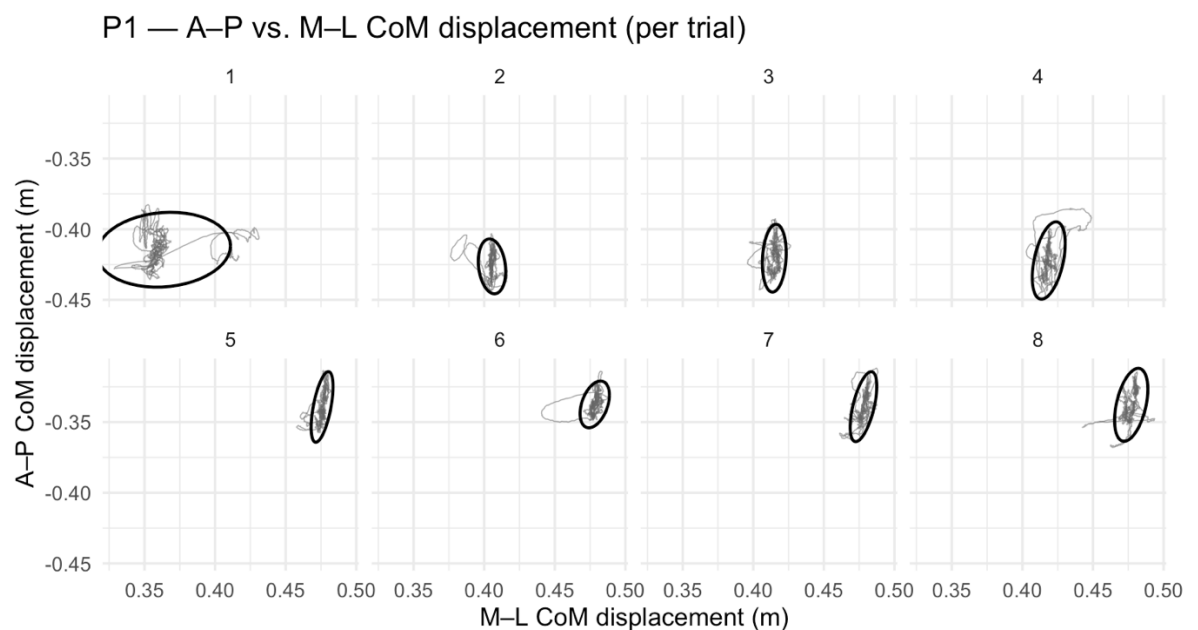


Figure 3.2: Example Participant’s AP vs. ML COM Displacement – Min Total Path length

Example participant's anteroposterior (A-P) vs. mediolateral (M-L) center of mass (CoM) displacement across eight trials. This participant demonstrated the **lowest total path length** across the sample (minimal sway). Each panel shows the two-dimensional CoM trajectory for one trial, with the black ellipse representing the 95% confidence region of sway.

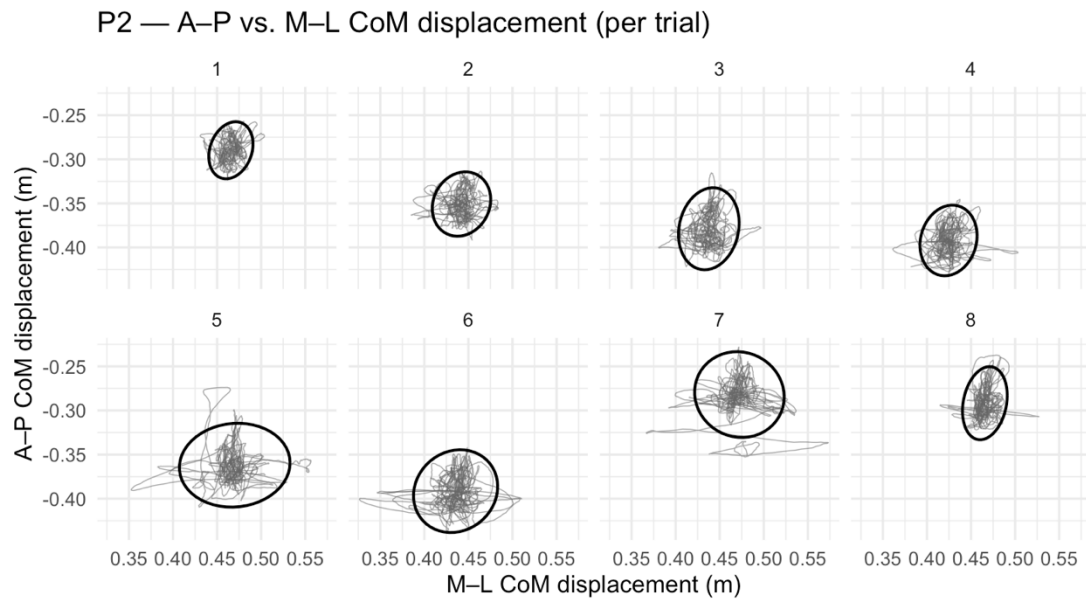


Figure 3.3: Example Participant's AP vs. ML COM Displacement – Max Total Path length

Example participant's anteroposterior (A-P) vs. mediolateral (M-L) center of mass (CoM) displacement across eight trials. This participant demonstrated the **highest total path length** among participants completing all eight trials (maximal sway). Each panel shows the two-dimensional CoM trajectory for one trial, with the black ellipse representing the 95% confidence region of sway.

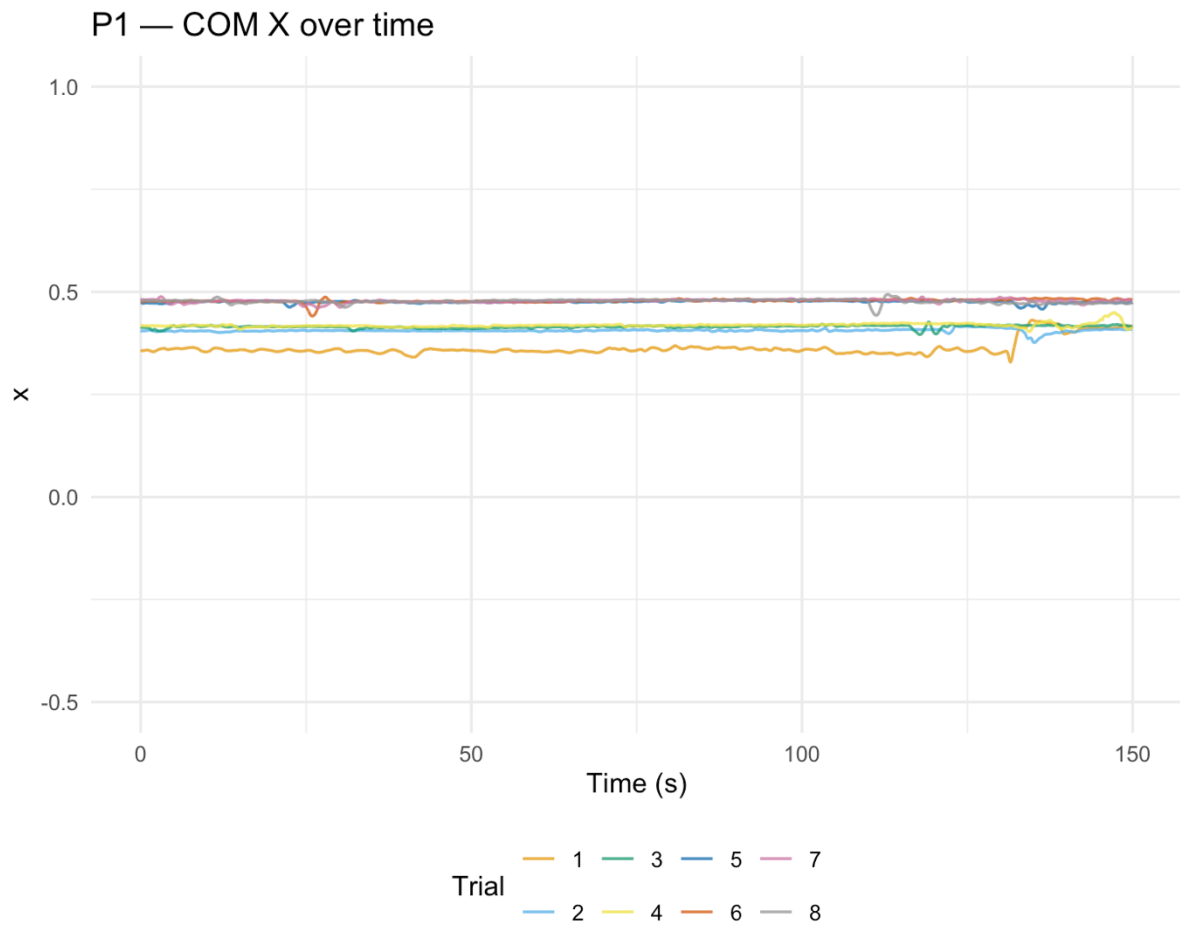


Figure 3.4: Example Participant's COM X vs. Time (s) – Min Total Path length

Example participant with the **minimum total path length**: Center of mass displacement in the mediolateral (X) direction across eight trials (150 s each). Each colored trace represents one trial.

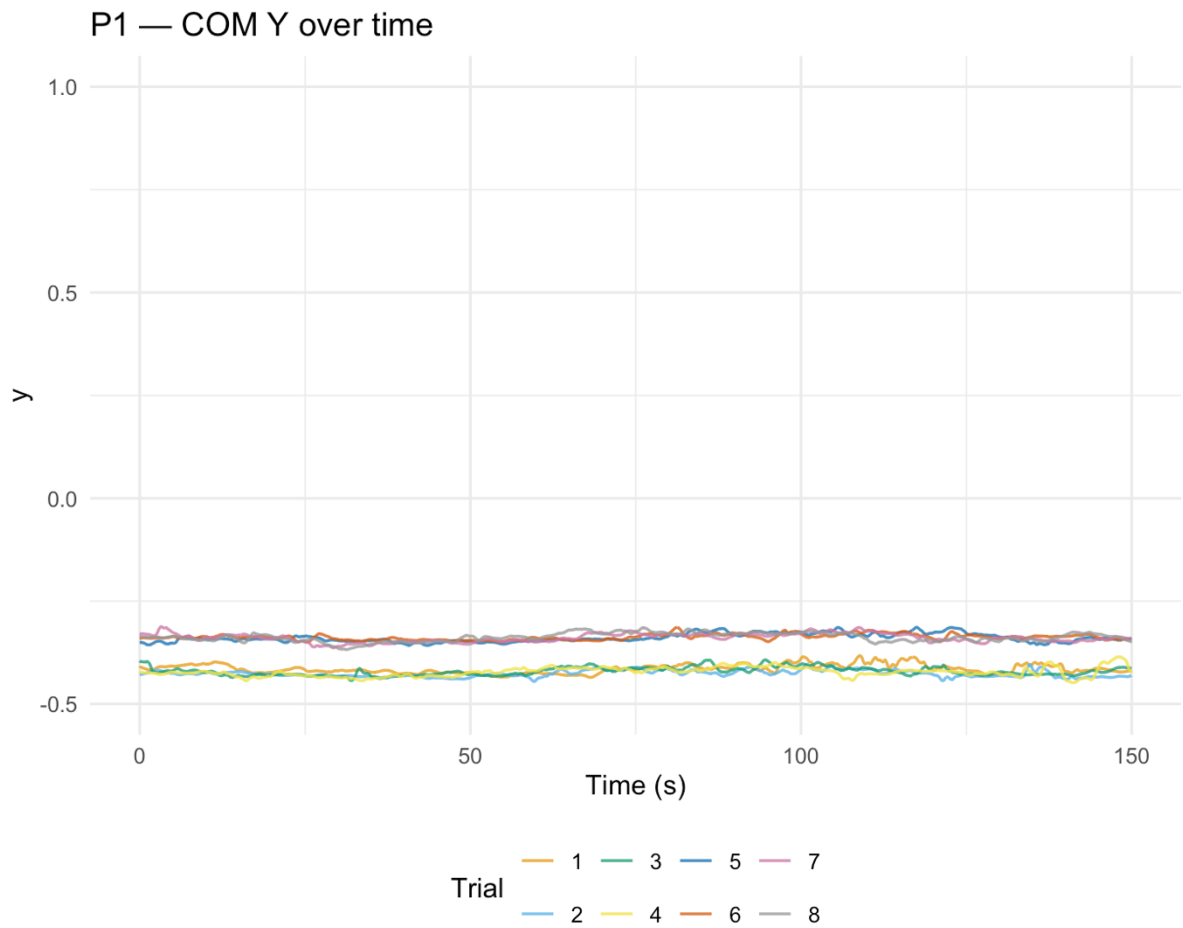


Figure 3.5: Example Participant's COM Y vs. Time (s) – Min Total Path length

Example participant with the **minimum total path length**: Center of mass displacement in the anteroposterior (Y) direction across eight trials. Minimal variability is observed across time and trials.

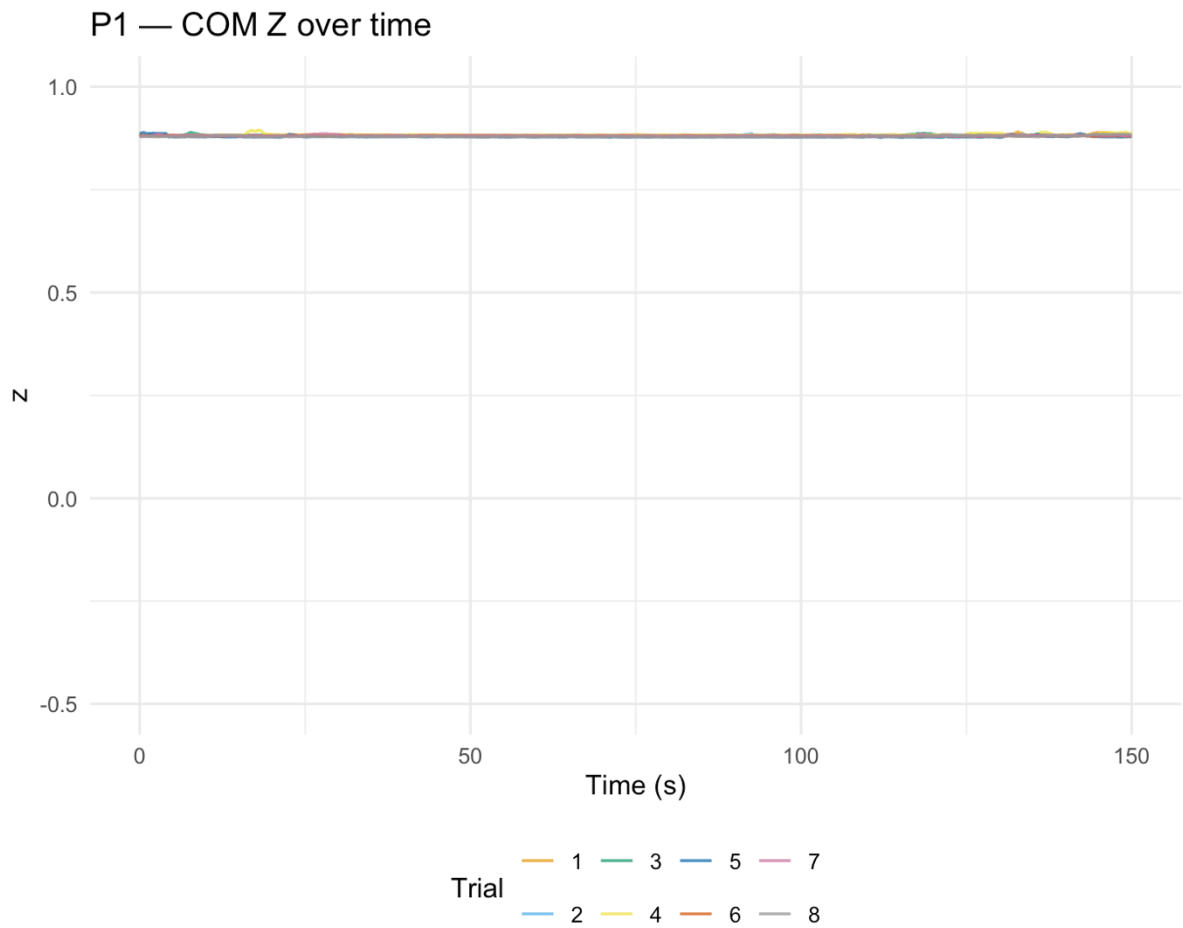


Figure 3.6: Example Participant's COM Z vs. Time (s) – Min Total Path length

Example participant with the **minimum total path length**: Center of mass displacement in the vertical (Z) direction across eight trials. Displacements remained highly stable over time.

