Influence of virtual reality height exposure on cognitive load and visual processing during balance beam walking

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July 2021

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Balance is a critical component of many activities of daily living and sports. Effective balance control relies on the input from multiple sensory systems, such as proprioceptive information about one's body position and visual cues from the surrounding environment. Conclusions for how balance varies during dynamic tasks have primarily been determined through low-variability tasks that may not offer adequate challenges for healthy individuals. Beam-walking has been proposed as a more effective and direct measure of dynamic balance for both healthy and diseased populations. Balance beam parameters such as length, width, and height can be altered to introduce various challenges for a wide range of individuals. In response to height exposure during beam walking, individuals tend to display cautious gait patterns and limited visual exploration of the surrounding environment. Head mounted displays, or immersive virtual reality (VR), allow individuals to experience a cognitive sense of presence similar to that experienced in a real environment, without the immediate risk of injury or danger. VR environments have been shown to induce physiological stress responses (i.e., elevated heart rate) that mirror those observed in real life situations. Further, investigating frontal lobe asymmetry during virtual height exposure and beam walking can provide insight on the approach or withdrawal behavior styles associated with immersive VR and challenging dynamic tasks. Thus, the purpose of this study was to observe how virtual reality height exposure induces stress and impacts balance performance, visual processing, and cognitive effort during beam walking. Sixteen healthy young adults (age = 22 ± 3 years, 7 males, 9 females) were recruited for voluntary participation. Participants completed a series of nine walking trials on a physical walkway with and without a virtual reality (VR) headset. The nine trials were divided into three walking conditions: no-VR (NVR), low-VR (LVR), and high-VR (HVR). Wireless electroencephalogram (EEG) and heart rate monitoring systems were used to record brain activity and physiological stress responses throughout all nine trials. For the VR conditions, participants wore a head mounted display and were first immersed in a city street landscape (LVR) and then up on a high-rise building (HVR). A virtual walkway that matched the physical walkway parameters was present in both VR environments. Balance performance significantly worsened from the NVR to LVR condition ($p < 0.001$) but slightly improved from the LVR to HVR condition ($p < 0.05$), while VR trial completion time significantly increased from the LVR to HVR condition ($p < 0.05$). The gaze behavior analysis revealed that participants spent most of their time viewing the three virtual walkway planks and the areas just below or around the walkway for both conditions ($p < 0.05$) and that there were no differences in object viewing time between the LVR and HVR conditions ($p = 0.058$). Frontal lobe alpha power significantly decreased from NVR to LVR and NVR to HVR ($p < 0.05$), yet no significant differences were found between LVR and HVR. Finally, participants exhibited elevated heart rate across all three conditions, with significant increases from NVR to LVR ($p < 0.05$), LVR to HVR ($p < 0.05$), and NVR to HVR ($p < 0.001$). These findings indicate that virtual reality height exposure can induce

physiological stress responses as well as impact balance performance, cognition, and visual processing.

Influence of virtual reality height exposure on cognitive load and visual processing during balance beam walking

A Thesis

Presented to The Faculty of the Department of Kinesiology

East Carolina University

In Partial Fulfillment of the Requirements for

The Master of Science in Kinesiology

Biomechanics and Motor Control

By

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Chapter I. Introduction

Balance is a critical component of many activities of daily living and sports. Balance has been previously defined as the body posture dynamics that reduce the risk of or prevent the act of falling (Winter, 1995). Whether an individual is attempting to maintain static or dynamic balance, effective balance control depends on the integration of the visual, vestibular, proprioceptive information regarding one's body position, biomechanical alignment, muscular strength, and coordinated muscle activation patterns (Meyer & Ayalon, 2006). During static balance tasks such as quiet standing, the postural control system is able to keep the body's center of mass over the base of support (BOS). For healthy individuals, single-legged standing and external perturbations lead to the displacement of the center of pressure (COP) and center of mass (COM), respectively, to compensate for changes in the BOS (Pope et al., 2011, Kanekar & Aruin, 2014). Likewise, the location of a body's COM and BOS fluctuate during movement. Voluntarily adjusting stride length and width to maintain instantaneous stability can influence both the anteroposterior and mediolateral margin of stability, the minimal distance from an extrapolated COM to the BOS boundaries (Young & Dingwell, 2012, Yiou et al., 2017). In response to external perturbations during walking, MOS in the anterior and medical directions has been shown to be lower prior to longer, wider, quicker steps, while MOS in the medial and lateral directions is lower before taking slower steps (Sivakumaran et al., 2018). Seeing how healthy balance control can change in response to low-variability conditions, such as external perturbations and voluntary gait changes, further investigation into more challenging balance tasks may offer insight on how healthy individuals respond to fluctuating conditions or environments. In turn, the insight gained on balance during challenging tasks could be applied to a wider range of real-life environments.

Conclusions for how balance varies during static and dynamic tasks have primarily been determined through low-variability conditions such as quiet standing or on a treadmill with constant speed. As a result, recent studies evaluating dynamic balance claim that previous balance measures do not offer sufficient challenges to assess and identify balance deficits (Sawers & Ting, 2015, Uematsu et al., 2018, Sawers & Hafners, 2018). Beam-walking has been proposed as a more effective and direct measure of dynamic balance for both healthy and diseased populations. Counting the number of beam step-offs, or balance failures, per unit of time provides researchers and clinicians with a direct and reliable method to quantify dynamic balance performance. Calculating balance failures per minute is a common measure used in studies evaluating balance-beam walking performance (Domingo & Ferris, 2009, Domingo & Ferris, 2010, Peterson, Furuichi & Ferris, 2018). Balance-beam parameters such as length, width, and height can be altered to introduce various challenges for a wide range of individuals. Both constant-width beam walking and narrowing-beam walking have been shown to alter step length, width, and walking time in healthy young individuals (Sawers & Ting, 2015, Sawers & Hafner, 2018). Therefore, beam-walking performance may provide further insight on how task difficulty influences balance and ultimately how that challenge may impact locomotion. Since successful balance control also relies on sensory input from the visual system, observing gaze behavior during dynamic tasks may offer more information on how challenging tasks influence visual processing and subsequently, dynamic balance performance.

In addition to the role muscles and joints play in balance, visual processing also influences dynamic balance control and successful locomotion. Healthy individuals typically display similar saccade patterns while walking along a predefined pathway, with most saccades being made towards the next intended foot placement before a step is initiated, indicating that visual processing assists with movement planning (Hollands et al, 1995). Further, Hollands and Marple-Horvat (2001) determined that the oculomotor and stepping motor control systems operate via an interactive feed-forward mechanism that results in saccade and next-step generation being temporally linked. This feed-forward mechanism allows individuals to gather relevant information about their environment to better navigate future obstacles and initiate safer movement patterns (Hayhoe et al, 2009, Zito et al, 2015). With the understanding of how vision influences human movement at the ground level, recent studies have investigated how height exposure impacts visual search and locomotion patterns.

Tersteeg, Marple-Horvat, and Loram (2012) found that individuals walking along a beam above the ground demonstrated cautious gait and that removing visual height information was not enough to restore normal gait and that retention of the known risk of falling contributed to modified walking. A later study focusing on how a known fear of heights impacted movement and gaze behavior demonstrated similar results. Kugler et al (2014) found that individuals susceptible to a fear of heights displayed limited visual exploration while suspended 20 meters above the ground. Those susceptible to a fear of heights primarily fixated on the walkway straight ahead, the floor, or the handrail. This gaze behavior was also associated with a slow and cautious gait. Though these studies demonstrated how visual processing changes in real-life height exposure situations, replicating these environments for future research may not be feasible. With the potential hazards of walking along a suspended beam or lack of resources to construct a safe and realistic height exposure, developing controlled environments that monitor gaze behavior during dynamic balance is critical for the transfer of skill to unpredictable real-life situations. Recent advancements in virtual reality (VR) technology that incorporate eye tracking show promise for monitoring gaze behavior in controlled and realistic environments (Park et al, 2019). Thus, VR may offer a more comprehensive approach to evaluating visual processing while simultaneously minimizing the risks associated with subjecting individuals to real-life height exposure or other unpredictable situations.

Virtual reality has been increasingly used in research due to its ability to provide novel sensory experiences in a controlled environment (Peterson et al, 2018). VR offers researchers and clinicians a way to develop realistic environments and situations that cannot be experienced in a rehabilitation center or fitness facility. Several rehabilitation studies have used VR as a balance training tool by displaying environments onto screens in front of and surrounding participants and have achieved promising results for the use of VR as a rehabilitation tool (Yang et al, 2008, Kim et al, 2009, Mirelman et al, 2011, & Liao et al, 2015). However, this form of VR may not provide realistic experiences for healthy populations.

Head mounted displays (HMDs), or immersive VR, allow individuals to experience a cognitive sense of presence similar to that experienced in a real environment, without the immediate risk of injury or danger. For example, Peterson et al (2018) developed an immersive VR environment that involved crossing a beam 15 meters off the ground. Results indicated that HMDs can provide realistic environments that induce physiological stress in humans during dynamic balance tasks. Likewise, Kisker, Gruber, and Schöne (2019) found that walking along a physical wooden plank while immersed in a ground level and high-rise building VR environment increased heart rate and led to a relatively high sense of presence. Despite these findings, Wuehr et al (2019) demonstrated that HMDs do not simulate realistic fear and physiological arousal at heights above 40m, suggesting that immersive VR may have limited effects. Based on the relatively new and contradicting findings regarding the realistic nature and effects of VR, further investigation into the use of HMDs during dynamic balance tasks is needed.

In addition to eliciting physiological responses, virtual navigation has been shown to impact cognitive exertion (Peterson et al, 2018). The hippocampus, parahippocampus, retrosplenial cortex, and posterior parietal complex have been identified as key brain regions involved in forming core navigation networks (Epstein et al 2017, Ekstrom et al, 2018). These regions function to promote place learning and self-localization. Furthermore, successful navigation also relies on decision-making, goal-tracking, and planning. The frontal lobe has long been recognized as a key player in executive functioning and adaptive behavior (Penfield & Evans, 1935, Luria, 1966). Thus, frontal lobe activation should be considered as an integral part of successful navigation. Despite the important role of decision-making and planning in navigation, the frontal lobe has often been overlooked in previous studies involving navigation and cortical activity. Through a comprehensive review of studies investigating the role of the prefrontal cortex (PFC) in physical and virtual navigation, Patai and Spiers (2021) determined that regions of the PFC are crucial for navigation, especially when environments are complex or dynamic, such as in virtual environments. Additionally, the frontal lobe is responsible for modulating emotions and behavior. Frontal alpha asymmetry (FA) has been speculated to underlie the balance between approach and withdrawal behavior and can be used as an indicator of positive and negative affect (Mennella et al, 2017). Greater right-side activation has been associated with negative affect and withdrawal behavior while increased left-side activation is linked to positive affect and approach behavior. Investigating right and left frontal lobe activation during virtual height exposure may provide further insight on how emotional responses to VR impact balance control.

Purpose

The purpose of this study was to observe how virtual reality height exposure induces stress and impacts balance performance, visual processing, and cognitive effort during beam walking.

Hypotheses

1) Beam step-offs and failures per minute will increase as participants complete the NVR, LVR, and HVR conditions.
2) Participants will demonstrate more restrictive visual search patterns during the HVR condition compared to the LVR condition.
3) Frontal lobe alpha spectral power will continuously decrease from the NVR to HVR condition.
4) Mean heart rate will increase from the NVR to LVR condition and will remain elevated throughout the HVR condition.

Significance

Previous research indicates that VR can impact several physiological systems that influence balance performance and can offer numerous research and clinical applications. However, few studies have attempted to observe how VR induces stress and simultaneously impacts cognitive loading and gaze behavior. Incorporating these variables into one study offers a more comprehensive overview of the effects of VR and can provide insight for future studies designed to use VR as a training or rehabilitation tool.

Delimitations

1) All participants will be healthy without previous or current lower limb injuries and neurological impairments that could impact balance or cognition.

2) All participants will not be knowingly prone to motion sickness or acrophobia.

3) All participants will have a Body Mass Index (BMI) of less than 30 kg/m^2

Chapter II. A review of the literature

Introduction

The purpose of this study is to observe how virtual reality height exposure induces stress and impacts physical and cognitive performance and visual processing while crossing a balance beam. This literature review will discuss: **1)** static and dynamic balance, **2)** visual processing during locomotion, **3)** cortical activity during balance, locomotion, and navigation and **4)** the various applications of virtual reality.

Balance

Static Balance

Balance is typically classified as static or dynamic. Static stability is important for maintaining posture during quiet standing and in response to perturbations. Orthopedic conditions and aging have been shown to impact foot COP locations and displacement. Thus, identifying COP during static balance tasks in healthy individuals has provided insight on how to better evaluate fall-risk characteristics in individuals experiencing various health conditions.

Static stability relates to balance in unperturbed situations, such as quiet standing (Macpherson & Horack, 2013). COP measurements from force plate data can be analyzed to determine the point at which ground reaction forces (GRF) act and are useful in quantifying the stability and function of the foot (McKeon et al, 2008). Pope et al (2011) investigated the differences in COP location and time to boundary (TTB) data points during single limb stance in healthy controls and individuals with chronic ankle instability (CAI). The findings indicated that healthy controls had a significantly higher percentage of COP and TTB minima data points in the posteromedial region of the foot while the CAI group demonstrated a significantly higher percentage of data points in the anterolateral region. Having a more lateral COP could result in less time to react to a lateral perturbation before the COP falls outside of the base of support. Mettler et al (2015) implemented a 4-week balance training program to determine if intervention could alter COP location in participants with CAI. The training incorporated single-legged balance tasks and dynamic tasks such as hopping with an emphasis on speed-of-movement execution. Following the intervention, the CAI group had fewer data points in the anterolateral section of the foot, whereas the COP location in no-balance training group did not change. Overall this study showed that balance intervention can help those who experience CAI shift their COP to a more posterior position, similar to that observed in uninjured participants.

The process of aging affects one's ability to control posture and therefore increases the risk of falling. Kanekar and Aruin (2014) hypothesized that when compared to young adults, anticipatory postural adjustments (APA) in older adults would be delayed resulting in larger COP and center of mass (COM) displacements after perturbations. Healthy young and old participants stood and experienced external perturbation via the pendulum impact paradigm. Using this paradigm allowed the perturbations to be equivalent magnitudes and eliminated the effect of age-related changes in voluntary movement on posture preparation. Results indicated that the onset of APAs was delayed in older adults when compared to younger adults and that there was a significant negative correlation between the COP displacement during anticipation and the peak COP displacement (after movement compensation) for older adults. Delayed APAs and smaller anticipatory COP displacement resulted in larger peak displacements of both the COP and COM in older adults following perturbation, indicating greater instability.

Further, Mileti et al (2020) investigated the effect of aging by observing reactive postural responses to continuous yaw perturbations. Ten healthy young adults and ten healthy older adults were subject to lower (0.2 Hz) and higher (0.3 Hz) frequencies while standing with their eyes open (EO) or eyes closed (EC) on a rotating platform. Age-related changes were found in balancing continuous yaw perturbation, regardless of frequency or eye condition. Older subjects demonstrated a more conservative and less destabilizing motion while working to maintain posture, suggesting that older individuals may be more cautious during postural tasks to compensate for reduced physical abilities.

Determining characteristics of healthy static balance and understanding how orthopedic conditions and aging influence them offers foundational knowledge that can be applied to balance performance during dynamic tasks. Comparing static measurements to dynamic measurements helps further distinguish between the mechanisms involved in stationary and dynamic postural control.

Dynamic Balance

Dynamic balance is critical for an individual to successfully navigate their environment and maneuver around or avoid obstacles within their pathway. Walking tasks are commonly used when assessing dynamic balance to better understand how changes in gait patterns influence dynamic stability. As with static stability, aging and other health conditions have been shown to impact dynamic stability. Since dynamic stability can serve as a measure of quality of life, several tests have been developed to quantify balance performance, yet there are still inconsistencies on whether these tests accurately assess healthy and diseased populations. Therefore, recent research has focused on the development of dynamic balance tasks that can offer sufficient challenges and accurate representations of dynamic stability for both populations.