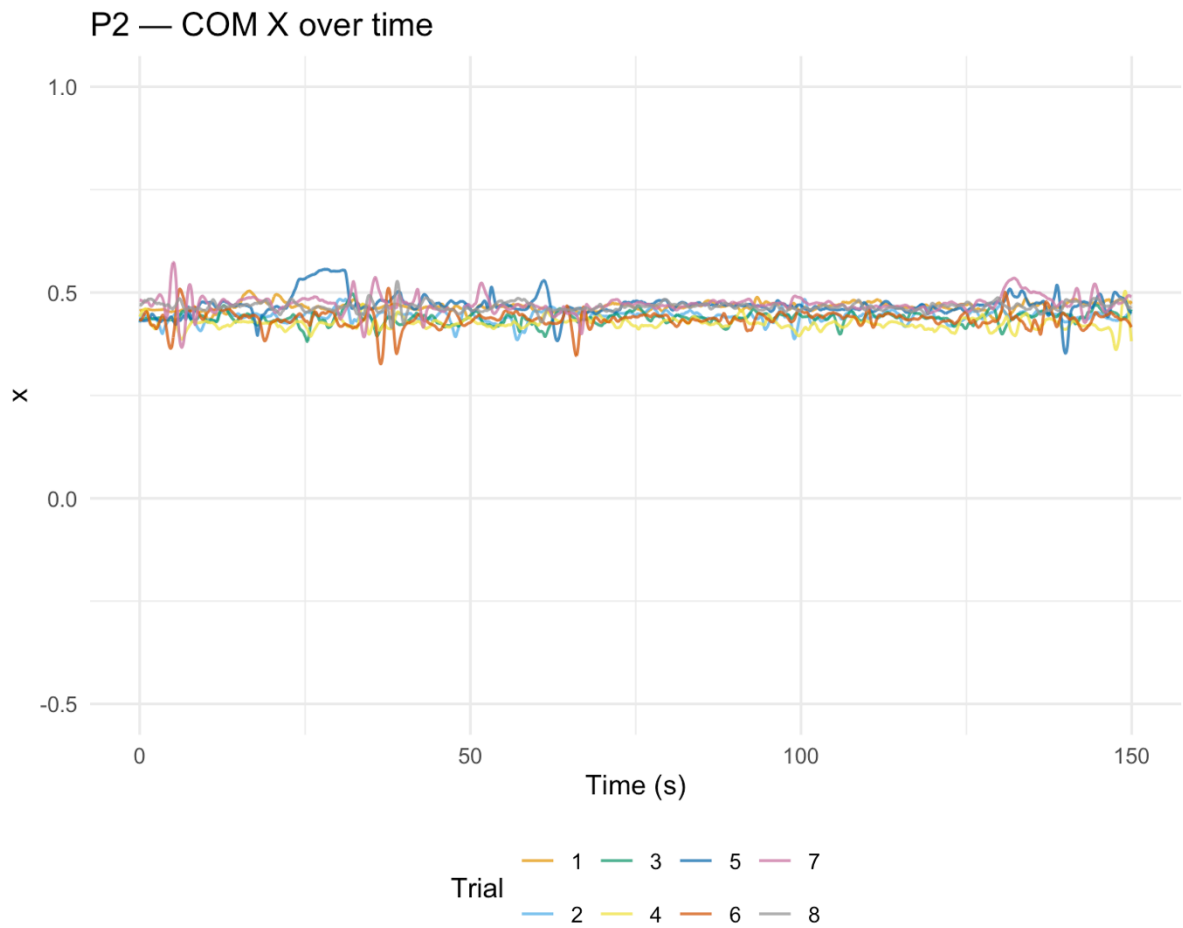


Figure 3.7: Example Participant's COM X vs. Time (s) – Max Total Path length

Example participant with the **maximum total path length**: Center of mass displacement in the mediolateral (X) direction across eight trials. Larger fluctuations are observed across time compared to the low-sway participant.

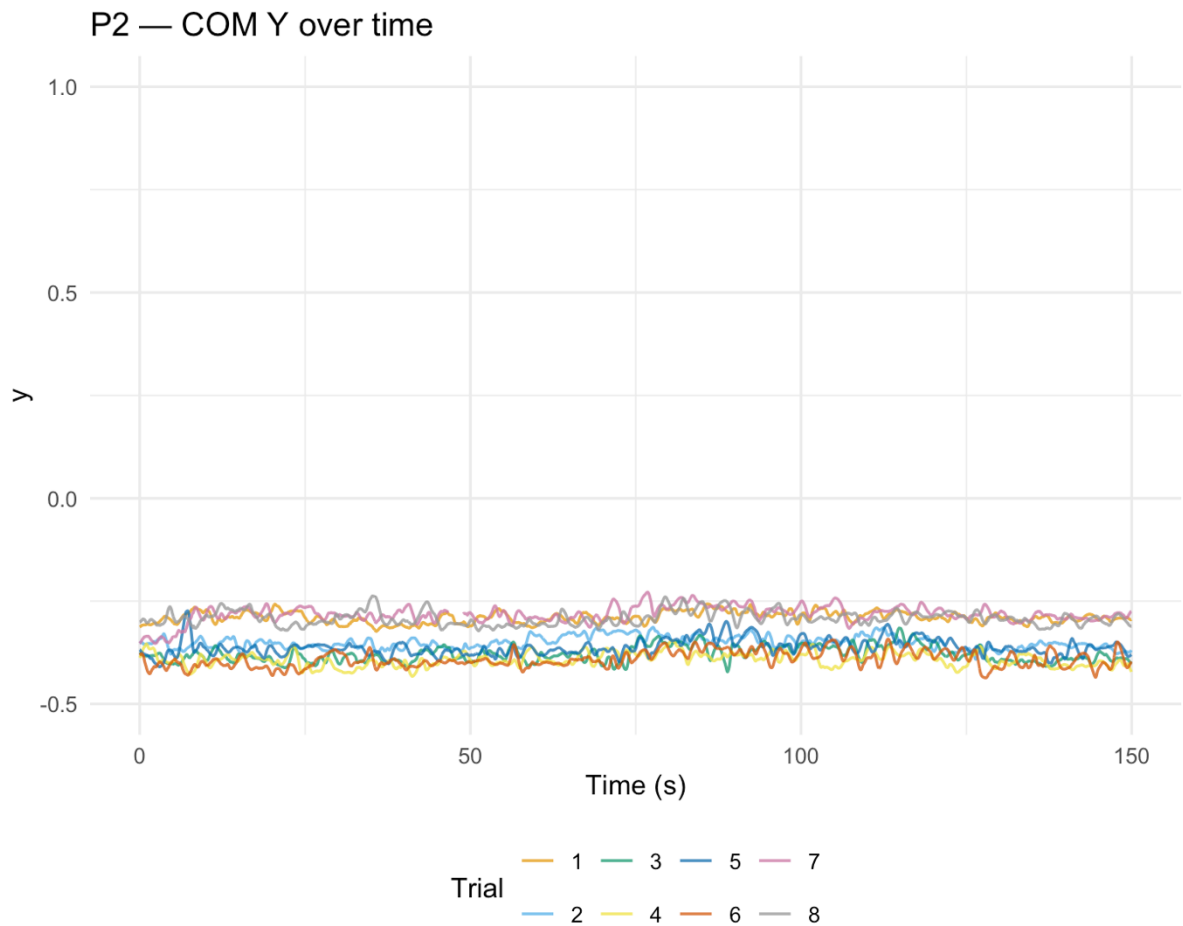


Figure 3.8: Example Participant's COM Y vs. Time (s) – Max Total Path length

Example participant with the **maximum total path length**: Center of mass displacement in the anteroposterior (Y) direction across eight trials. Trial-to-trial variability is more pronounced than in the minimal sway participant.

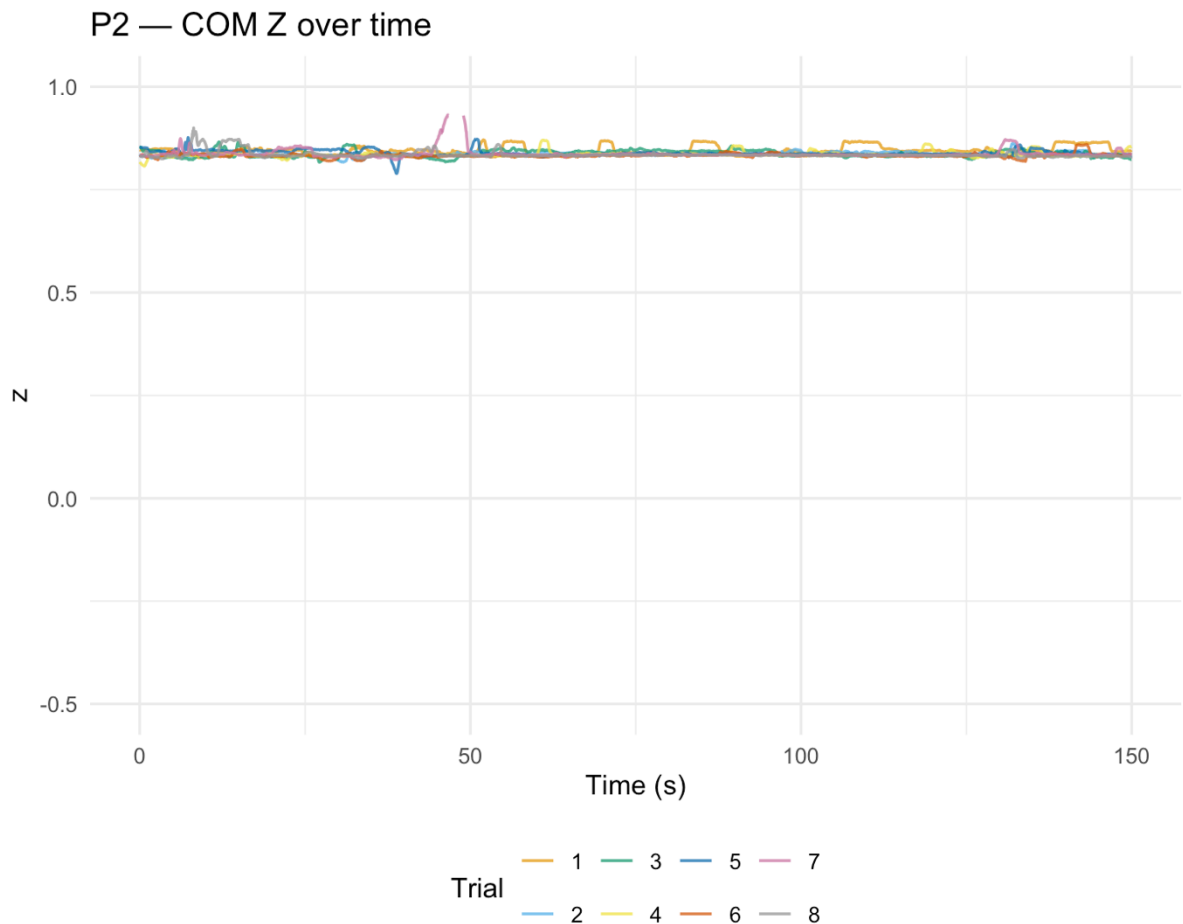


Figure 3.9: Example Participant’s COM Z vs. Time (s) – Max Total Path length

Example participant with the **maximum total path length**: Center of mass displacement in the vertical (Z) direction across eight trials. Variability is limited, with most movement occurring in the X–Y plane.

Velocity traces provided complementary insights into these differences (Figures 3.9–3.11). Whereas displacement reflects the magnitude of CoM excursions, velocity captures the *rate and intensity* of corrective movements, offering a dynamic perspective on balance regulation. For the minimal sway participant, velocity in all three axes remained tightly centered around zero, with low-amplitude oscillations in the mediolateral (X) and anteroposterior (Y) directions, and near-flat traces in the vertical (Z) direction. These stable velocity patterns reinforce the notion of constrained corrective control under VR conditions.

In contrast, the maximal sway participant demonstrated frequent, high-amplitude fluctuations in velocity, particularly along the mediolateral and anteroposterior axes. These bursts of corrective movements extended toward the upper and lower bounds of the standardized velocity scale, highlighting an instability characterized not only by larger displacement but also by erratic, rapid corrections. Vertical velocity also displayed intermittent spikes, though of smaller magnitude compared to the horizontal plane—consistent with the idea that most postural corrections occur in the horizontal axes. Importantly, high velocity does not always equate to maladaptive instability; it may also reflect *active engagement* or *exploratory sway*, whereby participants deliberately increase movement variability to probe multisensory cues and recalibrate balance.

This dual interpretation highlights a broader tension in the literature. While reduced sway and low-velocity corrections may indicate an adaptive stiffening strategy, they could also reflect diminished exploratory behavior, which some authors argue is necessary for effective sensory recalibration during VR exposure (Stoffregen & Bardy, 2001). Conversely, larger excursions and high-velocity bursts, although destabilizing, might reflect attempts to actively sample multisensory information when conflicts arise. This debate—whether increased sway is purely maladaptive or sometimes adaptive—remains unresolved (Stoffregen & Bardy, 2001; Palmisano et al., 2018). Our contrasting participants exemplify this ambiguity: one appeared to achieve stability by constraining movement, while the other displayed instability that could reflect either maladaptive reliance on visual cues or an unsuccessful attempt at adaptive reweighting.

To summarize, displacement and velocity analyses reveal divergent postural control strategies under identical VR conditions. Some individuals suppress sway and corrections to stabilize posture, while others exhibit broad excursions and high-velocity bursts that may either destabilize or serve as exploratory recalibration attempts. These observations provide a critical bridge to group-level analyses: if participants systematically differ in whether they adopt stabilizing versus destabilizing strategies, simple averaging may conceal meaningful variability. Instead, variability itself may be the key predictor of sensory reweighting ability and CS susceptibility. By integrating displacement and velocity perspectives into a single narrative, we provide a more comprehensive characterization of individual movement profiles, which sets the foundation for subsequent analyses linking balance behavior to OCHART and FMS outcomes.

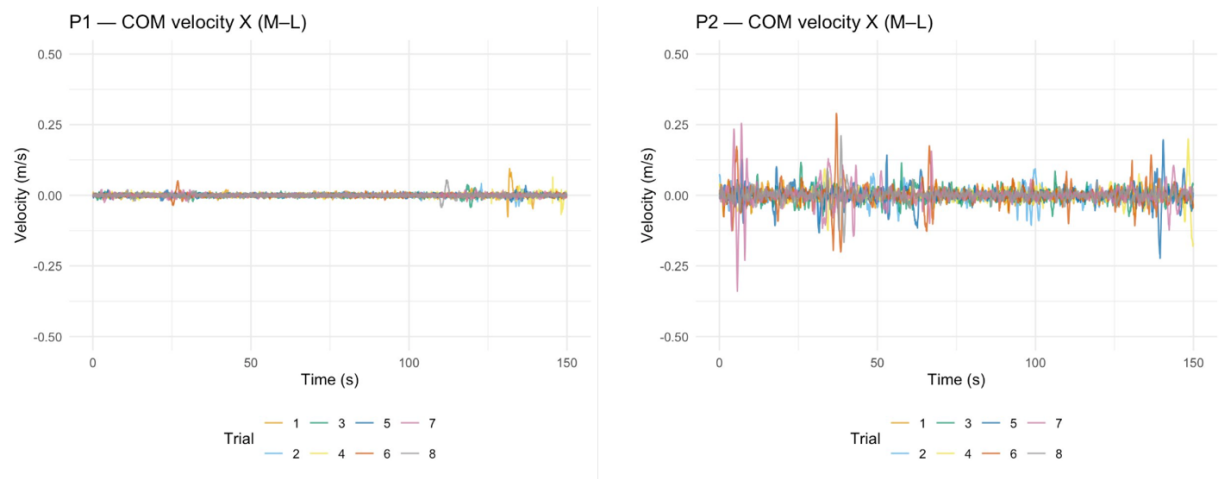


Figure 3.10: Example Participants' COM Velocity in the Mediolateral (X) Direction Across Trials

Time series plots of center of mass (COM) velocity in the mediolateral (M-L) axis for the low-sway participant (P1, left) and high-sway participant (P2, right). Each line represents one trial ($n = 8$ per participant), with the y-axis constrained between -0.5 and 0.5 m/s for comparability. P1 exhibited consistently small velocity fluctuations near 0 m/s across all trials, whereas P2 showed larger variability and transient peaks, indicating greater instability in mediolateral control.

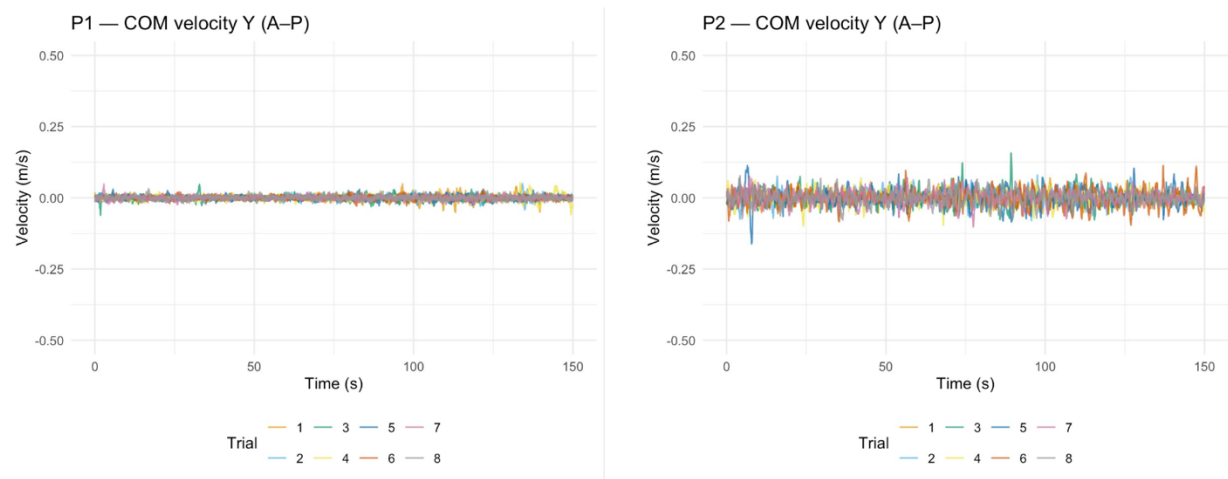


Figure 3.11: Example Participants' COM Velocity in the Anteroposterior (Y) Direction Across Trials

Time series plots of COM velocity in the anteroposterior (A–P) axis for the low-sway participant (P1, left) and high-sway participant (P2, right). The low-sway participant’s traces remained tightly centered around 0 m/s, while the high-sway participant demonstrated visibly greater fluctuations, with repeated oscillatory patterns suggesting greater corrective movements in the A–P direction. Axis limits were held constant (–0.5 to 0.5 m/s) across participants to enable direct comparison.