Changes in step length (SL) and step width (SW) have been shown to influence stability during movement. Young and Dingwell (2012) determined whether voluntarily adopting various SL and SW could alter instantaneous stability during walking. Thirteen young healthy participants walked on a treadmill at a normal self-selected pace or in time with a metronome that was set to a cadence that matched paces established during normal walking. During SW manipulations, participants were asked to walk with wider or narrower steps. For the SL manipulations, participants walked with longer or shorter steps. SL manipulation led to significant changes in margin of stability in the anterior-posterior direction but not the mediolateral position. Margin of stability (MOS) is defined as the minimum distance from an extrapolated COM position to the boundaries of the base of support (Yiou et al, 2017). Walking with longer steps increased the variability in the anterior-posterior and mediolateral MOS. Narrower steps resulted in a significant decrease in mediolateral MOS and wider steps led to a significant increase in anterior-posterior MOS and decrease in mediolateral MOS. Overall these findings indicated that simple, voluntary changes in gait characteristics can significantly impact anterior-posterior and mediolateral stability in human walking. Understanding how gait changes impact stability in healthy individuals is essential for determining risk factors that may lead to falls and subsequent injuries in aging or diseased populations.

Despite balance while walking being a critical factor for quality of life, there is no laboratory-based approach to evaluate and study balance ability during walking (Hamacher et al, 2011). The current laboratory measures implemented focus on the recovery of balance and the clinical instruments used only pose difficulty for highly impaired individuals. The Berg Balance Scale has been identified as the gold standard for static and dynamic balance assessment, yet this test does not include gait assessment. Major, Fatone and Roth (2013) evaluated the validity and reliability of the Berg Balance Scale (BBS) in 30 community-dwelling individuals with lower-limb amputations. The BBS consists of a series of tasks performed while standing or sitting in a chair. The BBS demonstrated high interrater reliability and internal consistency, but participant scores were skewed to the higher range of performance. Seventy percent of participants achieved a score of ≥ 50 and 10 percent of participants achieved the BBS maximum score (56), suggesting there was a small ceiling effect. Though the BBS has been shown to predict fall-risks for elderly and severely impaired populations, it does not provide a direct measurement of walking stability or any form of challenge for healthy individuals. Other clinical balance instruments such as the Activities-Specific Balance Confidence scale and Dynamic Gait Index are relatively quick and inexpensive tests to administer but are not without their limitations. These tests offer a nonspecific evaluation of balance and fail to specifically assess walking, the movement that typically leads to falling (Niino et al, 2000).

In an effort to develop more challenging and accurate balance assessments, Sawers and Ting (2015) tested whether a simple and low-cost beam-walking task could discriminate across the spectrum of walking balance proficiency. Ten expert ballet dancers, ten untrained novices, and five individuals with unilateral transtibial limb-loss (TTLL) were recruited for participation. Participants walked along three beams of varying width, classified as narrow (1.8cm), mid-width (3.8cm), and wide (23cm). Post-hoc analysis revealed that experts walked significantly further than novices or individuals with unilateral TTLL on the narrow and mid-width beams. Similarly, novices walked further on the narrow and mid-width beams than the TTLL individuals. These results indicated that beam walking can be used as a basic measure the analyze dynamic balance across a wide range of sensorimotor abilities. Uematsu et al (2018) expanded upon idea that beam walking distance serves as a marker for dynamic balance (Sawers and Ting, 2015) by including single and dual cognitive tasks during beam walking trials to quantify age-related differences in dynamic balance. Healthy young and old volunteers walked along beams of various widths first without (single-tasking) then with a calculation task (dual-tasking). During the single task, walking distance decreased for both old and young participants as the width of the beam decreased. For the dual task condition, walking distance for young adults decreased with decreasing beam width and a significant difference in distance was found between the medium (8cm) and narrow (4cm) width beam. Distances traveled for older adults gradually decreased with decreasing width. Younger adults walked at a faster pace than the older adults, however, walking velocity decreased and significantly differed for both groups between the medium and narrow widths. In response to decreased beam width, step length decreased for young adults while both step length and step number decreased in older adults. These results offered insight on how single and dual-tasking beam walking could be used as a diagnostic tool of dynamic balance and cognitive impairments in aging populations.

Although previous research suggests that beam walking can be used to effectively assess dynamic balance, Sawers and Hafner (2018) challenged this view by stating fixed-width beams do not offer a sufficient challenge to identify balance deficits. Thus, they examined whether narrowing beam-walking could overcome limitations, such as ceiling effects, that have been associated with fixed-width beam protocols. The beam was constructed using four-fixed width segments. Level of difficulty (too easy, appropriately challenging, and too hard) was quantified through pre-determined travel distance ranges. Forty unilateral lower-limb prosthesis users completed 10 beam walking trials. Narrowing beam walking was shown to be appropriately challenging for 98% of participants. Performance on the beam stabilized for 93% of participants within 5 trials while 62% were stable across all trials. Thus, narrowing beam-walking was shown to be a clinically viable method to evaluate balance deficits for individuals with lower-limb prosthesis. In addition to a narrowing beam, the authors suggested that using multiple beams could potentially address the limitations of fixed-width beams, but further research is needed.

Beam walking is an appealing approach for clinical testing because various levels of challenges can be created, such as varying the beam width. Since participants are either on or off of the beam during beam walking, the distance traveled serves as a direct measure of balance proficiency. Finding balance beam tasks that eliminate or reduce ceiling effects relative to traditional beam walking tasks may lead to measuring balance across a wider range of individuals and better discrimination between fallers and non-fallers.

In conclusion, voluntary changes in step length and step width can significantly impact an individual's margin of stability and ultimately their ability to perform successful locomotion. Current balance assessment techniques do not provide sufficient challenges to accurately assess dynamic balance in healthy individuals and those impacted by amputations or minor impairments. Seeing how gait changes on stable ground can alter dynamic balance performance, further investigation into beam-walking may provide information on how to adequately challenge and directly measure dynamic balance in healthy individuals.

Visual processing during locomotion

It has been well established that there is interaction between sensorimotor systems during motor tasks. Binocular vision plays an important role in movement planning and execution. Visual feedback enables an individual to survey the surrounding environment and determine which features are relevant for completing a movement or task. Efficient visual processing is critical for navigating through obstacles or deciding when to initiate a movement in situations such as climbing stairs or crossing a street. The effects of aging on vision have been evaluated to determine if changes in visual processing can also lead to changes in human movement patterns.

Eye fixations during locomotion have been identified as good indicators of an observer's strategy to use information present in an environment to complete a task (Hayhoe, Gillam, Chajka, & Vecellio, 2009). Hollands et al (1995) aimed to directly measure the point in time during a step cycle when visual information was sampled and what that information consisted of during a task that required accurate foot placement at every step. Under normal lighting, participants walked along a series of irregularly spaced stones while eye movement was recorded using electrooculography (EOG) and infrared reflectometry (IR). Results indicated there was a clear pattern of eye movements that included one major saccade per step cycle. The timing and direction of the saccade suggested that participants were consistently directing their gaze to the next target stone. On average, 68% of saccades made toward the next target foot placement were made while the foot was still on the ground. With the majority of saccades being made prior to stepping, these results support that visual information plays a role in movement planning.

Hollands and Marple-Horvat (2001) further evaluated the role of vision in locomotion by observing whether a close functional relationship existed between eye and leg movements while an individual stepped onto a target. Eye movement and foot placements were measured using the Hollands et al (1995) methodology. During one walk on the walkway, participants experienced four to five brief periods of visual denial at unpredictable times. When participants were exposed to the walkway path without ambient lighting and with each stone only indicated by a centrally placed red LED, the patterns of eye movements were similar to those made in normal lighting conditions. The mean interval between saccade onset and foot movement showed no significant variation in the different lighting conditions even though significant prolonged stance phases were observed. In contrast, there was a greater variation between saccade onset and contralateral footfall. These two findings support that the oculomotor and stepping motor control systems operate via an interactive feed-forward mechanism that results in saccade generation and next step generation being temporally linked. Hayhoe et al (2009) later observed the role of binocular vision in walking by monitoring eye positions while navigating around and over obstacles. Participants walked along a short path and stepped over two boxes of different heights and maneuvered around a small table using monocular or binocular vision. Participants spent approximately 10% more time completing the path in the monocular trials when compared to binocular trials. Participants also spent significantly more time fixating on obstacles during the monocular trials, suggesting that longer fixations on obstacles are used to compensate for the limited information provided via monocular vision. Despite difference in fixation duration, the location and sequences of fixation did not vary significantly between monocular and binocular vision. Participants demonstrated a consistent pattern of first fixating on the front of the box, then the top surface, and finally the back edge of the box. These findings support that individuals gather pertinent information on the location and dimensions of obstacles to facilitate successful navigation through a path.