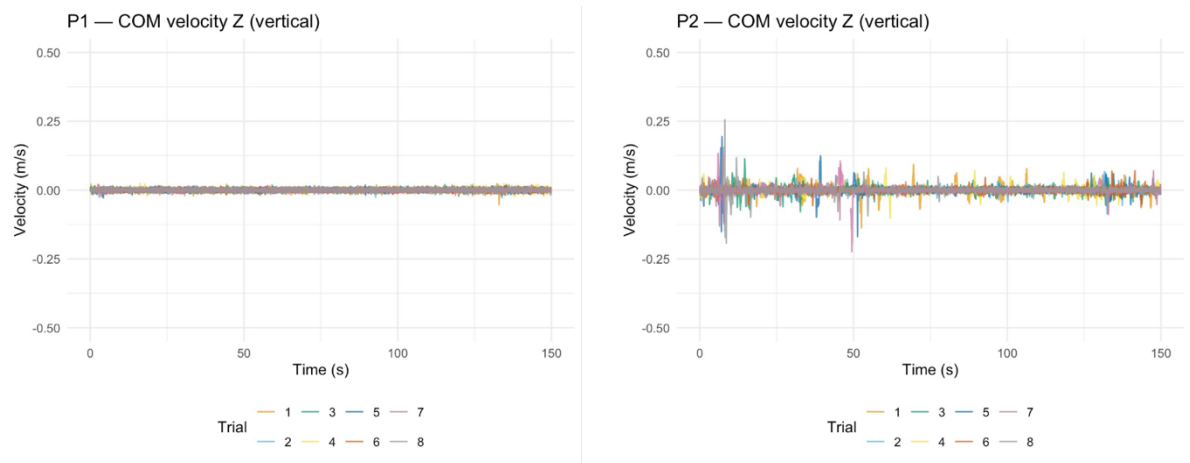


Figure 3.12: Example Participants’ COM Velocity in the Vertical (Z) Direction Across Trials

COM velocity in the vertical (Z) axis for P1 (left) and P2 (right). The low-sway participant showed minimal deviations from 0 m/s across trials, while the high-sway participant exhibited irregular bursts of vertical motion, particularly at trial transitions and during episodes of instability. Consistent scaling (–0.5 to 0.5 m/s) highlights the stark contrast in variability between participants.

3.1.3 Movement Analysis – Group level

While the individual-level analyses (Figures 3.1–3.11) highlighted striking heterogeneity in postural strategies, group-level summaries provide a broader perspective on the typical patterns of CoM displacement and velocity across all participants. These analyses allow us to assess whether VR exposure produced systematic trends in sway behavior and whether variability itself may be an important characteristic of adaptation to immersive environments.

Displacement trajectories (Figure 3.12) revealed that, on average, participants’ CoM excursions remained relatively constrained within ± 0.1 m in both the AP and ML axes. The grand-mean traces

suggested subtle drifts over time, particularly in the AP direction, where displacement variability increased after approximately 100 s. This late-trial divergence is consistent with prior reports that prolonged VR exposure can destabilize stance as sensory conflict accumulates (Palmisano et al., 2015). By contrast, the ML trace remained comparatively stable, reflecting the dominance of AP sway during upright stance and visually demanding balance tasks (Winter, 1998). The finding that ML displacements were more tightly regulated aligns with prior evidence that ML stability is often prioritized, as lateral loss of balance carries greater risk (Kiemel et al., 2011).

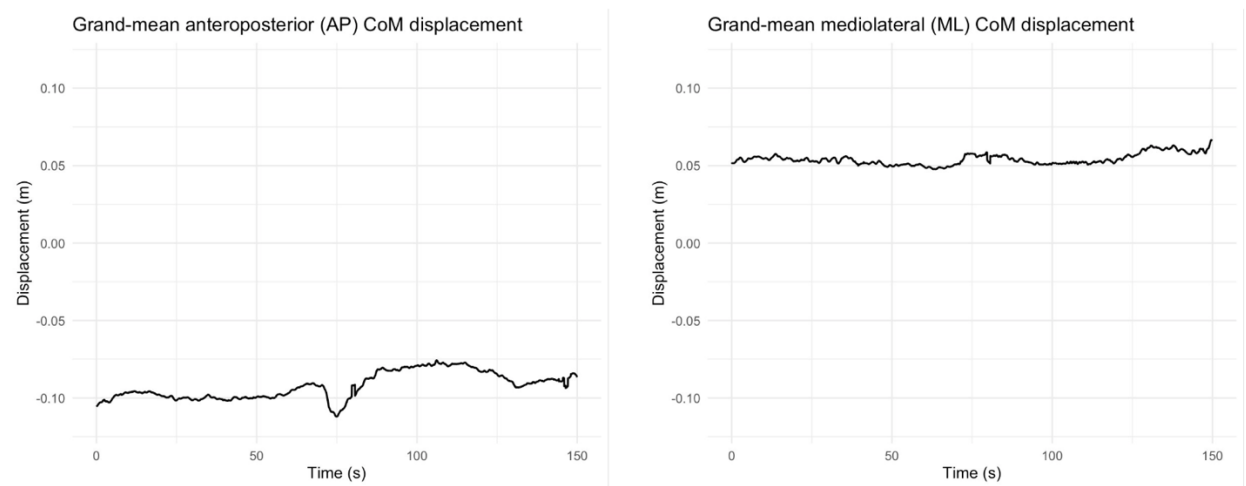


Figure 3.13: Grand-mean displacement trajectories in the anteroposterior (AP, left) and mediolateral (ML, right) axes across all participants and trials.

Solid lines represent the mean CoM displacement at each time point during the 150-s VR task. Shaded ribbons indicate 95% confidence intervals. Displacements remained constrained within ± 0.1 m, with greater variability observed in the AP axis, particularly toward the latter half of the trials.

Trial-level progression analyses (Figures 3.13–3.15) provide further context. Total path length (Figure 3.13) showed a modest upward trend across trials, which may suggest either an accumulation of instability with repeated VR exposure or a limited ability to habituate. This contrasts with some prior findings of adaptation and reduced sway over repeated exposures (Stanney et al., 1999; Kim et al., 2018), though others have reported sustained or even worsening instability under persistent

sensory conflict (Palmisano et al., 2015). RMS displacements revealed an axis-specific pattern: ML sway remained largely stable across trials with only a slight increase in later sessions (Figure 3.14), whereas AP sway exhibited more pronounced fluctuations, with peaks at particular trials (Figure 3.15). These results are in line with work showing that AP control is especially sensitive to visual–vestibular mismatch in VR (Palmisano et al., 2015; Risi & Palmisano, 2019). Importantly, the absence of a clear monotonic trend suggests that adaptation and destabilization processes may coexist across participants, with some individuals stiffening their posture and others becoming more unstable over time.

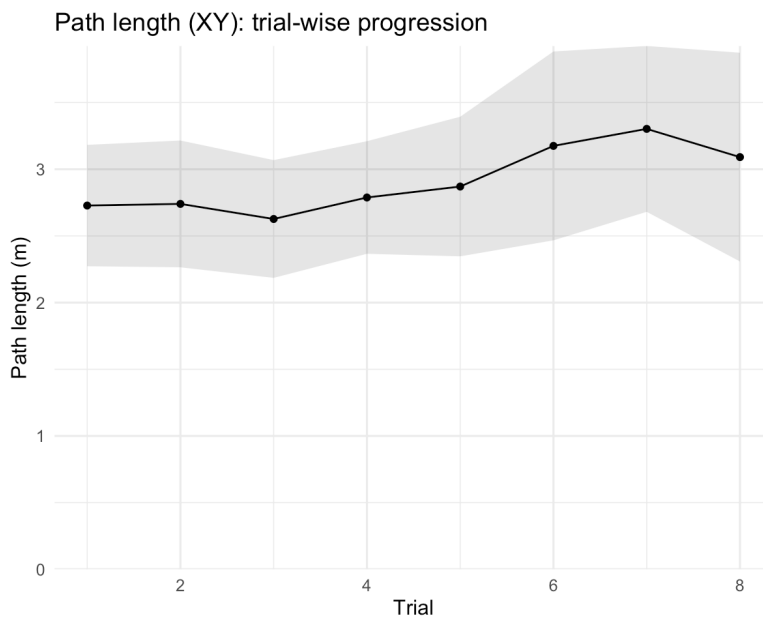


Figure 3.14: Trial-wise progression of total path length (XY plane).

Group mean CoM path length is plotted across the eight VR trials. The solid line denotes the mean; shaded ribbons represent 95% confidence intervals. Path length increased modestly over repeated exposures, suggesting potential accumulation of instability or limited habituation to the VR environment.

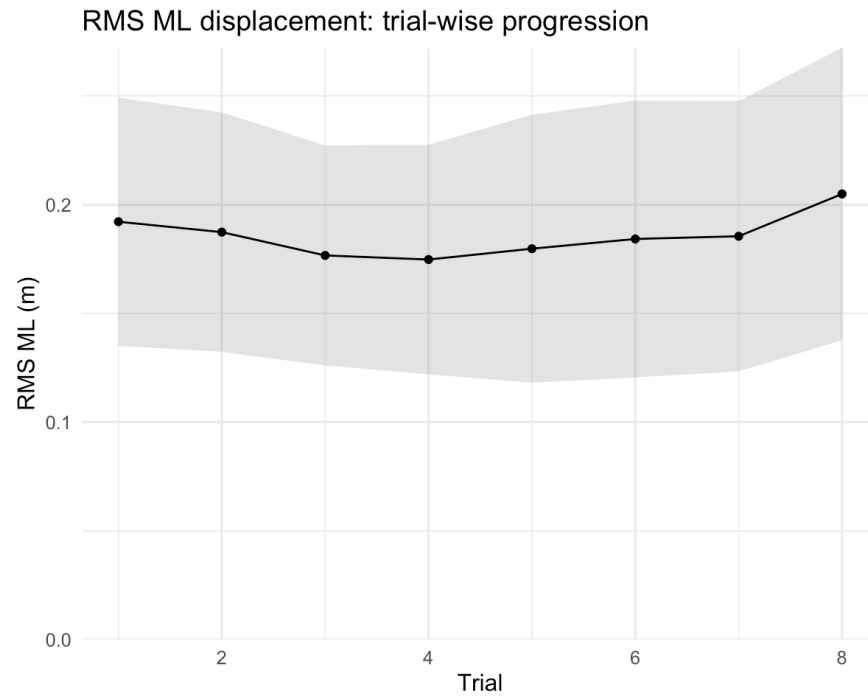


Figure 3.15: Trial-wise progression of root mean square (RMS) displacement in the mediolateral (ML) axis.

Group mean RMS ML displacement is shown across the eight VR trials, with 95% confidence intervals (shaded ribbons). ML sway remained relatively stable, with a slight increase in later trials, consistent with the lower sensitivity of ML control to visual–vestibular conflict compared to AP control.

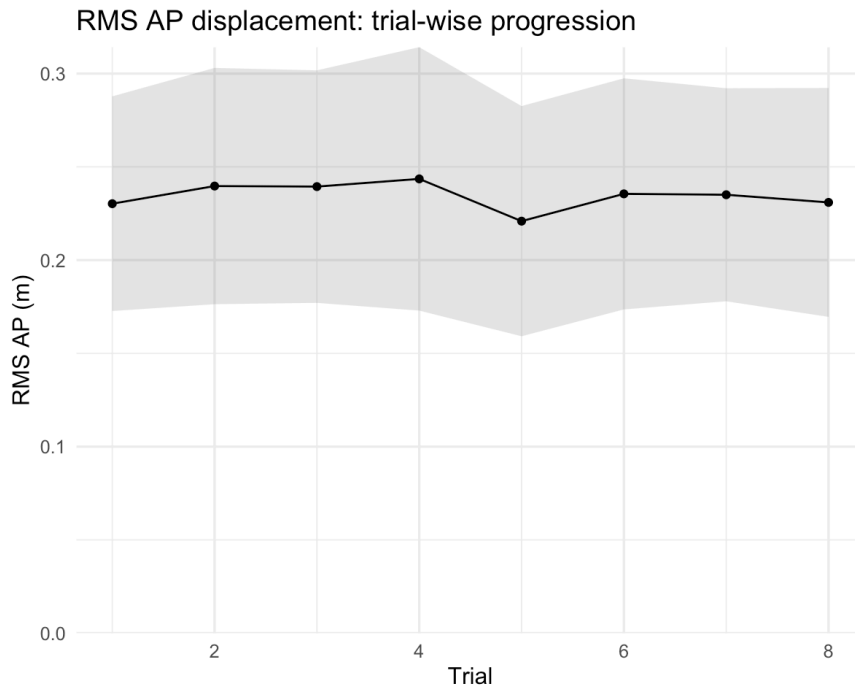


Figure 3.16: Trial-wise progression of root mean square (RMS) displacement in the anteroposterior (AP) axis.

Group mean RMS AP displacement is displayed across the eight VR trials, with shaded ribbons representing 95% confidence intervals. AP sway showed more pronounced variability across trials than ML sway, indicating greater sensitivity to visual–vestibular conflict in the AP direction.

Distributions across participants (Figure 3.16) make this heterogeneity especially evident. Median path length values spanned from under 2 m to nearly 5 m, while RMS displacements clustered more narrowly around 0.1–0.3 m. This variability indicates that while group means appear relatively constrained, individual participants adopted widely divergent strategies. These violin plots reinforce the central theme emphasized in previous literature: VR exposure does not produce uniform postural responses but rather amplifies inter-individual differences (Weech et al., 2018; Risi & Palmisano, 2019). Participants with low sway may reflect those capable of reweighting sensory cues effectively to maintain stability, whereas participants with high sway may represent either heightened susceptibility to CS or alternative strategies such as exploratory sway.

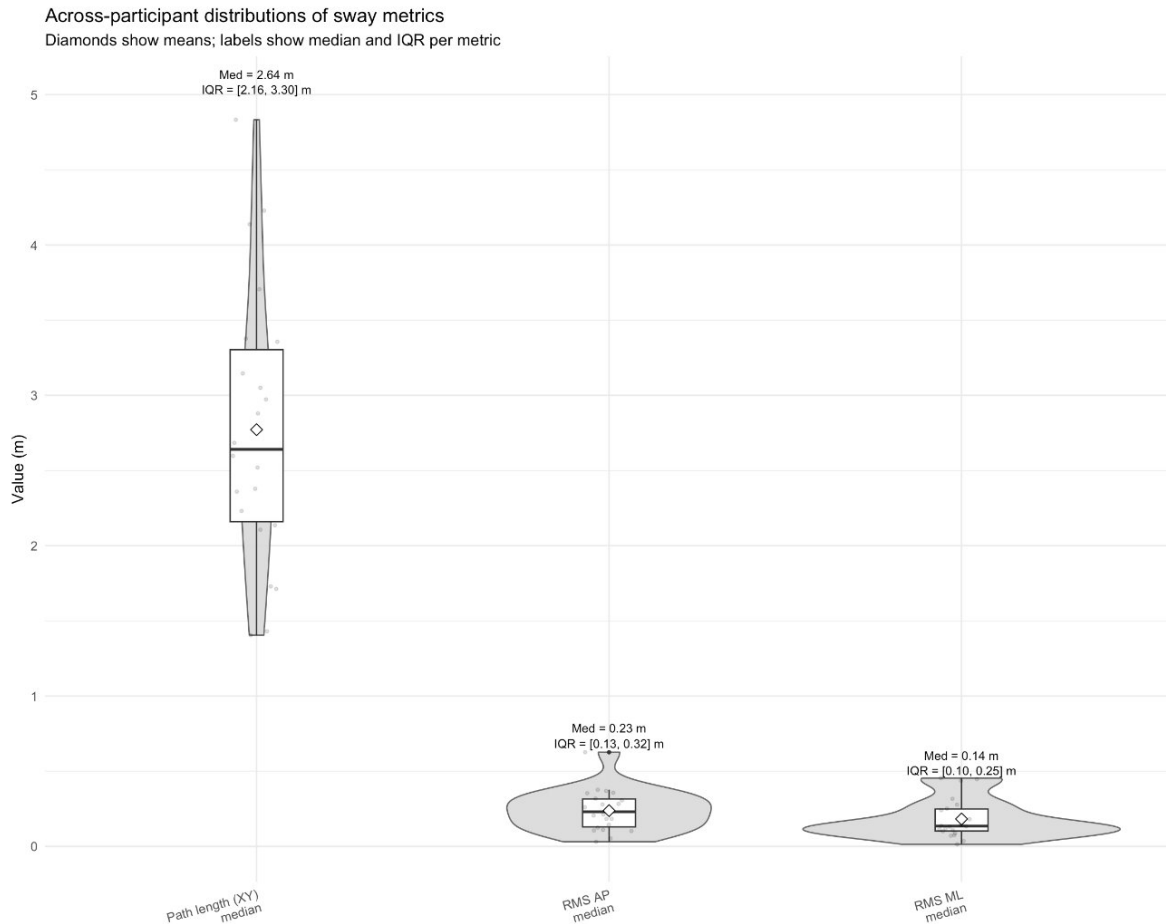


Figure 3.17: Across-participant distributions of sway metrics.

Violin plots depict the distribution of participant medians for total path length (XY), RMS AP displacement, and RMS ML displacement. Boxplots show interquartile ranges; diamonds indicate group means; numeric labels report metric-specific medians and interquartile ranges. Considerable inter-individual variability was evident, with path length spanning from under 2 m to nearly 5 m, while RMS displacement clustered more narrowly around 0.1–0.3 m.

Grand-mean velocity analyses (Figure 3.17) provided a dynamic perspective on these displacement findings. Mean velocities remained near zero, but confidence intervals widened across time, particularly in the AP direction. This widening suggests that postural control was maintained not by eliminating movement altogether but by continuous corrective adjustments. Interpretation of these

velocity patterns is complex. On one hand, low variability may indicate a stiffening strategy—consistent with reduced exploratory behavior and rigid stabilization (Stoffregen & Smart, 1998). On the other hand, higher variability in velocity does not necessarily reflect maladaptive instability; it may instead represent active sampling of multisensory information as participants attempted to recalibrate under conflict (Stoffregen & Bardy, 2001; Palmisano et al., 2018). Thus, the observed duality—some participants constraining sway while others exhibiting high-velocity fluctuations—exemplifies the ongoing debate in postural control research about whether increased sway is inherently maladaptive or can sometimes serve an adaptive, exploratory role.

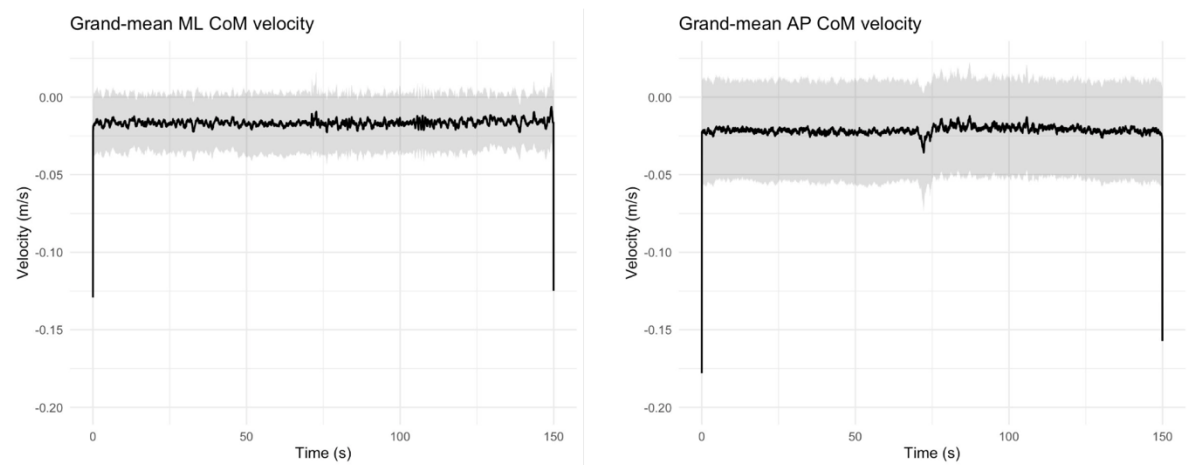


Figure 3.18: Grand-mean CoM velocity in the mediolateral (ML, left) and anteroposterior (AP, right) axes.

Solid lines represent mean CoM velocity across the 150-s VR task; shaded ribbons indicate 95% confidence intervals. The y-axis was fixed at -0.20 to 0.05 m/s for comparability across axes. Although mean velocities remained near zero, variability increased over time, particularly in the AP axis, reflecting ongoing corrective adjustments.

Taken together, Figures 3.12–3.17 demonstrate that, although average group-level trends suggest relatively constrained sway within VR, considerable variability exists both across trials and across participants. This variability reflects the co-existence of stabilizing and destabilizing strategies, aligning with prior reports that VR exposure can both reduce and amplify sway depending on the individual (Weech et al., 2018; Palmisano et al., 2015). Importantly, these findings emphasize that

group means may obscure meaningful individual differences, and that variability itself may be a critical predictor of sensory reweighting ability and CS susceptibility. By establishing these descriptive group-level patterns, the analyses provide a necessary foundation for subsequent statistical modeling of how sway behavior relates to perceptual upright (OCHART) and functional mobility (FMS) outcomes.

3.1.4 H1: FMS & Sensory Cue Weighting

To test whether changes in sensory cue weighting predicted CS severity, a series of linear regressions were conducted using both final and average FMS scores as outcomes. Analyses focused on three predictors: (1) the total magnitude of multisensory reweighting (combined change across cues), (2) the direction of each cue's weight change (increase or decrease), and (3) the absolute magnitude of change for each cue independent of direction. Data from 22 participants were included; three participants were excluded because their OCHART responses did not fit the vector-sum model, preventing estimation of cue weights.

We first examined whether the overall magnitude of multisensory cue reweighting predicted CS. This was calculated as the Euclidean distance of pre- to post-exposure changes in visual, body, and gravity cue weights. Results showed no significant relationship for either final FMS ($b = 0.095$, $t(20) = 0.823$, $p = .420$, $R^2 = .033$) or average FMS ($b = 0.068$, $t(20) = 0.873$, $p = .393$, $R^2 = .037$). Scatterplots (Figures 3.18–3.19) revealed weak, non-significant positive associations, indicating that participants who underwent larger overall changes in cue weighting did not necessarily experience more severe CS.

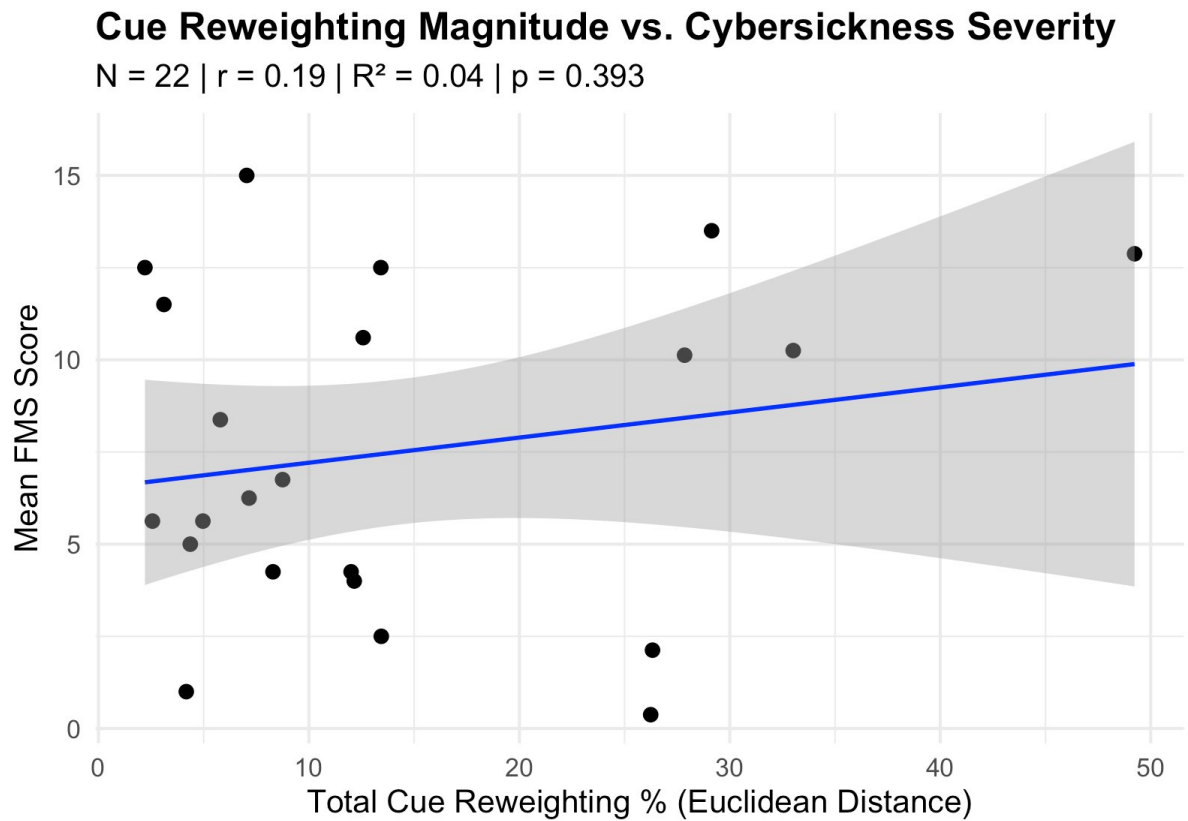


Figure 3.19: Relationship between cue reweighting magnitude and CS severity.

Scatterplot illustrating the association between total cue reweighting, expressed as Euclidean distance in percentage (x-axis), and mean Fast Motion Sickness (FMS) scores (y-axis). Each point represents a single participant (N = 22). A weak positive correlation was observed ($r = 0.19$, $R^2 = 0.04$, $p = 0.393$), indicating that greater cue reweighting magnitude was not significantly related to higher CS severity. The blue line depicts the linear regression fit, with shaded area representing the 95% confidence interval.

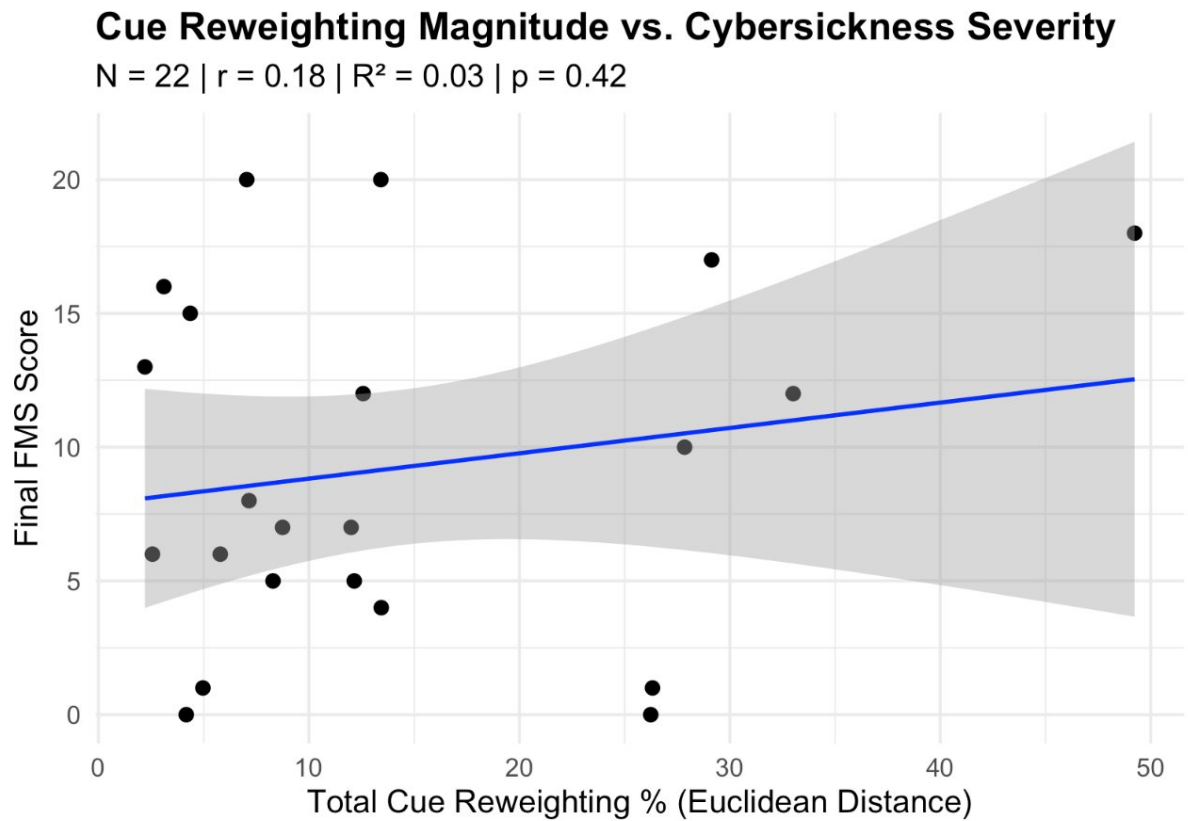


Figure 3.20: Relationship between cue reweighting magnitude and final CS severity.

Scatterplot illustrating the association between total cue reweighting, expressed as Euclidean distance in percentage (x-axis), and final Fast Motion Sickness (FMS) scores (y-axis). Each point represents a single participant (N = 22). A weak positive correlation was observed ($r = 0.18$, $R^2 = 0.03$, $p = 0.42$), indicating that total cue reweighting magnitude was not a significant predictor of final CS severity. The blue line depicts the linear regression fit, with shaded area representing the 95% confidence interval.

Next, we tested if the direction of cue weight change (whether it increased or decreased) was linked to CS. We ran separate regressions for each cue's change score. For vision cue change (Figure 3.20), neither final FMS ($b = -0.102$, $p = .771$, $R^2 = .004$) nor average FMS ($b = 0.056$, $p = .814$, $R^2 = .003$) showed any effect. For body cue change (Figure 3.21), final FMS was not predicted ($b = 0.100$, $p = .339$, $R^2 = .046$), and average FMS also showed no link ($b = 0.044$, $p = .540$, $R^2 = .019$). For gravity cue change (Figure 3.22), final FMS showed a small negative trend, but it was not significant ($b = -0.134$, $p = .292$, $R^2 = .055$). Average FMS showed similar results ($b = -0.073$, $p = .404$, $R^2 = .035$).

These findings (Figures 3.20–3.22) suggest that whether a cue increased or decreased in relative weighting was not systematically linked to CS outcomes.

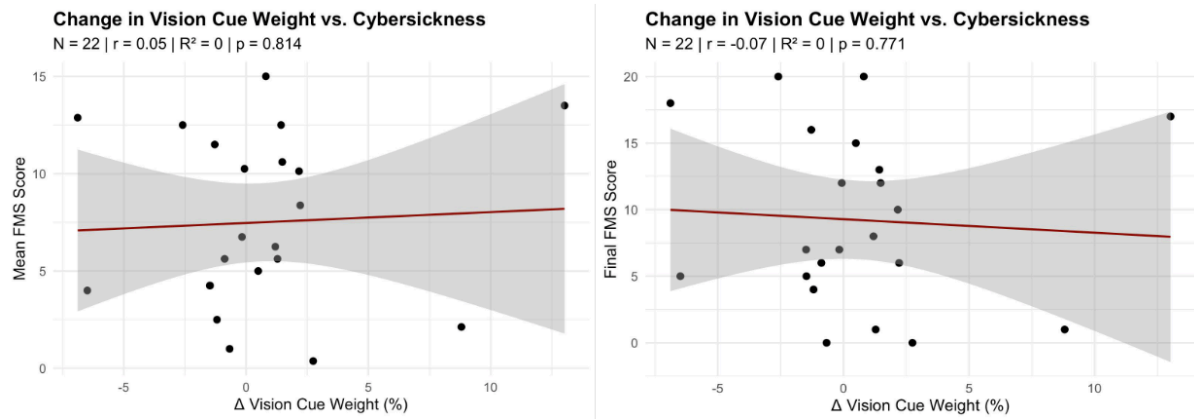


Figure 3.21: Relationship between change in vision cue weight and CS severity.

Scatterplots showing associations between change in vision cue weight (x-axis) and CS severity, measured as mean Fast Motion Sickness (FMS) scores (left panel) and final FMS scores (right panel). Neither regression was significant (mean: $r = 0.05$, $R^2 = 0.00$, $p = 0.814$; final: $r = -0.07$, $R^2 = 0.00$, $p = 0.771$), indicating that changes in visual cue weighting were not predictive of CS severity.

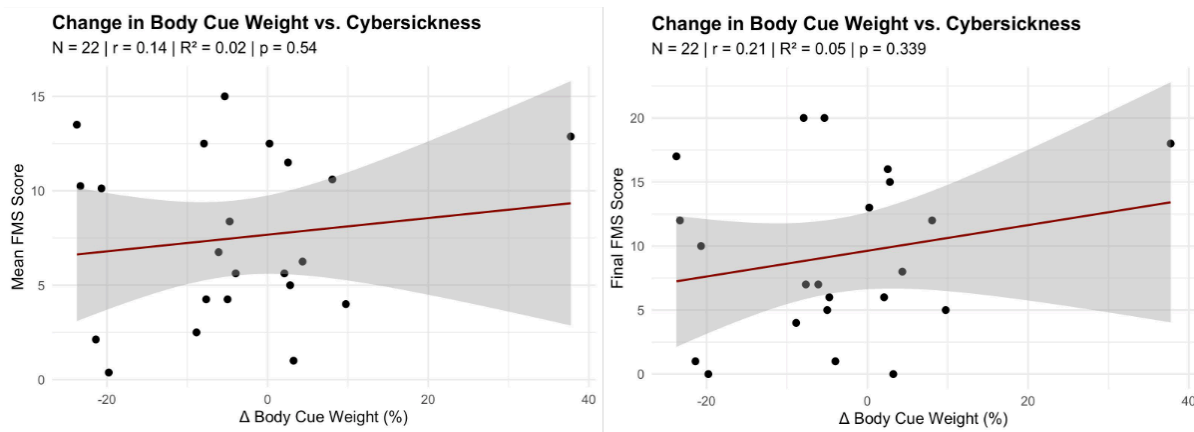


Figure 3.22: Relationship between change in body cue weight and CS severity.

Scatterplots showing associations between change in body cue weight (x-axis) and CS severity, measured as mean FMS scores (left panel) and final FMS scores (right panel). Neither relationship reached significance (mean: $r = 0.14$, $R^2 = 0.02$, $p = 0.540$; final: $r = 0.21$, $R^2 = 0.05$, $p = 0.339$), suggesting that changes in body cue weighting were not associated with CS severity.

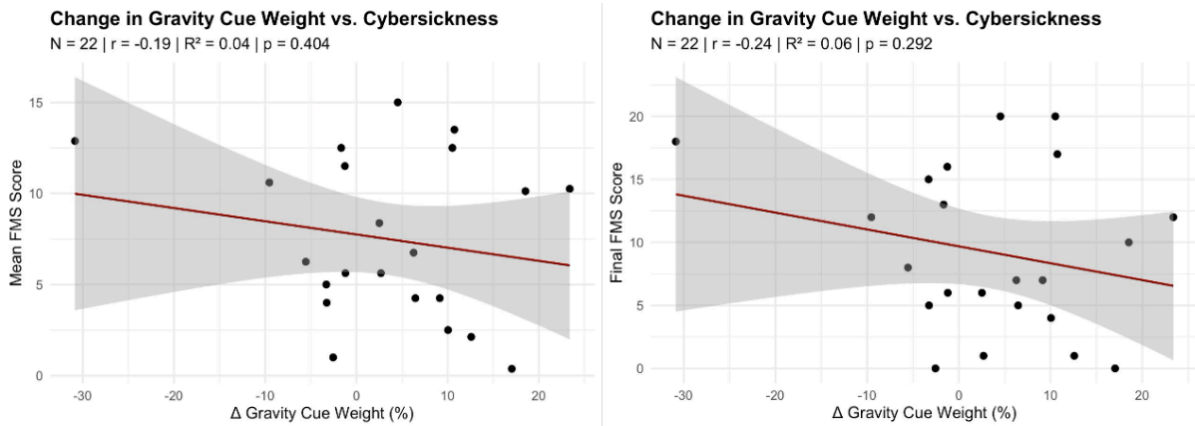


Figure 3.23: Relationship between change in gravity cue weight and CS severity.