Recently, several studies have focused on how gaze behavior may change with aging and how those changes may influence movement patterns and consequently, the risk of falling. Stanley and Hollands (2014) assessed differences in gaze behavior in younger and older adults during a novel virtual walking paradigm. The older adults were further classified as having a high or low risk of falling after completing the Berg Balance scale and Activities Balance Confidence Scale assessments and reporting their fall history within the past year. Eye movements were recorded as participants watched five first-person perspective movies that represented the viewpoint of a pedestrian walking through different environments. Participants also completed a series of cognitive tasks to determine if cognitive decline may contribute to changes in gaze behavior. High and low risk fallers scored significantly lower than younger adults on the cognitive tasks. High risk older adults were also significantly slower at completing the cognitive tasks than younger adults. Results from the visual search tasks (pop out and conjunction search) showed that high risk older adults spent significantly more time fixating on the aspects of the travel path than the lower risk older adults and younger adults. This was the first study to quantitatively describe age-related differences in gaze behavior using a novel video-based paradigm and offered support for the claim that gaze behavior is impacted by age, decreased functional mobility, and possibly cognitive decline. Zito et al (2015) displayed a virtual reality setting onto projection screens to examine street crossing behavior in younger and older adults. Eye and head movements were tracked to assess how the two age groups differed with regard to the number of safe crossings, virtual crashes, and missed crossing opportunities. During the simulation, participants watched cars driving by at 30 km/hour and 50 km/hour. Between the third and fourth car participants had to decide whether the time gap provided (between 1 and 7 seconds) was enough to safely cross the street. Eye tracking data showed that both younger and older participants fixated more on the left part of the screen, the direction from where oncoming traffic was flowing. These findings were congruent with a previous street crossing study that found individuals fixated on objects in front of them or onto oncoming traffic (Hollands, Patla, & Vickers, 2002). Older adults had a higher percentage of fixations on the floor below the screen than the younger adults, suggesting they needed more time to plan stepping movements. Overall, older adults showed a significantly higher number of virtual crashes and significantly lower number of missed opportunities when compared to the younger adults. This increase in risk-taking behavior could be due to the reduced ability of older adults to analyze movement of an approaching vehicle that is at the edge of their visual field.

Overall, healthy individuals display similar visual search patterns. The oculomotor and motor stepping control systems operate through a feed-forward mechanism, meaning individuals tend to sample information that informs subsequent movement prior to initiating that movement. In the event that vision is limited, such as in or monocular viewing, individuals fixate longer on obstacles to compensate for the lack of visual input and task completion times increase. Lastly, elderly individuals fixate longer on the travel path or ground below them when compared to younger adults, suggesting that aging may impact the process of movement planning.

Acrophobia has also been shown to have transient effects on gait and gaze patterns. Tersteeg, Marple-Horvat, and Loram (2012) addressed the question of how visual information at height impacts walking and aimed to determine if this effect could be eliminated by removing the visual information. Twelve healthy young participants walked along a 4.8m walkway under three height conditions. Participants first walked along a grounded walkway (GW), then on a walkway suspended 3.5m above ground with visual height exposure, and finally with sheets that eliminated the visual exposure to height. Average physiological responses significantly increased with increases in height and visual exposure. All gait measures were significantly different between the task at height with visual information and the task on the ground. However, there were no significant changes in gait measures when sheets were added to remove the visual information. Participants continued to demonstrate cautious gait and elevated arousal states. Thus, the elimination of visual height information alone was not responsible for altered gait. Instead, the retained knowledge of risk and danger was determined to be the main stimulus that contributed to modified walking. Kugler et al (2014) studied eye and head movements in subjects susceptible to a fear of heights (susceptibles) and non-susceptible controls while walking along an emergency escape balcony projecting from the fourth floor of a building. Sixteen susceptibles and sixteen controls were instructed to walk out to and focus on a designated support beam and then walk back and focus on the door leading to the building interior. Correlation analysis showed moderate, but mostly non-significant, correlations of eye movement parameters with subjective fear in susceptibles. Both groups performed more saccades in the vertical direction than the horizontal. Heatmaps of gaze-in-space distributions showed that both groups spent adequate time gazing towards the goal of movement (support beam or building door). Controls freely explored the environment while susceptibles primarily viewed the walkway straight ahead, the floor, or the handrail. Despite the non-significant differences in eye movements, the main difference between susceptibles and controls was that head movement across the three planes measured significantly decreased in the susceptibles. Reduced head movement and fewer saccades in the horizontal direction ultimately led to a smaller area of visual exploration for individuals susceptible to acrophobia. Based on the evidence supporting that the cognitive aspect of fear (the known risk of danger or presence of acrophobia) can influence gaze and gait patterns, evaluating eye movements and cortical activity simultaneously may indicate the cognitive effort needed to respond to visual cues gathered in times of stress or uncertainty.

Cortical activity in balance, locomotion, and navigation

Cortical activity during balance tasks

Despite what is known about the gait and gaze patterns associated with static and dynamic balance, less is known about the role higher cortical functions play in postural stability and the brain regions responsible for balance maintenance. Previous research has aimed to identify cortical activity during the initial stages of balance loss and during balance recovery. More recently, brain regions involved with executive functioning and decision-making have received greater attention due to their potential influence on navigation tactics and human movement.

To investigate if there are specialized neural detectors for goal-orientated behaviors, Slobounov et al (2005) examined the existence of a neural basis for initiating postural movement and signaling postural instability during whole-body postural tasks. Twelve healthy participants were instructed to stand upright on a force plate and move continuously in the forward and backward directions to produce oscillatory whole-body movement at the ankle joint. Scalp maps of the EEG energy distribution were created and showed that there was a maximal burst of gamma activity ($p < 0.001$) at the fronto-central electrodes approximately 200ms before reaching the forward sway stability boundary and initiating the backward sway. Slobounov et al. inferred that this short burst of gamma activity at the time when balance was in danger could indicate the existence of a neural detector for postural instability that triggers a compensatory response to prevent falling.

Similarly, Slobounov et al (2009) investigated the neural basis of signaling future instability during standing by assessing the dynamics of virtual time-to-contact (VTC) in conjunction with EEG. VTC provides predictive information on future postural instability and has been shown to be a sensitive measure when assessing postural control deficits in older individuals and those suffering from mild traumatic brain injuries. Twelve healthy young participants were instructed to stand on one leg with their eyes closed for as long and as still as possible. The VTC was divided into three stages (stable, transition, and falling). Central theta power increased during the transition from the stable to transition phase and then significantly decreased during the falling stage. Post hoc analysis revealed that the theta power was significantly higher in the transition stage than the stable or falling stage and was predominantly observed in the central-frontal regions of the brain. The power of the occipital alpha frequency was present during the stage and transition stages and also significantly decreased during falling.

The spectral analysis failed to show significant differences between the three stages in beta and gamma frequencies bands. However, short bursts of gamma activity during the transition-to-instability stage were revealed by the independent component analysis (ICA), offering further support for the existence of neural detectors for postural instability. Overall, these results suggest that low-theta frequency bands in the central-frontal areas and alpha and gamma bands in the parietal-occipital areas may serve as alert signals for compensatory postural control mechanisms aimed at reducing the risk of falling.

Cortical activity during locomotion and navigation

Based on the findings that identified cortical mechanisms for whole body postural responses, Sipp et al (2013) aimed to identify specific cortical regions with spectral power modulations related to loss of balance during locomotion. Twenty-six healthy participants walked on a 2.5cm wide by 2.5cm tall treadmill mounted balance beam (on-beam walking) and on the treadmill belt (off-beam walking). ICA identified electrocortical clusters in or near the anterior cingulate, anterior parietal, superior dorsolateral-prefrontal, and the medial sensorimotor cortex that displayed significantly higher spectral power in the theta band (4-7 Hz) while walking on the beam when compared to off-beam walking. During on-beam walking, the left and right hemispheres displayed significantly less spectral power in the beta band (12-30 Hz). Spectral power of the alpha band (8-12 Hz) was significantly less in the left hemisphere only. All clusters except the medial sensorimotor cortex demonstrated transient increases in theta band power during loss of balance. Thus, these results provided new insight on the neural correlates of walking balance. Further, Herold et al (2017) evaluated cortical activation while balancing on an unstable surface. Ten healthy adults balanced on a balance board while activity in the supplementary motor area (SMA), precentral gyrus (PrG), and postcentral gyrus (PoG) was recorded using functional near-infrared spectroscopy (fNIRS). fNIRS data showed that oxy-Hb values increased considerably from standing to balancing in the SMA. Kinematic and fNIRS data indicated there was a moderate negative correlation between the mean oxy-Hb values in the PrG and sway in the mediolateral direction. A highly significant and strongly negative correlation was found between changes in oxy-Hb in the SMA and mediolateral sway. These results help emphasize the influence higher cortical processes have on postural control during dynamic tasks.