Scatterplots showing associations between change in gravity cue weight (x-axis) and CS severity, measured as mean FMS scores (left panel) and final FMS scores (right panel). Although final FMS scores showed a small negative trend ($r = -0.24$, $R^2 = 0.06$, $p = 0.292$), neither regression reached significance (mean: $r = -0.19$, $R^2 = 0.04$, $p = 0.404$). These results suggest that changes in gravity cue weighting were not predictive of CS severity.

Since direction alone might miss some patterns, we then tested if the amount of cue change, regardless of direction, was a better predictor. We used the absolute values of each cue's weight change. For absolute vision cue change (Figure 3.23), the results were not significant for final FMS ($b = 0.398$, $p = .603$, $R^2 = .015$) or average FMS ($b = 0.339$, $p = .529$, $R^2 = .020$). For absolute body cue change (Figure 3.24), final FMS showed a small, non-significant trend ($b = 0.163$, $p = .480$, $R^2 = .033$). The model for average FMS also showed no effect ($b = 0.152$, $p = .426$, $R^2 = .032$). For absolute gravity cue change (Figure 3.25), final FMS showed a slightly stronger link ($b = 0.173$, $p = .392$, $R^2 = .043$), but this was still not significant. The average FMS model showed a similar result ($b = 0.162$, $p = .421$, $R^2 = .032$). Scatterplots (Figures 3.23–3.25) illustrate these weak associations. Although none of these effects reached significance, the fact that the absolute-change models explained somewhat more variance than the directional-change models suggests that the extent of sensory updating, rather than its direction, may be more relevant to CS.

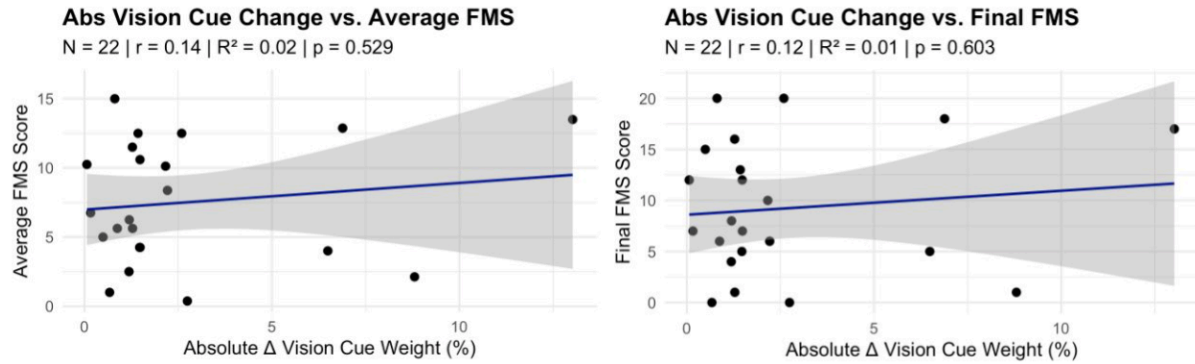


Figure 3.24: Relationship between absolute change in vision cue weight and CS severity.

Scatterplots showing associations between absolute change in vision cue weight (x-axis) and CS severity, measured as average Fast Motion Sickness (FMS) scores (left panel) and final FMS scores (right panel). Neither regression reached significance (average: $r = 0.14$, $R^2 = 0.02$, $p = 0.529$; final: $r = 0.12$, $R^2 = 0.01$, $p = 0.603$), indicating that the magnitude of vision cue weight change, irrespective of direction, was not related to CS severity.

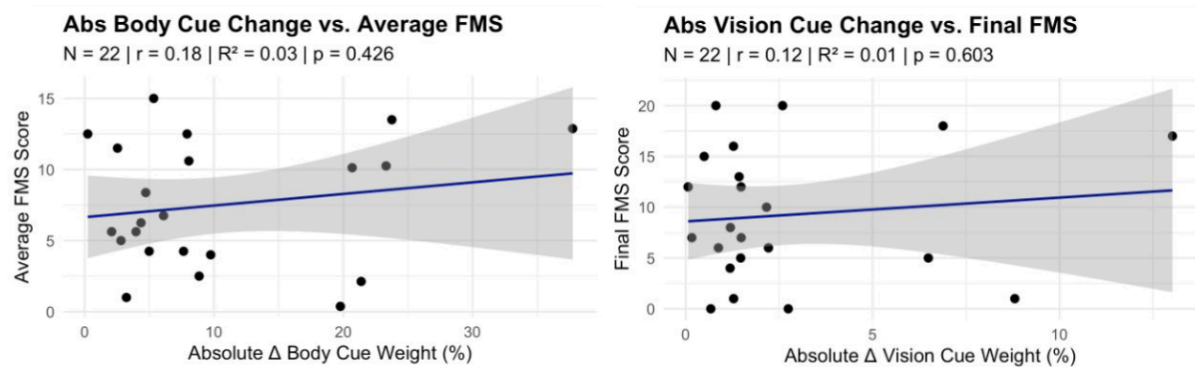


Figure 3.25: Relationship between absolute change in body cue weight and CS severity.

Scatterplots showing associations between absolute change in body cue weight (x-axis) and CS severity, measured as average FMS scores (left panel) and final FMS scores (right panel). Neither regression was significant (average: $r = 0.18$, $R^2 = 0.03$, $p = 0.426$; final: $r = 0.21$, $R^2 = 0.05$, $p = 0.339$), though a small positive, non-significant trend was observed for final FMS scores.

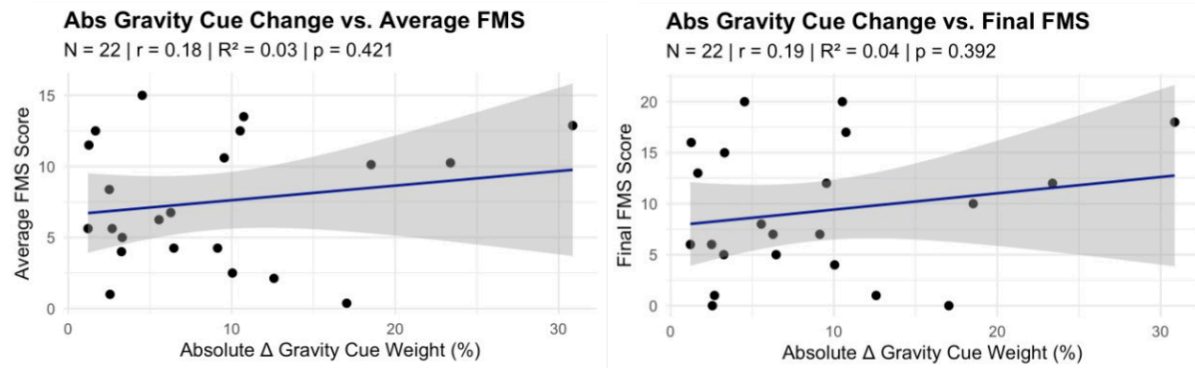


Figure 3.26: Relationship between absolute change in gravity cue weight and CS severity.

Scatterplots showing associations between absolute change in gravity cue weight (x-axis) and CS severity, measured as average FMS scores (left panel) and final FMS scores (right panel). Although final FMS scores showed a slightly stronger trend ($r = 0.19$, $R^2 = 0.04$, $p = 0.392$), neither regression reached significance (average: $r = 0.18$, $R^2 = 0.03$, $p = 0.421$). These results suggest that the overall magnitude of gravity cue weight change did not predict CS severity.

Taken together, these analyses indicate that sensory cue reweighting, as measured by the OCHART, was not a reliable predictor of CS in this sample. Neither the overall magnitude of multisensory reweighting nor cue-specific directional or absolute changes reached statistical significance. These findings therefore **do not support Hypothesis 1**, which predicted that larger cue weight changes would be associated with higher CS severity.

Nonetheless, the consistent—albeit weak—positive trends for body and gravity cue changes suggest that the capacity or attempt to adjust reliance on these cues may play a subtle role. This aligns with proposals that vestibular and somatosensory signals are critical in resolving visual–vestibular conflict (Chung & Barnett-Cowan, 2023). The absence of strong effects may reflect that cue reweighting is highly individualized and nonlinear, or that its influence on CS becomes detectable only when coupled with dynamic behavioral markers such as sway variability.

More broadly, these results raise questions about whether static perceptual measures of sensory integration are sufficient to capture susceptibility to CS. While reweighting reflects the brain’s ability to adapt to sensory conflict, the weak associations observed here suggest that real-time postural behavior (examined in H2) may provide a more sensitive marker. This finding echoes calls in the literature to integrate perceptual and movement-based measures to better understand CS vulnerability (Palmisano et al., 2018; Weech et al., 2018).

3.1.5 H2: FMS & Movement

To test Hypothesis 2, we examined whether postural movement predicted CS severity, as measured by FMS scores, using linear mixed-effects models with random intercepts for participants. Each movement metric was tested individually as a fixed effect.

Mean CoM velocity was not significantly related to CS severity ($\beta = -2.30$, $SE = 3.10$, $t(19.9) = -0.74$, $p = .466$), indicating that the average speed of movement did not differentiate participants who became more versus less sick (Figure 3.26). RMS displacement also showed no reliable association with CS ($\beta = 2.48$, $SE = 9.96$, $t(47.3) = 0.25$, $p = .804$; Figure 3.27). These null results suggest that neither gross movement amplitude nor average velocity captures the aspects of postural control most sensitive to VR-induced discomfort.

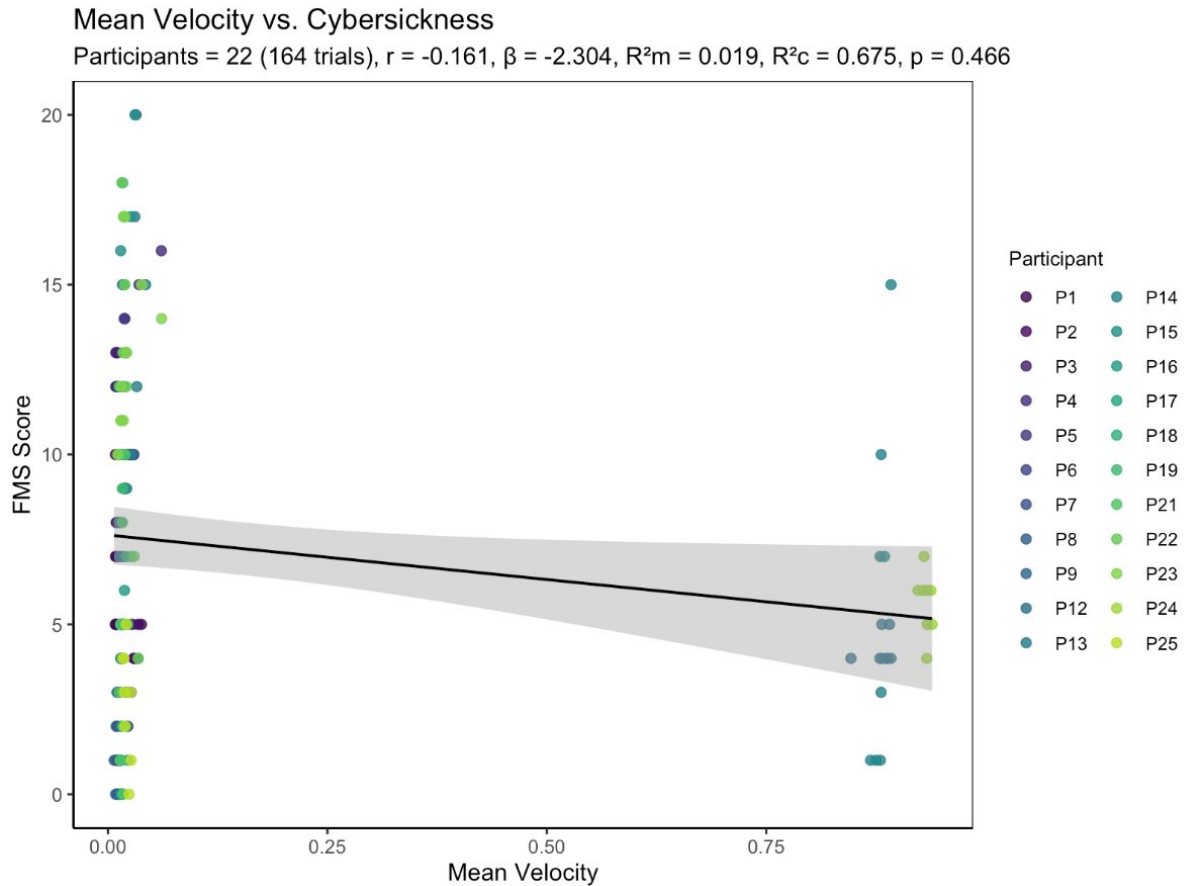


Figure 3.27: Association between mean CoM velocity and CS severity (FMS score).

Scatterplot of mean CoM velocity across all trials ($N = 164$) and participants ($n = 22$). The fitted regression line (black) with 95% confidence intervals (shaded) shows a weak, non-significant negative association ($r = -0.161$, $\beta = -2.304$, $p = 0.466$). While participants with higher mean velocities tended to report lower CS, the effect was small and not statistically reliable.

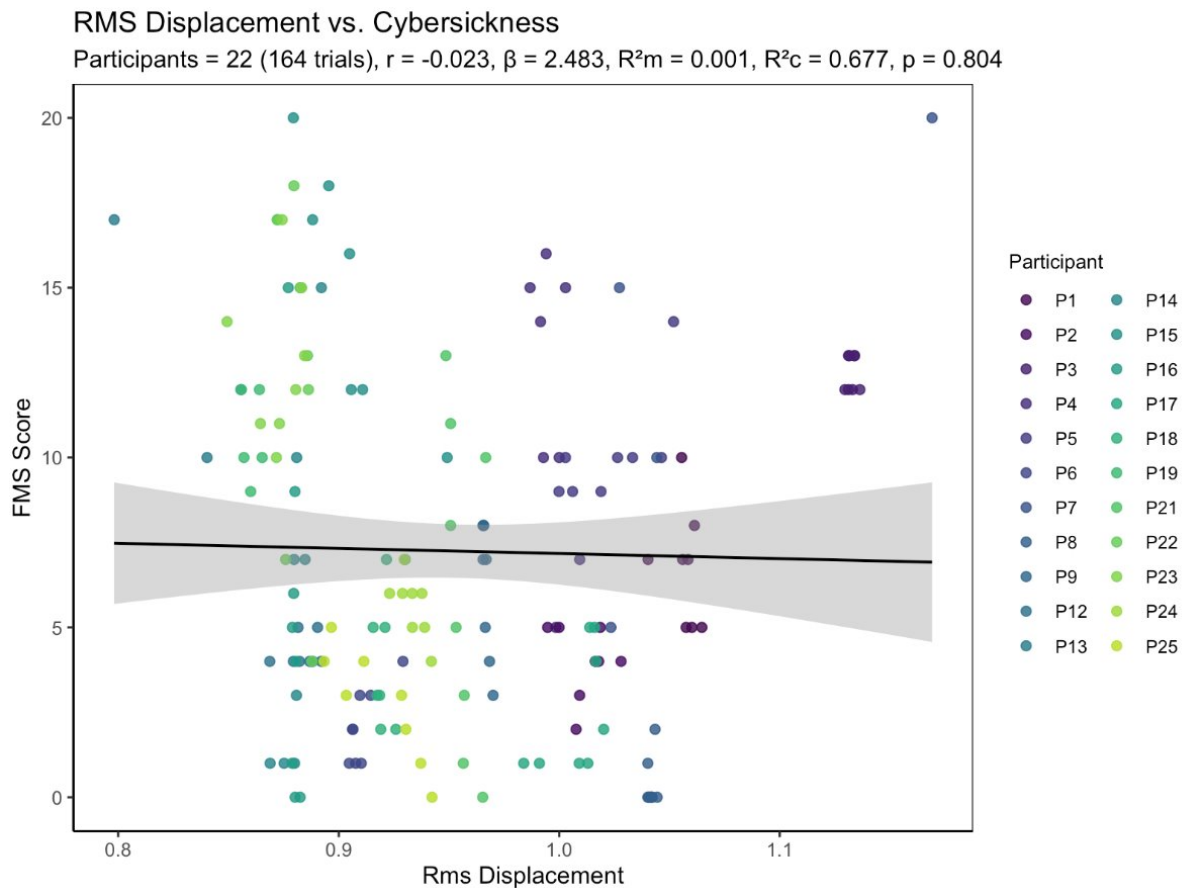


Figure 3.28: Association between RMS displacement and CS severity.

Scatterplot of RMS CoM displacement across participants and trials ($N = 164$). The fitted regression line indicated no meaningful relationship between displacement magnitude and FMS scores ($r = -0.023$, $\beta = 2.483$, $p = 0.804$). This suggests that absolute displacement amplitude was not predictive of CS severity.

By contrast, measures reflecting the *total extent* of postural excursions—path length and sway area—were significant predictors of CS severity. Path length demonstrated a robust positive association with FMS scores ($\beta = 0.39$, $SE = 0.15$, $t(151.0) = 2.57$, $p = .011$; Figure 3.28). Similarly, sway area showed a significant effect in the original model ($\beta = 91.38$, $SE = 34.07$, $t(160.1) = 2.68$, p

= .008; Figure 3.29). These findings indicate that participants who explored a larger region of space, or accumulated greater overall CoM travel, tended to experience more severe CS.