Although previous studies have investigated cortical activity before and at the start of falling, it is still unclear how cortical activity is related in reactive balance recovery. Payne, Hajcak, and Ting (2019) tested whether perturbation-evoked cortical responses shared simultaneous balance-correcting muscle activity. The initial burst of the muscle autonomic postural response, startle-related muscle responses, and the perturbation-evoked cortical N1 potential, a negative peak in the EEG activity of the SMA, were measured in sixteen healthy young adults. Participants experienced forward and backward translational support-surface balance perturbations of varying accelerations and timing and were instructed to recover balance without moving their feet. Results showed very weak correlations between the single-trial muscle and cortical response. Individuals with larger cortical N1 activation required more compensatory steps to maintain balance, despite the instructions to recover balance without foot movement. Further, there was a reduction in cortical response amplitude across trials that was related to a reduction in the startle-related, but not balance-correcting, muscle activity. Therefore, cortical responses may play a role in reducing the perceived threat of instability instead of in motor adaptations.

Payne and Ting (2020) designed a follow-up study to assess the relationship between the cortical N1 response and difficulty recovering balance that was suggested but not tested by the previous study. Twenty young and healthy adults experienced 48 backward translational support-surface perturbations of unpredictable amplitudes and onset. Following the perturbation trials, participants completed six trials of balance beam walking. EEG data was recorded during the perturbation series but was excluded during the walking trials. As the perturbation amplitude increased, cortical N1 responses increased ($p< 0.0001$) and latencies decreased within participants. Worse beam walking performance was associated with larger cortical N1 responses during standing and distance traveled on the beam was inversely proportional to cortical N1 activity. Significant interactions between beam walking and the effect of perturbations on cortical N1 responses was primarily driven by medium and large perturbation amplitudes. In conclusion, these results support that individuals display greater cortical activity when balance is challenged, however, further investigation into cortical activity while completing challenging dynamic balance tasks is needed.

While several studies have used fMRI to observe cortical activity in relatively static or controlled dynamic tasks, the question of how those results translate to real-world navigation still remains. Spiers and Maguire (2006) developed a realistic virtual simulation of central London city streets and used fMRI to examine the neural correlates underlying navigation. Twelve right-handed male London taxi drivers were tasked with navigating a series of virtual streets depending on a destination request from a passenger when the city scene was played on a computer screen. Throughout each route, participants heard the passenger request a direction change or make a navigationally irrelevant statement. Results indicated that thoughts made during navigation were associated with distinct patterns of brain activation. During initial exposure to the virtual city and responding to specific destination requests, participants displayed increased activity in the left and right hippocampus, left parahippocampal cortex, bilateral retrosplenial cortex, superior and middle temporal gyri, and the lateral and medial regions of the prefrontal cortex (PFC). Interestingly, when participants heard the direction change request, the hippocampus did not activate. Instead, several regions of the PFC, right parietal, and retrosplenial cortices were active. Further, when pre-existing expectations were violated, such as a route being unexpectedly blocked, the right parietal cortex and right lateral and anterior insula/ventrolateral regions of the PFC were recruited. The recruitment of PFC during initial route planning and response to unexpected barriers indicates that frontal lobe activation may play a vital role in human navigation in addition to the previously identified cortices associated with human movement and motor control.

Examining how PFC activation influences human behavior may provide a more comprehensive explanation for its role in route planning and adaptive navigation. Extensive research has indicated the existence of two fundamental motivational systems, approach and withdrawal, in the human brain (Davidson, 1992, Lang, Bradley, & Culbert, 1997, Lang, 2010). The approach motivation system drives behavior towards positive stimuli or desirable outcomes while the withdrawal system motivates avoidance behavior towards unwanted stimuli or experiences. The PFC has been identified as the brain region responsible for modulating these two systems (Damasio et al, 2000, Spielberg et al, 2011, Spielberg et al, 2012). Frontal alpha asymmetry serves as the basis for the balance between approach and withdrawal behavior (Coan & Allen, 2004, Mennella, Patron, & Palomba, 2017). Greater right-sided activity has been linked to withdrawal behavior and negative emotions, meanwhile elevated left-side activity is associated with approach behavior and positive emotions (Harman-Jones, Gable & Peterson, 2010, Papousek et al, 2012). Based on these associations, it could be inferred that changes in right and left frontal activation would lead to differences in navigation patterns or strategies.

Therefore, measuring frontal asymmetry during virtual navigation tasks may provide valuable insight to how approach and withdrawal activation patterns influence human behavior and subsequent movement.

Conclusively, extensive research on the neuromotor correlates of balance control exists, yet the role of frontal lobe activation in balance control remains unclear. Short bursts of gamma activity may serve as a trigger for static balance instability. Increases in central theta activity have been observed during the transition from stable posture to the initial phase of falling. During beam walking the anterior cruciate, anterior parietal superior dorsolateral-parietal, and the medical sensorimotor cortex have demonstrated significantly highly spectral power in the theta band. In balance recovery tasks, higher cortical N1 activity was shown to require more compensatory action to maintain balance. Lastly, frontal asymmetry may serve as an indicator for how emotional responses to fluctuating environments influence navigation strategies. Thus, monitoring cortical activity throughout beam walking and virtual simulations may offer further clarification on the neuromotor and emotional components of balance control.

Virtual reality applications

Within the past decade, VR has received more attention as a vital research and clinical tool. VR allows researchers to develop safe and realistic environments that have the potential to elicit physiological responses similar to those experienced in the real world (Peterson et al, 2018). Constructing realistic VR environments in laboratory settings offers researchers the chance to simultaneously measure multiple physiological and human movement variables without having to relocate equipment to offsite locations. In addition to research applications, VR has been shown to offer several clinical applications in regard to Parkinson's disease (PD) and stroke (Mirelman et al, 2011, Liao et al, 2015, Mirelman, Bonato, &Deutsch, 2009).

Since PD impacts gait, motor function, and cognition, Mirelman et al (2011) aimed to determine if treadmill training (TT) combined with VR could improve gait, dual-tasking abilities, and obstacle negotiation in twenty idiopathic PD patients. Participants received six-weeks of TT+VR intervention training and results were compared to previous studies involving TT without VR. The VR environment was projected onto screens in front of the treadmills. Participants walked in a well-lit hallway for 1 minute under three conditions: 1) comfortable walking speed 2) walking while completing a serial 3 subtraction from a predefined number (DT) and 3) negotiating two obstacles, both physically and in VR. Initial session measurements showed a mean of 17% of errors in navigating virtual obstacles while the last session assessments showed an average of only 9% error. Gait speed increased by 8.9% following training and during DT gait speed improved by 17.4% with significant improvements in stride length and time. Gait speed during over ground walking and negotiating obstacles improved after training and was still apparent in the one-month follow-up assessment. Participants also made 31% fewer mistakes on the cognitive task after training compared to pretraining values. These results show that intensive TT combined with VR intervention may significantly improve physical performance and gait parameters in patients suffering from PD.

Liao et al (2015) developed a similar study that evaluated the effect of VR-based Wii fit exercise training on obstacle crossing and dynamic balance ability in PD patients. Thirty-six participants were randomized into the VR-Wii fit group, traditional exercise (TE) group, or the control group who only received fall-prevention education. Both exercise groups participated in 12 training sessions (2 times per week for 6 weeks). The VR environment and avatar characters were displayed on projection screens. The TE group received stretching, strength, and balance training while the VR-Wii group received yoga, strength, and balance games training.

Individuals in the VR group watched the on-screen avatars and adjusted their movements according to the real-time feedback. Both groups received 15 minutes of treadmill training after the regimens mentioned above. The VR-Wii group showed significant improvements in obstacle crossing stride length and velocity compared to controls at the 1-month post training follow-up assessment, however, no significant differences were found between the VR-Wii and TE groups. Both exercise groups exhibited significant improvements in movement velocity in comparison to controls at the 1-month follow-up, with the VR-Wii group showing greater improvements than the TE groups. The VR-Wii group also showed significant improvements in movement excursion and directional control compared to the control group immediately after training and at the follow-up session. These findings further support the supplemental use of VR to improve dynamic balance in PD patients.

The loss and impairment of walking ability is one of the more severe outcomes following a stroke. Thus, gait restoration has been identified as a primary goal of stroke rehabilitation programs. Yang et al (2008) investigated the effect of VR-based treadmill training on community ambulation in patients with stroke. Twenty-four participants were randomized into experimental (treadmill and VR) and control (treadmill) groups. The virtual environment was displayed on a visual screen during treadmill walking and simulated the typical local community. Each group received nine sessions of training throughout a 3-week period. Participants walked comfortably on a treadmill and speed was gradually increased each session. Walking speed, community walking ability, a walking ability questionnaire (WAQ), and the Activities-specific balance confidence (ABC) scale were used to quantify performance. Following the VR-based treadmill training, participants showed significant improvements in all of the measured outcomes at the post training and demonstrated significant improvements in walking speed, community walking time, and WAG scores at the one month follow up assessment. Controls only showed improvements in community walking time at the post training and follow-up periods and also improvements in WAQ scores at the follow-up. In a similar study design, Kim et al (2009) examined the additive effect of VR on balance and gait function in patients with chronic hemiparetic stroke. Participants were divided into two groups (experimental and control) and each received conventional physical therapy 40 minutes a day, 4 days per week, for 4 weeks. The experimental group received an additional 30 minutes of VR therapy each session. A portal VR system consisting of a television monitor, video camera, virtual objects, and a large screen was used to capture body images and immerse individuals in the environment without a head mounted display. Balance was assessed using the Berg Balance Scale (BBS) and Balance Performance monitor. Gait performance was determined using a 10-m walking test and Modified Motor Assessment scale (MMAS). For the experimental group, BBS scores and dynamic balance angles (the ability to control weight shifting) significantly improved compared to controls. Gait analyses showed the experimental group exhibited significant improvements in velocity, MMAS scores, cadence, step time, step length, and stride length. Overall, these studies provide evidence that VR can be a useful tool for gait restoration post-stroke.

Despite the promising results showing how VR can benefit PD and stroke rehabilitation, the virtual environments implemented may not have elicited realistic physiological responses that are typically experienced in real life situations. Head mounted VR displays enable participants to be fully immersed and add to the realistic nature of virtual environments. Using a head mounted display, Peterson et al (2018) determined if height exposure in virtual reality induced stress and if the virtual environment affected physical and cognitive performance during a dynamic beam walking task. Nineteen young and healthy subjects walked along a beam under three conditions: 1) no VR exposure (unaltered view), 2) low height exposure (2.5cm off the ground) in the VR and 3) high height exposure (15m above the ground) in the VR. Cognitive performance was assessed by instructing participants to click a hand-held remote when they heard an auditory tone. Significant increases in heart rate variability and heart rate frequency power were observed during the high height exposure when compared to low exposure. Neither measure significantly differed between the unaltered and low exposure viewing conditions. Heart rate and response time significantly increased in the low exposure condition in comparison to unaltered viewing, indicating VR induced increased physical and cognitive exertion. During low height exposure, the peak activity of the anterior cingulate significantly increased from 500-600ms after the tone compared to the unaltered view trials. Balance performance worsened during low exposure trials when compared to the unaltered viewing, however, there were no significant differences between the VR conditions. Thus, these findings offer insight on how VR can be used to create immersive environments that elicit a number of physiological responses commonly observed in the real world.

Likewise, Kisker, Gruber, and Schöne (2019) further investigated whether VR resembles physical reality to the degree needed to observe real-life behavior in controlled environments. Participants walked along a steel girder walkway at ground level or on the side of a high-rise building in a virtual city and also on real wooden planks for haptic feedback. Following VR immersion, participants completed questionnaires about their subjective feeling of presence in the environment. Individuals in the high-rise height group typically felt more present in the VR environment than the ground group, but both reported a relatively high sense of presence. Heart rate for both groups significantly increased during the initiation and total walking time compared to baseline measurements. Conversely, Wuehr et al (2019) determined that virtual height stimulation did not evoke subjective fear and physiological arousal. This study also used a head mounted system to display an urban city at eight different elevations ranging from 0-100m. Subjective fear ratings were close to zero at ground level but increased with higher elevation. However, this effect was saturated for heights over 40m. Physiological arousal measures (heart rate and galvanic skin response) were not modulated by different height exposure. Participants experienced instability of stance and gait with virtual elevation and there was a general increase in whole body sway amplitudes during virtual height exposure. Thus, future research on VR height exposure is needed to address the controversy surrounding the realistic effects of VR.

In sum, VR has a wide range of clinical and research applications. VR can benefit balance training and rehabilitation in diseased populations. However, further validation of HMDs in healthy individuals is needed to establish safe guidelines for use in populations with neurological impairments. Due to the recent controversy on the effects of VR, continued investigation into how immersive environments simultaneously impact balance, cognition, and physiological responses is needed to provide a more comprehensive understanding of VR.

Summary

Static and dynamic balance are crucial for postural control and safe locomotion. Both forms of balance can be hindered by disease, orthopedic conditions, and the aging process. Although there are techniques to assess balance, there is no consensus for one method that directly evaluates dynamic balance and offers an adequate challenge. Balance beam walking has potential to serve as a direct measure of balance ability as well as offer appropriate challenges for healthy and diseased populations. Balance and walking performance can be further influenced by visual processing. During walking, individuals tend to fixate on the walkway ahead and on objects that may be in their path. Aging and height exposure have been shown to narrow or limit visual exploration thus impact walking speed, step length, and step frequency. Cortical activity patterns during stable standing, the transition to falling, and during falling have been identified and offer insight to the cognitive processes associated with recognizing and responding to loss of balance. However, continuous recording of cortical activity during walking is still needed to further understand the neural component of dynamic balance. Lastly, virtual reality offers researchers and clinicians the ability to construct safe and realistic environments that can elicit physiological, behavioral, and cognitive responses similar to those observed in real life situations.

Chapter III. Methods

Participants

Sixteen healthy young adults (age = 22 ± 3 years, 7 males, 9 females) were recruited for voluntary participation. Participants completed lower extremity and neurological medical history questionnaires prior to participation. This study was be approved by the East Carolina University institutional review board for human subjects. Written consent was obtained from each participant before testing began.

Inclusion Criteria

1) Be within the age range of 18-40 years old.
2) Healthy young adults without any current or previous lower-extremity injuries or surgeries that may hinder walking and/or balance.
3) Have no history of or current neurological disorders that could impact physical or cognitive performance.
4) Have normal to normal-corrected vision.

Exclusion Criteria

1) Falling outside of the specified age range.
2) Currently recovering from or having a history of lower-limb injury, neurological disorder, or ocular impairment that may interfere with locomotion or cognition.
3) Current use of lower-extremity brace that limits full range of motion.
4) Prone to acrophobia.

Procedures

Dynamic Balance Tasks

Participants completed a series of nine walking trials on a physical walkway with and without a virtual reality (VR) headset. The nine trials were divided into three walking conditions: no-VR (NVR), low-VR (LVR), and high-VR (HVR). The walkway was constructed using two 1-inch x 4-inch x 12-foot wooden boards and one 1-inch x 4-inch x 4-foot board (Figure 1). Prior to testing, participants were equipped with the wireless heart rate monitor, EEG cap, reflective motion capture markers, and vive controllers. HTC vive controllers were strapped to each participant's left and right distal shank region so they could visualize their feet in the virtual environment. For each trial and condition, participants were instructed to walk heel-to-toe across the full length of the walkway with their arms at their sides and to maintain a natural gait pattern and pace. If a participant stepped off of the beam, they were told to regain their footing and continue walking. All trials started on the right-hand beam and ended on the left-hand beam of the walkway (Figure 1). Following the equipment set-up and task instructions, participants completed three trials of the NVR condition.