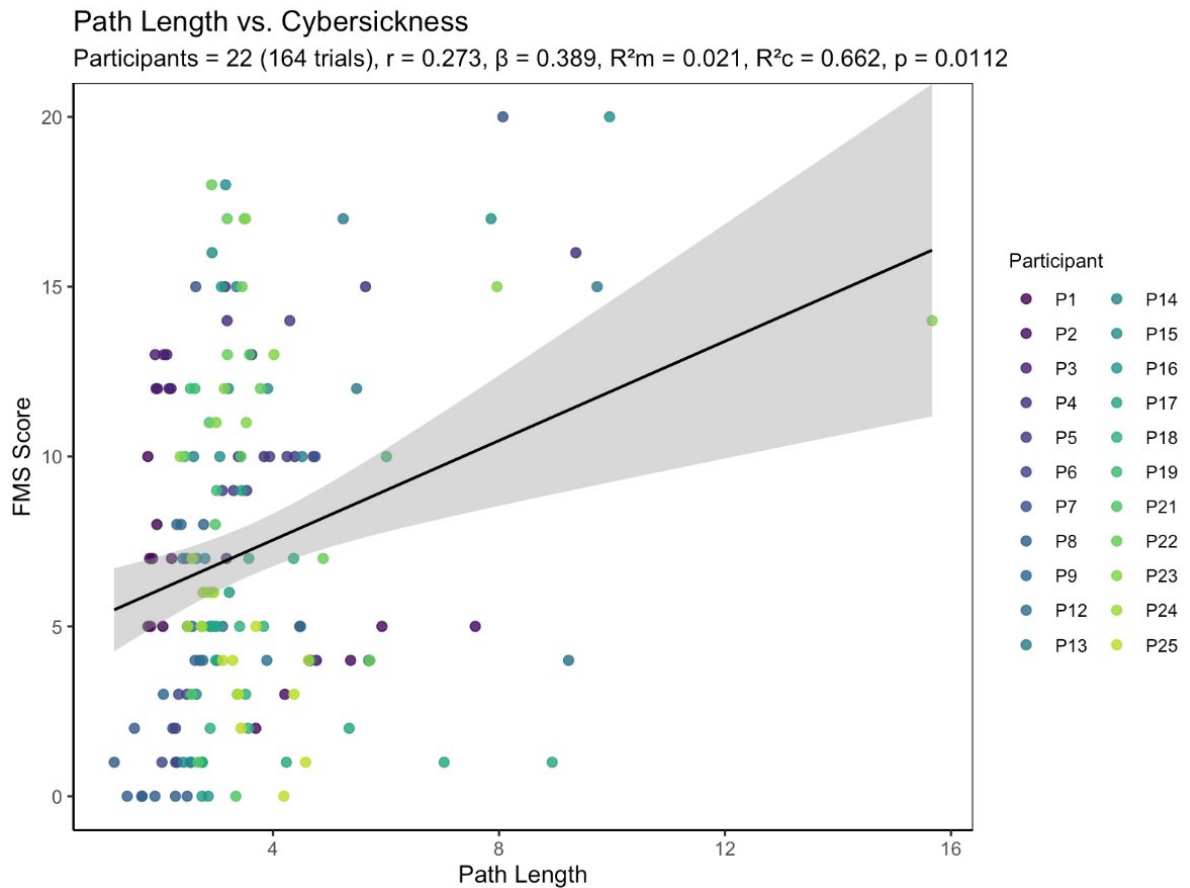


Figure 3.29: Association between path length and CS severity (original dataset).

Scatterplot of path length and FMS scores across all trials ($N = 164$). A significant positive association was observed ($r = 0.273$, $\beta = 0.389$, $p = 0.011$), indicating that greater path length was linked to higher CS severity. Shaded regions represent 95% confidence intervals.

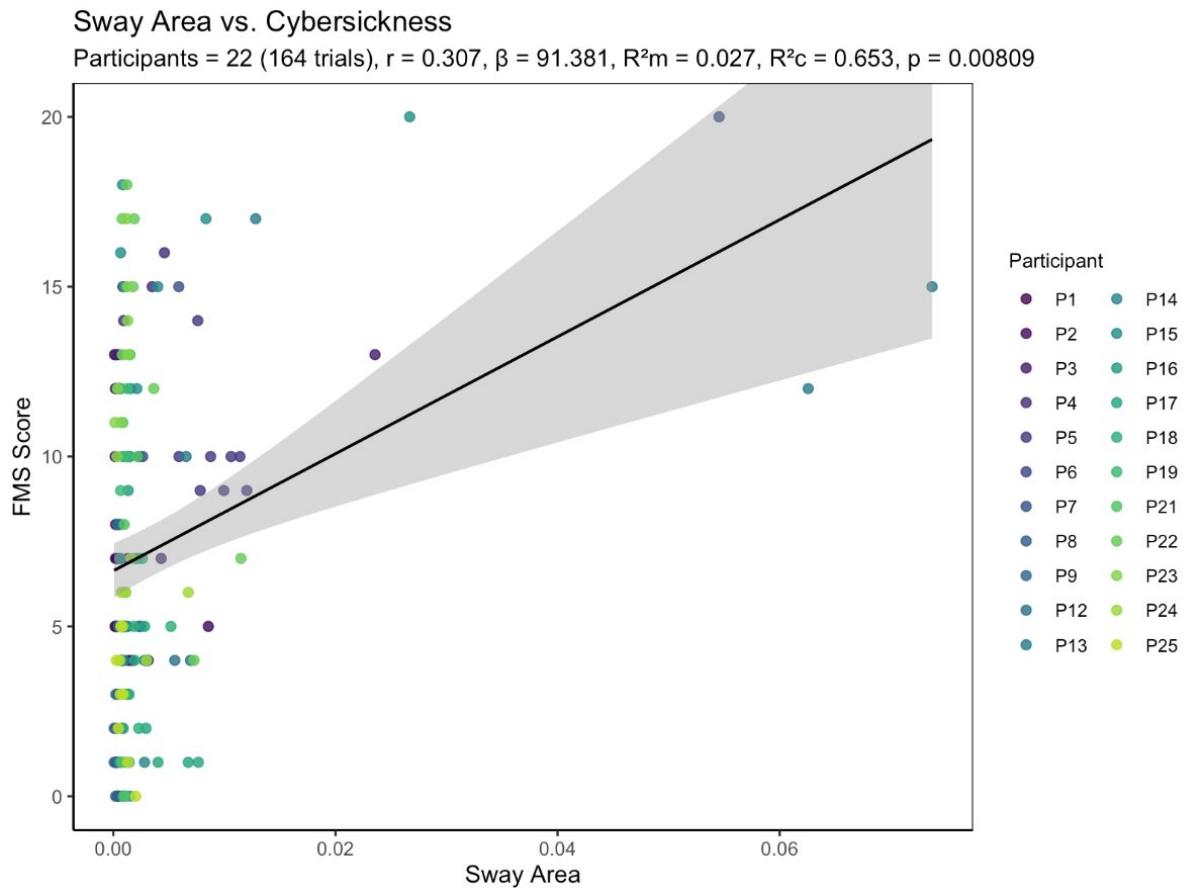


Figure 3.30: Association between sway area and CS severity (original dataset).

Scatterplot of sway area and FMS scores across all trials ($N = 164$). A significant positive association was observed ($r = 0.307$, $\beta = 91.381$, $p = 0.008$), suggesting that larger sway area corresponded to higher CS severity. Confidence intervals are shown in grey.

Robustness checks confirmed that path length was a stable predictor. After removing an extreme case identified by Grubbs' test (Participant 16), the effect became slightly stronger ($\beta = 0.50$, $SE = 0.18$, $t(152.8) = 2.76$, $p = .0065$; Figure 3.30, Table 3.1). This demonstrates that the association was not driven by outliers. In contrast, sway area effects were less stable. Removal of three extreme cases identified by the ESD method rendered the effect non-significant ($\beta = 117.85$, $SE = 77.12$, $t(149.0) = 1.53$, $p = .129$; Figure 3.31, Table 3.2). This suggests that while sway area correlated with CS, its predictive value was more dependent on a few influential participants.

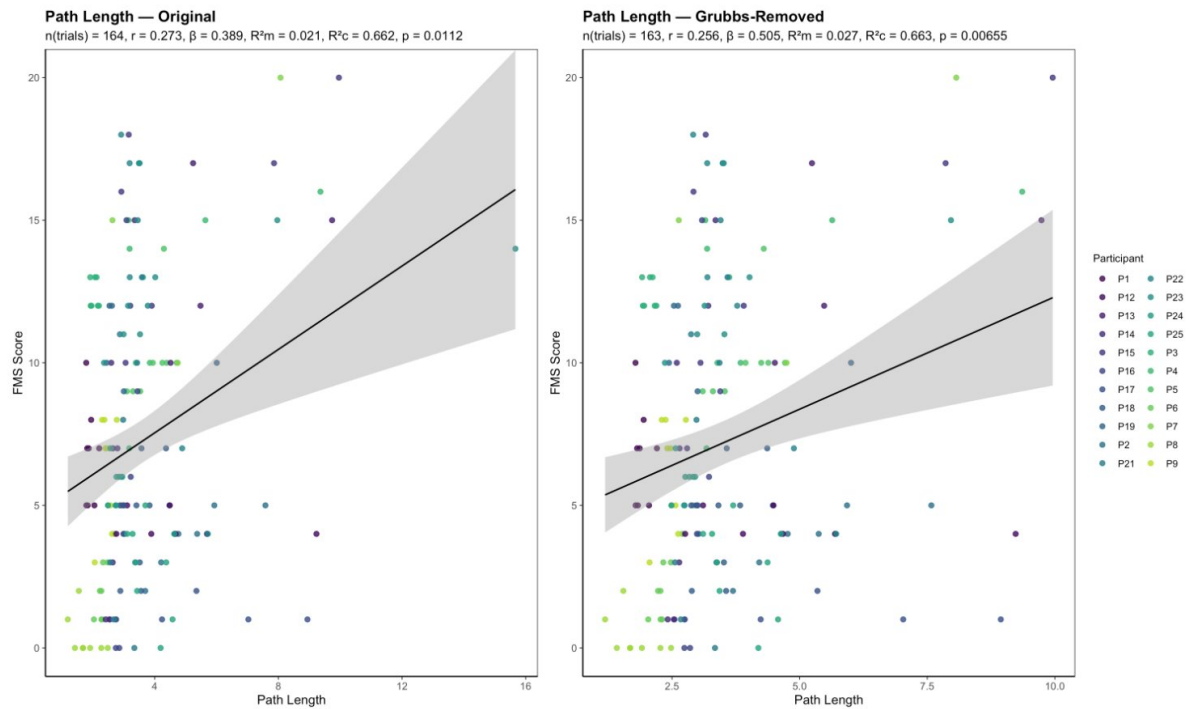


Figure 3.31: Association between path length and CS severity after removal of statistical outliers.

Scatterplots of path length and FMS scores before (left) and after (right) Grubbs’ outlier removal. Associations remained significant in both models (original: $\beta = 0.389$, $p = 0.011$; Grubbs-removed: $\beta = 0.505$, $p = 0.007$). Outlier removal slightly strengthened the relationship, confirming robustness of the effect.

Table 1: Path length and CS: model comparison before and after outlier removal.

Estimates and significance tests for linear mixed models predicting FMS scores from path length. Both original and Grubbs-removed models showed significant positive associations, with slightly stronger effects in the cleaned dataset.

Table 3.1. Path Length Model Comparison

model	estimate	SE	df	t	p
Path Length (Original)	0.3886	0.1513	151.0423	2.5683	0.0112*
Path Length (Grubbs-Removed)	0.5048	0.1831	152.7784	2.7568	0.0065**

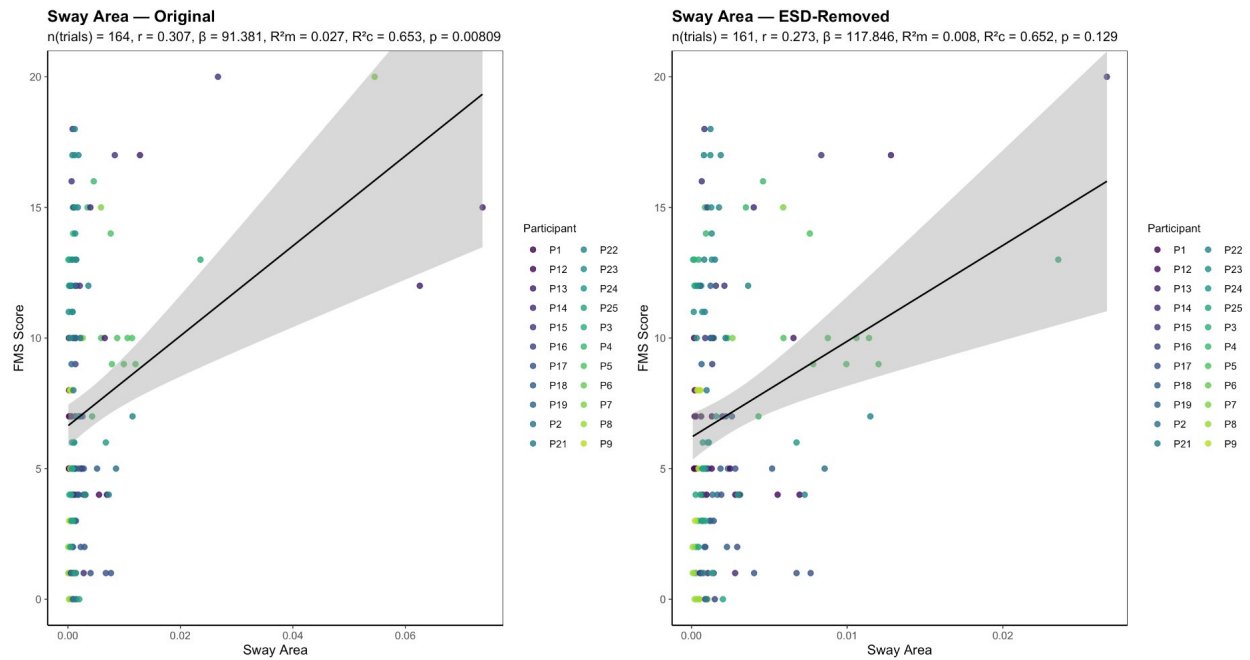


Figure 3.32: Association between sway area and CS severity after removal of statistical outliers.

Scatterplots of sway area and FMS scores before (left) and after (right) extreme studentized deviate (ESD) outlier removal. The original model showed a significant positive association ($\beta = 91.381$, $p = 0.008$), whereas the relationship was attenuated and non-significant after outlier removal ($\beta = 117.846$, $p = 0.129$). This suggests that the original association may have been disproportionately influenced by extreme cases.

Table 2: Sway area and CS: model comparison before and after outlier removal.

Estimates and significance tests for linear mixed models predicting FMS scores from sway area. While the original model showed a significant positive association, this effect was not sustained after ESD-based outlier removal.

Table 3.2. Sway Area Model Comparison					
model	estimate	SE	df	t	p
Sway Area (Original)	91.3813	34.0722	160.1118	2.6819	0.0081**
Sway Area (ESD-Removed)	117.8456	77.1220	148.9836	1.5280	0.1286

To further probe the source of the path length effect, we examined sway in the AP and ML directions separately. Both AP and ML path lengths were positively related to CS when modeled independently (AP: $\beta = 0.99$, $SE = 0.38$, $p = .010$; ML: $\beta = 0.92$, $SE = 0.31$, $p = .004$). RMS displacement in each direction also showed small positive associations (AP: $\beta = 21.6$, $SE = 10.6$, $p = .042$; ML: $\beta = 34.2$, $SE = 15.2$, $p = .026$), though these did not survive correction for multiple comparisons. However, when AP and ML path lengths were entered into the same model, neither remained significant, reflecting their moderate correlation ($r = 0.64$). This suggests that both axes contribute to CS susceptibility, but they capture overlapping variance in overall postural instability.

Overall, these findings partially support Hypothesis 2. Among the four global movement metrics, only **path length consistently predicted CS severity**, even after rigorous outlier removal, highlighting it as the most reliable marker of VR susceptibility in this dataset. Sway area also predicted CS, but the effect weakened substantially once extreme cases were removed. In contrast, mean velocity and RMS displacement showed no predictive value.

Importantly, the predictive strength of path length underscores the role of cumulative postural excursions—rather than instantaneous velocity or displacement magnitude—in reflecting the destabilizing effects of sensory conflict in VR. This aligns with prior work showing that greater sway path length is associated with motion sickness onset in both real and virtual environments (Palmisano et al., 2015; Stoffregen et al., 2017). It also supports theories that CS emerges not simply from momentary instability but from the accumulation of corrective postural adjustments over time.

The directional analyses further suggest that both AP and ML sway contribute similarly, consistent with evidence that visual–vestibular conflict disrupts balance in multiple planes (Risi & Palmisano, 2019). However, their shared variance indicates that path length as a composite metric may provide the clearest and most parsimonious index of CS risk.

To summarize, these results highlight postural path length as a promising candidate biomarker for CS susceptibility. In contrast to sensory cue reweighting measures (H1), which failed to predict sickness, path length consistently captured meaningful variation in how participants responded to VR exposure. This supports the broader argument that movement-based markers—especially those

quantifying accumulated sway—may be more sensitive and reliable indicators of CS than static perceptual indices alone.

3.1.6 Summary of results

Across the VR balance task, participants displayed heterogeneous postural strategies that were apparent at both the individual and group levels. The exemplar traces showed one participant who constrained displacement and velocity—consistent with a conservative “stiffening” approach—and another who produced larger excursions and frequent high-velocity bursts. Group summaries reinforced this pattern: mean CoM displacement stayed relatively small ($\approx \pm 0.1$ m), mediolateral sway was generally more stable than anteroposterior sway, and confidence bands widened across time—especially in the anteroposterior axis—suggesting continual corrective activity rather than simple drift. Violin plots further revealed wide between-participant variability, indicating that averages may conceal meaningful differences in strategy and stability.