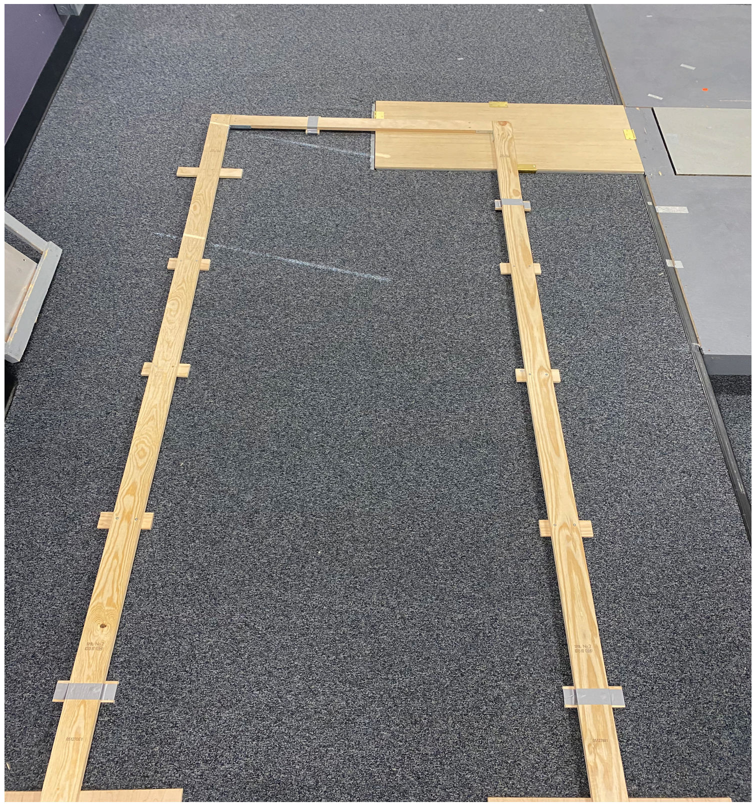

Figure 1. Physical Walkway

Next, participants were seated in a chair and fitted with the VR headset for the virtual conditions. Once the headset was properly fitted and aligned using an eye tracking positioning guide, each participant completed a five-point eye calibration. For the calibration, participants were instructed to fixate on each dot until it disappeared and to only follow the dots with their eyes. Once the calibration was deemed successful, participants completed three trials of the LVR condition. For this condition, participants walked along a virtual walkway that aligned with the physical walkway (Figure 2). The virtual walkway was of the same height, length, and width as the physical walkway. The eye positioning guide was checked between each trial to ensure that the participant's eyes were in the correct location and the calibration was repeated if the headset shifted during trials.

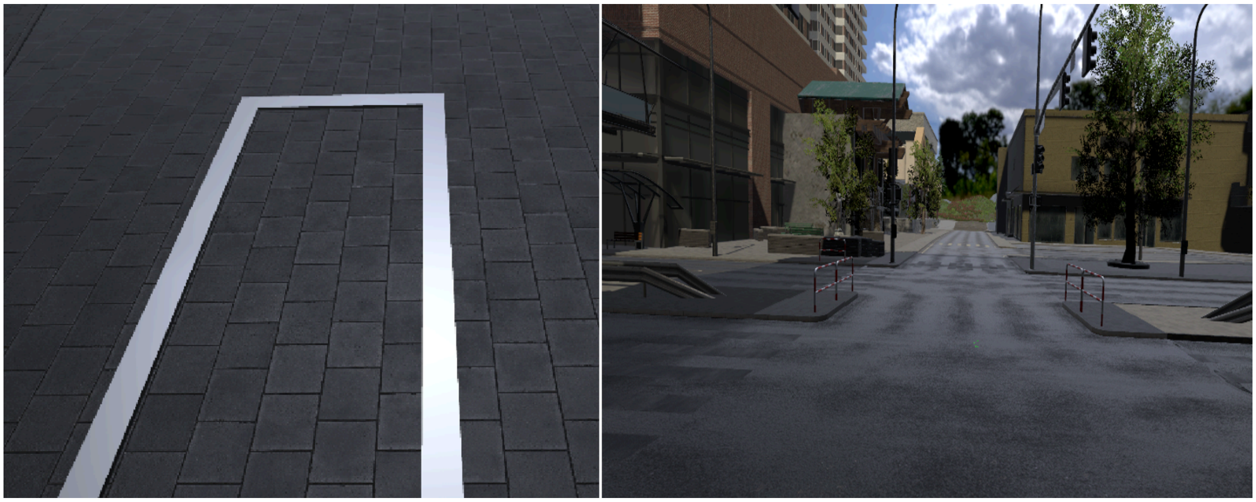

Figure 2. Participant view during the LVR condition

Lastly, participants completed three trials of the HVR condition. The positioning guide and calibration process was repeated upon starting the HVR scene. Again, participants walked along a virtual walkway of the same parameters as the physical walkway but this time the virtual walkway protruded from a high-rise building (Figure 3).

Figure 3. Participant view during the HVR condition

Virtual Reality Environment

An HTC Vive Pro Eye VR headset (HTC, New Taipei City, Taiwan) was used to run the environment that included a virtual walkway at ground level and extending from a high-rise building. The virtual environment was developed using the Windridge City 3D roadway asset package from Unity (Unity Technologies, San Francisco, California). Standard Unity and custom-made scripts were incorporated into the virtual environment that enabled eye positioning and calibration, height scaling to account for differences among participants, and trial data saving.

Gaze Behavior

The HTC Vive Pro Eye headset integrated with Tobii eye tracking technology (Tobii Technology, Danderyd Municipality, Sweden) was also utilized to record gaze behavior data at a sampling rate of 120 Hz. Gaze behavior was quantified by calculating the number of fixations and the length of fixations on predetermined areas of interests (AOIs). For both the LVR and HVR conditions the AOIs included the: right plank (RP), front plank (FP), left plank (LP), areas just around or below the walkway (On RP, On FP, and On LP), the center area between the right and left planks (Off C), and areas beyond the walkway planks (Off RP, Off FP, and Off LP). For the LVR condition, there was a specific AOI for the area behind the start of the walkway that participants viewed as they reached the end of each trial (Out B). For the HVR condition, the building wall served as the AOI equivalent of the scene behind the walkway in the LVR condition since the walkway extended from a high-rise building. Raw data files from the Tobii Pro software were saved as XML files.

Electrocardiogram

Heart rate was monitored and recorded using a three-lead BioNomadix wireless respiration-ECG transmitter and Biopac MP 150 receiver system (Biopac Systems, Inc., Goleta, California). Alcohol swabs were used to prepare the skin on the superior medial region of the left pectoralis major muscle, the center region of the left external oblique in line with the seventh rib, and the sternoclavicular (SC) joint. Two electrodes were placed diagonally across the heart on the pectoralis major and external oblique muscle while the ground electrode was placed on the

SC joint. Each participant was fitted with a fabric strap that held the wireless transmitter in place on the superior region of the right pectoralis major muscle.

Electroencephalogram

Participants were fitted with a 32-channel g.Tec Nautilus wireless electroencephalogram (EEG) headset (g.Tec Neurotechnology USA Inc., Albany, New York) prior to testing. Data was sampled at a frequency of 500 Hz. The cap was centered on the participant's forehead at 10% of the distance (in centimeters) between the nasion and inion. Lemon prep gel and alcohol swabs were used to exfoliate the skin on the left and right mastoid bones. A ground electrode was placed on the left mastoid and the reference electrode was placed on the right mastoid. g.Recorder software (g.Tec Neurotechnology USA Inc., Albany, New York) was used for data collection and analysis.

Motion Capture

A twelve-camera 3D motion capture system (Opus 300+ Cameras, Qualisys, Goteborg, Sweden), sampling at a frequency of 100 Hz was used to record left and right foot placement during each trial. Two 14 mm sphere reflective markers (B & L Engineering, Santa Ana, California) were placed on each of the participant's shoes, one on the toe and one on the heel. An embedded, triaxial ATMI force plate (AMTI, Newton, Massachusetts) was used to collect ground reaction force data at the first turn in the walkway. Since each participant navigated the walkway at their own pace, motion capture time periods were determined before each trial based on the speed of the participant's preceding trial. To account for the wooden platform forces being applied to the embedded force plate, the force plate was zeroed out before each trial started. Hinges were attached to the wooden platform to reduce the potential of the walkway shifting off the embedded plate (Figure 4).