With this context, we tested whether changes in sensory cue weighting predicted CS severity. Neither the overall magnitude of pre- to post-exposure reweighting nor cue-specific changes—considering both direction and absolute magnitude—were reliable predictors of FMS scores. Scatterplots showed only weak, non-significant tendencies, with small hints that larger body and gravity updates might accompany higher sickness for some individuals. These null results indicate that static, pre/post perceptual estimates of cue weights, as captured by the OCHART procedure, did not track the processes most closely tied to CS in this sample. This pattern is compatible with the view that cue reweighting is highly individualized and nonlinear, and that its influence on symptoms may be revealed only when considered together with dynamic behavioral markers of balance regulation (e.g., sway variability), as suggested by work emphasizing the complex coupling between perception and action in visually driven instability (e.g., Palmisano et al., 2018; Weech et al., 2018).

In contrast, movement-based measures were more informative. Mean velocity and RMS displacement did not predict FMS, implying that neither average speed nor instantaneous amplitude captured the relevant instability. By comparison, metrics indexing the cumulative extent of postural excursions did. Path length showed a robust positive association with CS that persisted—and slightly strengthened—after outlier removal, whereas sway area was significant in the full dataset but attenuated to non-significance once influential cases were excluded. Directional analyses indicated that anteroposterior and mediolateral path lengths each related to FMS when modeled alone, but

neither remained significant in a joint model, consistent with shared variance between axes. Together, these findings point to total CoM travel over time—rather than moment-to-moment velocity or displacement amplitude—as the clearest and most parsimonious indicator of susceptibility.

Interpreted alongside prior work, the pattern suggests that CS is better indexed by the *accumulation* of corrective postural work under visual–vestibular conflict than by static perceptual reweighting alone. Reports that VR can destabilize stance and widen sway envelopes—especially in the anteroposterior direction—provide a coherent backdrop for the present path-length effects (e.g., Palmisano et al., 2015; Risi & Palmisano, 2019; Winter, 1998). At the same time, the coexistence of low- and high-sway strategies observed here echoes the broader literature showing that some individuals suppress sway, while others exhibit large, variable excursions that may reflect either maladaptive instability or exploratory attempts to recalibrate multisensory cues (Stoffregen & Bardy, 2001; Palmisano et al., 2018). This variability helps explain why group means remain modest while path length, which integrates corrections across axes and across time, emerges as a robust predictor of symptoms.

Taken together, the results indicate that Hypothesis 1 was not supported: changes in sensory cue weights did not predict CS in this dataset. By contrast, the analyses partially support Hypothesis 2: among the movement metrics, path length consistently predicted FMS, even after rigorous outlier handling, while sway area was less stable and mean velocity and RMS displacement were not predictive. The larger message is that movement-based markers—particularly those quantifying accumulated sway—capture consequential aspects of how the postural system engages with VR-induced conflict. This strengthens the case for integrating dynamic movement measures with perceptual assessments to characterize susceptibility and, ultimately, to inform mitigation strategies.

Chapter 4

Discussion

The aim of this thesis was to investigate whether CS in immersive VR could be predicted more reliably from perceptual indices of sensory cue reweighting or from dynamic measures of postural movement. Two hypotheses were formulated. Hypothesis 1 (H1) predicted that greater sensory cue reweighting would be associated with more severe CS, whereas Hypothesis 2 (H2) predicted that greater postural movement would be associated with more severe CS. The findings provided clear support for H2 but not for H1. This section discusses these outcomes in detail, situates them within prior research, and considers their implications for theory, methodology, and application.

4.1.1 Movement Analysis

The individual- and group-level analyses revealed two characteristic patterns of postural control under VR exposure. Some participants constrained their movements tightly, producing low-amplitude displacements and slow, steady corrections. Others displayed much broader excursions with frequent, high-velocity bursts. These contrasting profiles reflect distinct postural control strategies employed to resolve sensory conflict. In a roller-coaster simulation where optic flow is overwhelming but vestibular and somatosensory cues provide little confirmation, these center-of-mass traces effectively serve as motor signatures of how participants negotiated the mismatch.

From the perspective of sensory reweighting theory, these two strategies can be understood as alternative weighting approaches. Participants who showed constrained sway may have down-weighted unreliable visual cues and leaned more heavily on body or vestibular anchors, effectively stiffening their posture to suppress instability (Horak, 2006; Peterka, 2002). Such stiffening has been described as a short-term compensatory strategy in balance research, where reduced sway reflects increased joint stiffness and reliance on ankle strategies (Winter, 1995; Peterka & Loughlin, 2004). By contrast, those who showed expansive sway may not have down-weighted visual input sufficiently, leaving themselves vulnerable to destabilization. Alternatively, their higher variability could reflect exploratory sway—an adaptive attempt to sample multisensory information in order to recalibrate under conflicting inputs (Stoffregen & Bardy, 2001; Palmisano et al., 2018). Prior work has emphasized that exploratory postural activity may provide critical sensory information for resolving conflicts, though it comes at the cost of increased short-term instability (Stoffregen &

Smart, 1998). Thus, both strategies are plausible, and which one an individual adopts may depend on prior VR experience, sensory sensitivity, or preferred control policies.

The presence of these two strategies also clarifies why static measures of sensory reweighting, such as OCHART, did not directly predict CS in this study. Even if participants' internal cue weights shifted, their relevance depends on whether these changes manifest in observable motor behaviour. In an active, room-scale VR task, reweighting can be expressed through head turns, locomotion, or shifts in stance, thereby reducing conflict through action (Chung & Barnett-Cowan, 2023). In contrast, the present task was passive: participants were instructed to remain upright with minimal freedom to move while the roller coaster drove visual input. Under these conditions, perceptual reweighting had little behavioral outlet. What became observable instead was the continuous corrective work of the postural system. This explains why cumulative movement measures, such as path length, were more sensitive predictors of CS than static perceptual indices.

Theoretical accounts of CS provide complementary but distinct emphases that are directly relevant to these observations. Sensory Conflict Theory (Reason & Brand, 1975; Oman, 1990) highlights the mismatch between visual, vestibular, and proprioceptive cues and predicts that individuals who can flexibly reweight cues should experience less sickness. If this framework alone were sufficient, we would expect strong associations between cue weight changes and symptom severity. Instead, what emerged was that the way posture was stabilized—or failed to be stabilized—was the more proximal driver of discomfort. This finding aligns more closely with Postural Instability Theory (Riccio & Stoffregen, 1991), which proposes that sustained difficulty in maintaining balance, rather than conflict per se, is the critical mechanism behind sickness. The dual strategies observed here illustrate this point. A stiffening response may suppress symptoms in the short term but limit flexibility to adapt if conflicts intensify, while an exploratory response may facilitate recalibration but, when unsuccessful, produce cumulative instability that drives discomfort (Stoffregen & Smart, 1998; Palmisano et al., 2020).

These findings underscore the limitations of relying solely on group averages in CS research. On the surface, mean displacements across participants were modest, but widening confidence intervals revealed diverging strategies. One group effectively locked down stability, while another moved more variably and accumulated greater path length over time. When averaged, these differences cancel each other out, obscuring the predictive role of instability. It is precisely this variability itself—

captured most effectively by cumulative measures such as path length—that carries explanatory and predictive value for CS. This observation not only sets the stage for interpreting why sensory reweighting failed to predict symptoms in this context, but also explains why movement, especially path length, emerged as the most reliable predictor.

Kinematic data in this study were acquired with Qualisys Track Manager, processed with Theia Markerless to generate 3D joint and segment estimates, and then imported into Visual3D for model definition and parameter extraction. Center-of-mass (CoM) position and velocity were computed in the global laboratory coordinate system, and all derived movement variables—including path length, displacement, sway area, and velocity measures—were expressed relative to this fixed frame of reference. This approach enabled consistent time-locking of movement data to the VR stimulus and allowed for straightforward comparisons across trials and participants. However, it also introduced an important methodological limitation related to how participant alignment and stance geometry can influence the variability of kinematic outcomes.

When movement is expressed in a fixed global reference frame, even small differences in stance configuration—such as foot width, foot angle (toe-out/toe-in), body yaw relative to the lab axes, or slight misalignments between the body and the global frame—can be projected differently along the global X and Y axes. As a result, two individuals adopting the same underlying postural control strategy may appear to exhibit different mediolateral or anteroposterior excursions, simply because their stance orientation was offset relative to the room. Furthermore, small systematic offsets introduced during markerless pose estimation or calibration drift can compound these discrepancies, leading to inflated between-participant variability that reflects differences in alignment rather than true differences in postural control.

This issue has specific consequences for the variables used in this study. Because path length sums the total displacement over time, stance width or rotation can increase the magnitude of the measured signal without necessarily reflecting greater instability. Similarly, interpretations of AP versus ML sway components may be skewed if the participant's foot orientation is rotated relative to the global axes, making an exploratory or corrective movement appear more prominent in one axis than the other. While standardized instructions and a consistent setup were used to reduce this variability, it cannot be fully eliminated when global-frame measures are used.

Going forward, several methodological refinements could mitigate this limitation. Transforming the kinematic data into a participant-centered coordinate system (e.g., aligning the AP axis with foot progression or the pelvis orientation at trial onset) would reduce the impact of stance misalignment. Standardizing and recording stance geometry (foot width, angle, and position) would provide more control and allow these parameters to be included as covariates in analyses. Additionally, implementing trial-specific axis realignment or “re-zeroing” at the beginning of each exposure could help ensure that observed differences reflect true control strategies rather than geometric artifacts. Incorporating such procedures would sharpen the interpretability of movement outcomes, especially for axis-specific measures, and strengthen inferences about the link between postural instability and cybersickness. In this context, while the use of a global reference frame in the current study was appropriate for capturing overall instability, future research would benefit from more participant-aligned analytical frameworks to minimize confounds and improve precision.

4.1.2 H1: Sensory Cue Weighting and CS

Hypothesis 1 was not supported: changes in sensory cue weights, as estimated using the OCHART task, did not predict CS severity. This null result is not a trivial footnote but an important test of long-standing assumptions in the field. According to sensory conflict theory (Reason & Brand, 1975; Oman, 1990), motion sickness arises when incoming visual, vestibular, and proprioceptive signals are mismatched. The theory predicts that individuals who can flexibly reweigh their reliance on these cues should manage conflict more effectively and experience less discomfort. Indeed, recent work has provided support for this claim in more interactive VR contexts. For example, Chung and Barnett-Cowan (2023) showed that changes in perceptual upright after VR exposure were linked to sickness levels, suggesting that reweighting ability can shape susceptibility. By contrast, the current study demonstrated no such association. The finding therefore qualifies the generality of the conflict account: reweighting ability does not automatically translate into lower (or higher) sickness across all VR contexts.

Several aspects of the experimental design help explain why reweighting did not emerge as a reliable predictor here. A first consideration is timing. The OCHART task provides pre- and post-exposure snapshots of perceptual upright, but CS unfolds dynamically within trials as conflict accumulates (Keshavarz et al., 2015). If cue reweighting occurs rapidly, nonlinearly, or in a participant-specific manner, static pre/post difference scores will necessarily miss the adjustments

most relevant to symptom generation. A second consideration is context. In room-scale or exploratory VR, changes in cue weighting can be expressed through movement—participants can reorient, step, or turn their head to test and reinforce new sensory balances (Weech et al., 2018). In the present study, however, the roller-coaster simulation created a passive, vision-dominant setting. Participants were essentially immobilized while optic flow drove the scene, meaning that even if internal cue weights shifted, there was limited opportunity to act on those adjustments through motor behavior. A third consideration concerns construct alignment. The OCHART task taps into perceptual judgments of letter orientation, a useful index of perceptual upright (Dyde et al., 2006; Barnett-Cowan & Harris, 2009). But such judgments do not directly reflect the control policies implemented second-by-second by the postural system when balancing under conflict. In other words, OCHART measures what participants perceive to be upright, not how they keep themselves upright.

Additional practical factors may have compounded this mismatch. The roller-coaster stimulus was deliberately intense, ensuring robust induction of CS but also potentially saturating visual drive. In such conditions, subtle individual differences in cue weighting may have been overwhelmed, making them harder to detect as predictors. Excluding participants with unstable OCHART fits also reduced the range of variability in reweighting scores, restricting statistical power. Finally, participants adopted different postural strategies in response to conflict—some constrained their movements (stiffening), while others moved more variably (exploratory). Averaging across such divergent strategies can flatten relationships between a static perceptual delta and a dynamic symptom trajectory, further weakening observable links.

Importantly, these postural strategies likely interacted with the task instructions. Participants were required to keep their feet planted and minimize movement but were allowed to sway if needed to maintain balance. This constraint may have accentuated individual tendencies: participants who naturally rely on stiffening could easily comply, whereas those inclined toward exploratory strategies were forced to express this adaptation through within-stance adjustments only, rather than through stepping or larger-scale repositioning. Consequently, task instructions may have amplified velocity differences between groups and limited the behavioral channels through which sensory reweighting could manifest, potentially obscuring its relationship with symptom severity.

Theoretically, these null results are instructive. They do not undermine the basic tenets of sensory conflict theory since conflict is still the backdrop against which sickness arises. But they do challenge

the assumption that offline perceptual reweighting measures are sufficient to predict symptoms in all VR contexts. A more nuanced interpretation is that conflict is necessary but not proximal: what ultimately drives CS is how the body manages stability under conflict. In a passive, vision-led task, the proximal mechanism appears to be sustained postural instability, not the magnitude of a pre/post perceptual shift. This interpretation resonates with postural instability theory (Riccio & Stoffregen, 1991), which posits that sickness emerges not simply from mismatched sensory inputs but from the body's failure to maintain stable control in the face of them.

This comparison also clarifies why movement measures outperformed reweighting in the present study. Path length integrates both frequency and amplitude of corrective actions, offering a dynamic measure of postural instability over time, providing a continuous readout of the corrective work required to stay upright under conflict (Palmisano et al., 2015). Because this corrective work is the final common pathway to either stability or discomfort—particularly in passive contexts—it aligns more closely with symptom reports than does a static perceptual index. In essence, while sensory reweighting may initiate adaptation, it is postural instability that most directly drives CS in passive VR contexts.

The practical message for research and design is clear. If the goal is to predict or mitigate CS in passive VR, pre/post perceptual measures alone should not be expected to provide reliable signals of risk. Instead, they should be paired with online, behavior-proximal markers of stability. Promising directions include embedding brief perceptual probes such as subjective visual vertical (SVV) tasks within trials (Witkin & Asch, 1948; Chung & Barnett-Cowan, 2023) and continuously monitoring cumulative postural effort (e.g., path length thresholds). These approaches could be used to trigger adaptive VR responses, such as reducing optic-flow gain, inserting stable visual references, or scheduling micro-breaks before symptoms escalate. Conceptually, this supports a hybrid model: sensory conflict provides the cause, postural instability provides the mechanism, and task context (passive vs. interactive) determines whether perceptual reweighting is expressed behaviorally or remains latent.

4.1.3 H2: Movement and CS

The results for Hypothesis 2 stood in clear contrast to those of Hypothesis 1. Greater postural movement was linked to more severe CS, and among the measures tested, path length emerged as the most reliable marker. This matters because it shows that what predicts discomfort in a passive,

visually intense VR environment is not a static perceptual estimate, but the dynamic accumulation of corrective movement over time. In other words, CS severity reflects how much “work” the postural system is forced to do to maintain balance when vision and vestibular inputs are in conflict.

The theoretical implications of this are important. Postural Instability Theory (Riccio & Stoffregen, 1991) argues that motion sickness arises when individuals cannot maintain stable control over their posture. Sensory Conflict Theory (Reason & Brand, 1975; Oman, 1990) highlights mismatched signals as the source of discomfort. The present results suggest that while conflict provides the background condition, it is instability itself that most directly explains symptoms in passive VR. Path length is a sensitive index of this instability because it integrates both the size and frequency of corrections. Unlike mean velocity or RMS displacement, which compress movement into a single average value, path length sums each correction, showing how the struggle builds as exposure continues.

The strength and consistency of this relationship further reinforce the conclusion. Path length predicted sickness even after outlier removal, which means the effect was not driven by a few extreme participants. Sway area initially showed a link to symptoms, but this weakened once influential cases were excluded, highlighting its vulnerability to extreme excursions. By comparison, path length remained stable because it reflects the total burden of corrections across the entire trial, not just the largest displacements. This cumulative quality makes it a stronger candidate as a biomarker of CS (Palmisano et al., 2015; Kim et al., 2021).

Looking more closely at sway directions provided additional insight. Both anteroposterior (AP) and mediolateral (ML) path lengths predicted CS when considered independently, but their shared variance meant neither axis uniquely explained symptoms once modeled together. This suggests that CS in this context reflects global destabilization across planes, rather than imbalance along one axis alone. Such a finding aligns with research showing that VR challenges the whole-body control system, which coordinates balance in multiple axes simultaneously (Kennedy & Stanney, 1996; Horak, 2006). A composite measure like path length therefore provides the clearest signal of risk.

The comparison with sensory reweighting further clarifies why movement emerged as the stronger predictor in this study. In the roller-coaster task, participants had little opportunity to act on perceptual adjustments through exploration or locomotion. Even if internal cue weights shifted, those changes influenced sickness only to the extent that they affected posture. Path length, as a continuous

record of postural effort, became the most direct marker of that influence. Put simply, reweighting may set the conditions for adaptation, but instability is what makes people feel sick.

There are also different ways participants might arrive at high path length, and both fit the current data. One possibility is a primarily reactive mechanism, in which participants fail to stabilize entirely and produce repeated corrective movements in response to perceived errors. Here, sway reflects feedback-driven postural adjustments, likely dominated by late-stage sensorimotor responses to mismatched visual–vestibular signals, leading to ongoing instability. The other possibility involves a more mixed predictive–reactive mechanism, where participants deliberately engage in exploratory sway to probe the environment and recalibrate their internal estimates of upright. In this case, movement reflects both top-down predictive strategies (e.g., active generation of multisensory input to reduce uncertainty) and bottom-up corrections, with the nervous system testing and refining its internal model of orientation. Regardless of the route, the outcome was the same: greater cumulative corrective work and higher symptom severity. This also explains why group averages of displacement looked modest even as confidence intervals widened. By summing corrections across time, path length preserved these diverging strategies, which is precisely why it held predictive power. It is also important to note that increased movement may not always reflect passive destabilization. In some individuals, sway could represent an active coping or recalibration strategy—an attempt to generate sensory information to resolve conflict or maintain equilibrium in the absence of other adaptive behaviors (e.g., locomotion). From this perspective, high path length does not necessarily signal failure to stabilize but may reflect different strategies for coping with VR-induced sensory mismatch.

These findings carry both theoretical and practical weight. They tilt the balance toward Postural Instability Theory as the proximal mechanism of CS in passive VR, while still acknowledging Sensory Conflict Theory as the initiating cause. Importantly, they suggest that cumulative measures of instability—not static perceptual indices—are the best predictors of risk when users must remain still under strong optic flow. For designers and researchers, this positions path length as a promising biomarker of CS. It can be calculated easily from motion capture or wearable sensors and could serve as an early-warning signal to trigger adaptive interventions. By adjusting visual intensity, adding stable reference frames, or scheduling short breaks when path length begins to climb, VR systems could become more responsive to each user’s stability profile.

It is also important to consider how the task instructions shaped the expression of postural responses. Participants were instructed to keep their feet planted and remain as still as possible but were permitted to sway if needed to maintain balance. This minimized voluntary movement unrelated to sensory conflict while preserving natural corrective responses. As a result, high velocity and path length in this context likely reflect reactive or exploratory postural adjustments rather than arbitrary movement. At the same time, these instructions constrained how participants could respond to instability: individuals who might otherwise have stepped to regain balance were limited to within-stance corrections, potentially amplifying velocity fluctuations for those using exploratory strategies. This methodological factor is important for interpreting path length as a marker of CS in this study.

Collectively, these findings demonstrate that movement-based metrics outperformed sensory reweighting as predictors of CS due to their closer alignment with real-time physiological responses. This reinforces the broader point that understanding CS requires not only measuring sensory mismatches but also tracking the body's ongoing efforts to cope with those mismatches. Path length, more than any other movement measure examined here, captured that process.

4.1.4 Individual Differences and Methodological Considerations

The trial-by-trial progression of FMS scores provides additional insight into the heterogeneity of cybersickness development across individuals. While some participants displayed low and stable symptoms throughout the VR exposure, others showed gradual or abrupt increases, and a small subset exhibited decreasing trajectories suggestive of adaptation. These divergent trajectories are consistent with prior work highlighting wide variability in susceptibility and adaptation to VR-induced sickness (Saredakis et al., 2020; Luong et al., 2022). Participants showing increasing symptom trajectories tended to exhibit larger path length and velocity fluctuations, supporting postural instability theory, which posits that sustained difficulties in stabilizing posture are a proximal driver of symptom severity. Conversely, participants with stable or decreasing FMS may have engaged more flexible and effective sensory reweighting strategies, enabling them to tolerate or adapt to the repeated visual-vestibular conflict.

These patterns underscore the value of treating cybersickness as a dynamic process rather than a single end-point measurement. FMS trajectories revealed that symptoms do not accumulate uniformly but evolve through distinct temporal patterns that likely map onto different underlying mechanisms—

ranging from early stabilization and adaptation to progressive destabilization and sensory conflict escalation. Methodologically, this highlights the importance of incorporating within-session measures rather than relying solely on pre- and post-exposure assessments, as these would have masked meaningful differences between adapters and accumulators.

At the same time, the use of the Fast Motion Sickness (FMS) scale carries both advantages and limitations that shape how these patterns can be interpreted. FMS provides a low-burden, high-temporal-resolution index of symptoms, making it well suited to tracking rapid changes in sickness over time and linking them to concurrent movement measures. This was particularly important in the present study, where participants were standing in a motion capture environment, and longer or more complex questionnaires would have disrupted the natural flow of the task. However, as a single global measure, FMS lacks symptom-specific resolution and may be sensitive to ceiling or floor effects, potentially underrepresenting specific symptom domains such as nausea, oculomotor strain, or disorientation.

By contrast, the Simulator Sickness Questionnaire (SSQ) remains the field's standard for profiling symptom clusters across these domains. It allows for richer symptom characterization and facilitates comparison across studies. Yet, SSQ is less practical for capturing within-session dynamics due to its episodic administration and greater participant burden. For these reasons, the FMS was better suited to the aims of this study, which required trial-level resolution to examine the relationship between postural instability and symptom trajectories.

To summarize, these considerations point toward the value of a multimodal assessment approach in future work. A combination of high-frequency global symptom tracking (FMS) with periodic SSQ administration would enable both temporal precision and symptom profiling. Integrating subjective measures with physiological markers (e.g., heart rate variability, galvanic skin response) and movement-based indicators (e.g., path length slope, velocity volatility) would further strengthen inferences about the mechanisms underlying cybersickness onset and progression. This multimodal framework would provide a more comprehensive picture of how sensory reweighting, postural instability, and symptom experience interact over time and across individuals.

A striking feature of the present study was the emergence of distinct postural control strategies across participants, reflecting meaningful individual differences in how people coped with VR-induced conflict. Some participants adopted what can be described as a stiffening strategy, marked by constrained sway and minimal variability. This pattern is often interpreted as a protective approach, in which unreliable visual inputs are down-weighted and vestibular or somatosensory cues are emphasized to stabilize posture (Horak, 2006). Similar patterns have been described in balance research, where reduced sway amplitude corresponds with increased joint stiffness or muscular co-contraction in the lower limbs, reflecting a compensatory effort to preserve stability (Winter et al., 1996). By contrast, other participants displayed a more exploratory strategy, characterized by larger sway excursions and higher variability. From an ecological perspective, such exploratory movements may not simply represent instability but can also serve as an active strategy to combat CS, allowing individuals to generate the sensory feedback needed to recalibrate under conflicting conditions (Stoffregen & Bardy, 2001; Palmisano et al., 2018). In this sense, movement may reflect both vulnerability and resilience, depending on whether it leads to successful sensory realignment or escalating instability. These contrasting patterns suggest that CS vulnerability cannot be fully understood by looking at mean sway values alone. Instead, it must be examined in terms of how individuals balance rigidity and exploration when confronted with sensory conflict.

This variability is consistent with prior research documenting wide differences in susceptibility to CS (Saredakis et al., 2020; Howard & Van Zandt, 2021; Luong et al., 2022). Several factors likely contributed to this heterogeneity. Individual differences in sensory thresholds mean that some participants are more sensitive to visual–vestibular discrepancies than others (Dennison & D’Zmura, 2017). Attentional strategies also matter: participants who focused narrowly on the visual display may have become more destabilized than those who distributed attention across sensory channels (Hettinger & Riccio, 1992). Prior VR experience is another key moderator, since repeated exposure is known to reduce CS severity through habituation (Luong et al., 2022). Cue integration strategies themselves vary as well. For example, Chung and Barnett-Cowan (2023) demonstrated that variability in perceptual upright adaptation maps directly onto CS, suggesting that some individuals anchor more strongly to body or gravity cues, while others rely more heavily on visual information. The widening variability in sway observed across trials in this study likely reflects these diverse strategies, and it was precisely this variability that cumulative metrics such as path length were able to capture effectively.

The coexistence of stiffening and exploratory strategies also connects to ongoing theoretical debates about whether increased sway is inherently maladaptive or can sometimes serve an adaptive function. Postural Instability Theory (Riccio & Stoffregen, 1991) emphasizes that sustained instability is the proximal driver of motion sickness, implying that individuals who destabilize continuously are at greatest risk. Other perspectives argue that variability may be adaptive in some contexts, as exploratory sway provides the nervous system with opportunities to recalibrate under novel or conflicting conditions (Stoffregen & Bardy, 2001; Palmisano et al., 2020). The present findings suggest that both interpretations hold merit. For some participants, exploratory sway may have facilitated recalibration, while for others, it may have amplified instability without resolution. Likewise, stiffening may suppress immediate symptoms, but at the cost of flexibility if conflicts intensify. CS vulnerability, then, does not stem from a single “bad” strategy but from the dynamic interplay between adaptive and maladaptive control responses, shaped by each individual’s sensory and motor preferences.

Methodological choices also shaped how these individual differences became visible. The use of linear mixed-effects models allowed repeated-measures noise to be handled effectively, while still accounting for participant-level variability (Bates et al., 2015). Outlier analyses confirmed that the association between path length and CS was not simply the product of extreme cases. However, technical challenges reduced analytic power: three participants were excluded due to unstable OCHART fits, and motion capture data were lost for others due to recording errors. These constraints limited the ability to detect smaller effects, particularly for Hypothesis 1. Yet they also highlight the broader practical challenges of aging and VR research, where participant attrition and technical failures are common obstacles (Stanney et al., 2020). Far from being incidental, such challenges underscore the difficulty of conducting ecologically valid studies in demanding VR environments.

Another methodological factor was the passive roller-coaster context. Unlike interactive VR tasks where participants can move freely and recalibrate actively, the present study constrained participants to maintain stance while exposed to strong optic flow. This context likely magnified the role of postural instability, since small corrections accumulated into large path lengths, while muting the role of sensory reweighting, since perceptual adjustments could not be expressed behaviorally. This helps explain why prior studies using interactive VR have reported stronger links between reweighting and CS (Chung & Barnett-Cowan, 2023), while the present study identified movement—and path length in particular—as the clearest predictor of symptoms.

To sum up, these findings highlight the importance of considering both individual variability and methodological context in interpreting CS outcomes. Participants adopted heterogeneous strategies that reflected both adaptive and maladaptive responses to conflict, and these strategies interacted with task design to shape results. At the same time, rigorous statistical modeling ensured that the predictive role of path length was robust, while technical limitations and task constraints provided valuable lessons about the trade-offs of ecological validity. Importantly, movement should not be viewed solely as a marker of postural failure but also as a potential adaptive mechanism, reflecting active attempts by some individuals to recalibrate and maintain equilibrium under sensory conflict. Ultimately, CS is best understood as a dynamic, individualized phenomenon shaped by sensory integration, motor behaviour, and contextual factors.

4.1.5 Limitations and Future Directions

Several limitations of the present study must be acknowledged. The sample size was modest, and attrition was especially high among older adults, which prevented meaningful age-based comparisons. Although this constraint limited the intended analysis, it also reveals something important in its own right: older adults remain difficult to recruit and retain in VR studies because they often withdraw early due to heightened discomfort with visually provocative content (Saredakis et al., 2020). High dropout rates are not simply an obstacle but a finding that highlights the need for age-sensitive recruitment strategies and more tolerable VR protocols if aging is to be studied systematically in this context.

While FMS provided the necessary temporal resolution for this study, it remains a subjective, global index. Future work should integrate FMS (for dynamics) with SSQ (for symptom composition) and physiological markers to build multimodal models of CS onset. This will help distinguish nausea-driven vs. oculomotor-driven profiles and clarify how these map onto postural instability and sensory reweighting processes during VR.

Technical challenges further reduced usable cases. Some participants were excluded due to unstable OCHART fits, and several datasets were lost when the motion capture system defaulted to the wrong recording mode. These setbacks reduced analytic power, particularly for testing Hypothesis 1, and should be considered when interpreting the null results. At the same time, they underscore the inherent difficulty of collecting high-quality, multimodal data in naturalistic VR environments. Rather

than diminishing the contribution, these obstacles illustrate the real-world challenges of designing studies that integrate perceptual tasks with motion capture.

Another limitation concerns the stimulus context. Unlike earlier reweighting studies that used exploratory, interactive VR scenarios such as space navigation or free exploration (e.g., Weech et al., 2018; Chung & Barnett-Cowan, 2023), the present study employed a passive roller-coaster simulation. This choice had strengths and weaknesses. On one hand, it was highly effective in reliably inducing CS, which allowed movement predictors such as path length to emerge robustly. On the other hand, its intensity may have overshadowed subtler reweighting effects. Moreover, participants were required to remain still while visually “moved,” creating conditions where postural instability was unavoidable and perceptual reweighting had limited opportunity for behavioral expression. This methodological difference likely explains why reweighting failed to predict symptoms here while it has in more interactive contexts. Future research should therefore test across a continuum of VR environments—from mild to intense, and from exploratory to passive—to clarify the boundary conditions under which sensory conflict versus postural instability theories best account for outcomes.

Finally, CS in this study was assessed solely with the Fast Motion Sickness Scale (FMS). While this tool is validated and widely used (Keshavarz & Hecht, 2011), it remains a subjective measure of symptom severity. Integrating self-report with physiological markers such as heart rate variability, galvanic skin response, or EEG could provide a more multidimensional account of how sensory conflict and instability interact to produce sickness. Combining subjective and objective indicators would also allow researchers to capture both the conscious experience of discomfort and the autonomic responses that may precede it.

Building on this, future work could extend the current behavioral approach by pairing OCHART with neurophysiological recordings. Time-locked ERP and ERSP analyses may help identify neural signatures of sensory reweighting—for example, early components reflecting visual–vestibular conflict processing and later decision-related potentials. Spectral modulations in parietal alpha or beta bands could further reveal how efficiently individuals adjust cue weights, offering a more mechanistic account of why some people are more susceptible to CS than others. Incorporating these neural measures would move beyond correlational behavioral findings toward uncovering the temporal dynamics and neural basis of sensory reweighting.

Taken together, these limitations and opportunities highlight several concrete directions for future work. Researchers should: (1) develop methods for integrating online perceptual probes during VR exposure to capture the dynamic unfolding of reweighting processes, (2) recruit larger and more diverse samples, including older adults, to examine how age modulates sensory integration and sickness susceptibility, (3) combine subjective reports with physiological measures to build richer, multimodal models of symptom onset, and (4) systematically manipulate VR contexts to determine when reweighting predicts discomfort and when cumulative instability is the dominant driver. Pursuing these directions will allow future studies to move beyond documenting CS toward explaining its underlying mechanisms, ultimately informing the design of VR systems that are safer, more adaptive, and more inclusive.

4.1.6 Conclusion

This thesis set out to compare sensory reweighting and postural movement as predictors of cybersickness (CS) in immersive VR. The findings pointed to two different conclusions. Hypothesis 1 was not supported: changes in sensory cue weighting measured with OCHART did not predict CS severity during a passive, vision-dominant roller-coaster simulation. This suggests that reweighting ability may not consistently predict sickness in all contexts. It may play a larger role in interactive VR settings, where participants can use movement to actively respond to conflicts. Hypothesis 2, on the other hand, was supported. Greater postural movement, especially higher cumulative sway path length, was a reliable predictor of CS severity. This provides clear support for postural instability theory, highlighting instability as the immediate factor that drives symptoms when visual–vestibular conflicts persist.

A key strength of this study was the use of trial-by-trial FMS scores, which allowed the temporal progression of symptoms to be captured more precisely. The trajectories revealed clear individual differences: some participants experienced increasing discomfort, some remained stable, and others showed decreasing symptoms over time, suggesting adaptation. These patterns closely followed changes in postural movement, reinforcing the link between instability and symptom severity. Analyzing FMS over time, rather than only pre- and post-exposure, provided a richer understanding of how CS develops across repeated exposures and why some individuals are more vulnerable than others.

There are also important methodological considerations. The kinematic outcomes in this study were calculated using CoM trajectories expressed in a global laboratory coordinate system. This approach allowed for standardized comparisons and time-locking of movement data to VR exposure, but it also introduced potential variability related to stance and alignment differences. Factors such as foot width, foot angle, or slight body rotation could affect how movements were represented along the global axes. As a result, some of the variability in kinematic measures may reflect these geometric differences rather than true differences in postural control. Future studies should address this issue by aligning movement data to participant-specific frames, standardizing stance, and incorporating alignment checks to reduce these sources of variability and improve interpretability.

From a theoretical perspective, these findings refine how sensory conflict and postural instability theories are understood together. Sensory conflict remains the underlying condition that makes sickness possible, but instability appears to be the proximal cause of discomfort in passive VR. Sensory reweighting likely contributes to how well individuals adapt, but it is less predictive when opportunities to act on those adjustments are limited. Path length, as a continuous measure of the corrective work required to maintain balance, was a stronger and more consistent predictor of symptoms in this context.

These results also have practical implications. Movement-based measures, combined with real-time symptom tracking, can provide early warning of rising sickness. Future VR systems could monitor instability continuously and adapt in real time, for example by reducing visual intensity or prompting short breaks before discomfort escalates. Adding additional measures, such as the Simulator Sickness Questionnaire (SSQ) or physiological signals, could give a more complete picture of the onset and progression of symptoms.

In sum, this study shows that predicting CS requires understanding both sensory conflicts and how the body responds to them over time. Path length captured this process more effectively than sensory weighting measures in a passive VR context. By incorporating temporal symptom data, movement-based predictors, and careful reflection on methodological choices, this work advances both theoretical understanding and practical strategies for making VR safer and more comfortable.

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Appendix A- Participant Attrition

- **Younger adults (n = 25):**
 - 3 participants were excluded due to motion capture recording errors (system defaulted to “Marker” mode instead of “Video”).
 - 3 participants excluded due to unstable OCHART responses that prevented reliable computation of cue weights.
 - **Final analyzable younger adult sample = 19.**
- **Older adults (n = 8):**
 - 2 withdrew immediately upon encountering the VR environment.
 - 4 withdrew after completing the first trial, citing discomfort and strong motion effects.
 - Of the remaining 2, one completed all trials and the other completed only half.
 - **Final usable older adult sample = insufficient for analysis.**

This level of attrition (75% of older adults) is consistent with prior reports that CS contributes disproportionately to dropout among older participants (Saredakis et al., 2020), underscoring the need for modified recruitment strategies and more tolerable VR protocols in aging research.