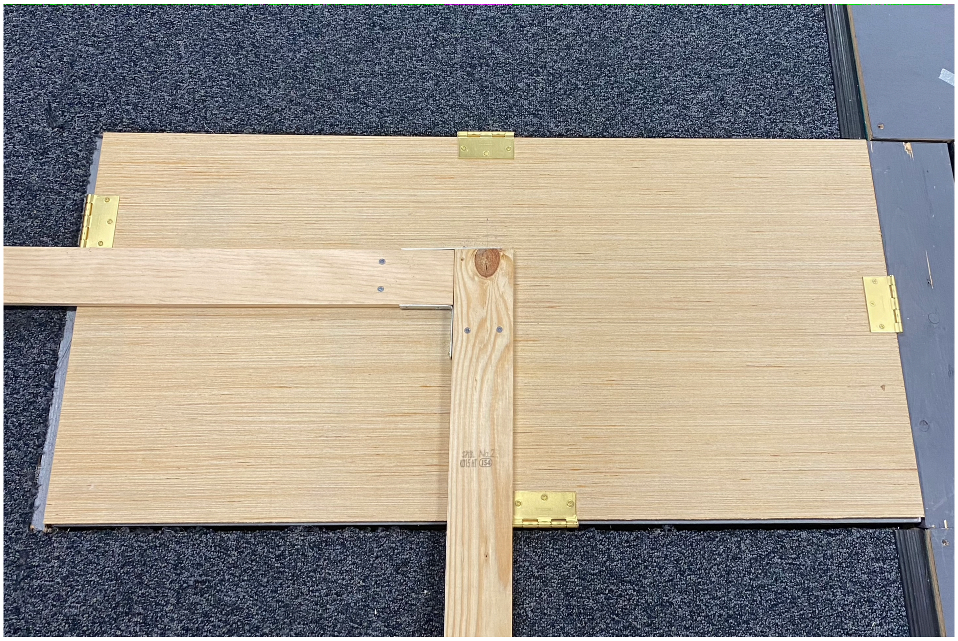

Figure 4. Wooden platform over embedded force plate

Data Processing

Gaze Behavior Analysis

Custom python scripts were used to extract left and right eye angle displacements and AOI data point counts from the raw XML files and to export these measures into excel spreadsheets. The total number of data points for each AOI (AOI count) were divided by the total number of data points (total count) for each trial to calculate the percentage of times a participant viewed the AOIs. The three trials for each condition were averaged for all participants. Next, total trial time (in seconds) for all nine trials for each participant was computed by dividing the total data point counts by 120. Trial times were then sorted according to condition. These trial times were then multiplied by the AOI count percentages to determine the percent of time participants spent viewing the AOIs with respect to the total trial time. The three-trial means for each participants' AOI time percentage for the LVR and HVR conditions were combined into one Microsoft Excel spreadsheet for statistical analysis.

Heart Rate Analysis

Since activation of the autonomic nervous system, more specifically the sympathetic and parasympathetic branches, provide the most immediate response to stress exposure, fluctuations in heart rate were used to quantify stress (Martens et al, 2019). Heart rate data was processed using AcqKnowledge 5.0 software (Biopac Systems, Inc., Goleta, California). Each data file was visually inspected for movement artifacts and baseline wander. In accordance with previously validated filtering techniques, files containing movement artifacts and baseline wander were preprocessed using a built-in digital high pass filter with a frequency range of 1-20 Hz (Kher, 2019, Lehavi et al, 2019). The initial filter frequency was set to 1 Hz and was increased by increments of one until artifacts and baseline wander were minimized. Heart rate was determined with the AcqKnowledge Find Rate function. The cycle interval detection window was set to have a minimum value of 30 beats per minute (bpm) and a maximum value of 180 bpm. Participant data was sorted by trial number and condition in Microsoft Excel in preparation for statistical analysis.

EEG Analysis

MATLAB R2020b and EEGLAB version 2021 (MathWorks Inc., Natick, Massachusetts) were utilized for EEG data preprocessing and analysis. EEGLAB was first used to manually add event markers to trials to mark when participants were two seconds, or approximately two steps, away from the first turn in the walkway. The Darbeliai serial processing component of EEGLAB was used for preprocessing following the addition of event markers. Channels were re-referenced to the Cz electrode. After re-referencing, data was filtered with a high pass filter set to 1 Hz, followed by artifact subspace reconstruction (ASR). To remove remaining artifacts and noise, data was further processed using independent component analysis (ICA) and a low pass filter at

35 Hz. Epochs were extracted from 1 to 1.7 seconds from the start of the event markers. Frontal lobe channels (Af3, Af4, F3, F4, F7, F8, Fc1, Fc2, Fc6, Fp1, Fp2, and Fz) for select participants were reprocessed and interpolated to retain alpha spectral power values that were excluded during the initial robust filtering process. Spectral power at the alpha range (8-12 Hz) was extracted for all frontal lobe channels from the EEGLAB power spectrum output that contained all other frequency intervals (delta, theta, and beta). The natural log of each frontal channel for all trials across the three conditions was calculated using Microsoft Excel. The natural log of channels F3, F4, F7, and F8 were grouped to compute frontal asymmetry.

FA is commonly calculated by subtracting the natural log of the left hemisphere alpha power (F3) from the natural log of the right hemisphere alpha power (F4) (Coan & Allen, 2004, Sun, Perakyla, & Hartikainen, 2017). This formula was repeated for electrodes F7 and F8. The natural log of both right hemisphere electrodes (F4 and F8) and both left hemisphere electrodes (F3 and F7) were averaged for each trial and condition and frontal asymmetry was again calculated by subtracting the left hemisphere average from the right hemisphere average. Frontal asymmetry values for the specific electrodes and overall hemispheres for the NVR, LVR, and HVR conditions were sorted into one excel spreadsheet.

Balance Performance Analysis

Motion capture data was labeled using Qualisys Track Manager (QTM) 2019 software (Qualisys, Goteborg, Sweden). Since accuracy was the goal for each walking condition, balance performance was quantified using the metric known as failures per minute. Failures per minute is calculated by dividing the number of times each participant stepped off the beam by the total time spent on the beam. In addition to failures per minute, average beam step-offs were also determined and analyzed. Motion capture data files were manually reviewed, and the total number of beam step-offs and time spent on the beam were recorded in an excel spreadsheet. Failures per minute and average step-offs were calculated for all nine trials for each participant.

Statistical Analyses

Statistical analyses were conducted using SPSS version 27 (SPSS, IBM, Chicago, Illinois). Repeated measure one-way ANOVAs were used to compare mean heart rate, frontal lobe asymmetry (electrode pair F8, F7), VR trial completion times, AOI viewing times for both VR conditions, failures per minute, and average step-offs for each participant and condition.

Chapter IV. Results

Virtual Reality and Gaze Behavior

The ANOVA results for VR Trial Time demonstrated a significant main effect for Condition [F (1, 15) = 5.764; p < .05, η_p^2 = 0.28]. The data revealed a significant difference between HVR Trial Time (M = 41.67, SD = 11.86) and LVR Trial Time (M = 34.51, SD = 12.61). For both VR conditions, participants spent a significant amount of time viewing the predetermined AOIs [F (12, 180) = 126.35; p < .001, η_p^2 = .894) (Figure 5), however, there was not a significant difference between the two conditions [F (1, 15) = 4.219; p = 0.058, η_p^2 = .220]. Of the thirteen AOIs, participants spent the majority of the time viewing the three walkway planks (Figure 5). The right plank had the highest view time for the LVR (M = 13.45, SD = 4.49) and HVR (M = 15.14, SD = 4.29) conditions, while time spent viewing the left plank decreased for both conditions (LVR: M = 10.03, SD = 4.64, HVR: M = 11.06, SD = 5.04), despite it being the same length as the right plank. Front plank view times were lower in comparison to the left and right planks due to the shortened dimensions. In contrast to the view times for each plank, view times for the areas just around or below the planks slightly increased from the right to left plank. Pairwise comparisons revealed significant differences between viewing times of each plank and areas surrounding the planks for both VR conditions (p < 0.001). Three AOIs were excluded from the analysis due to their total view time being less than one second.

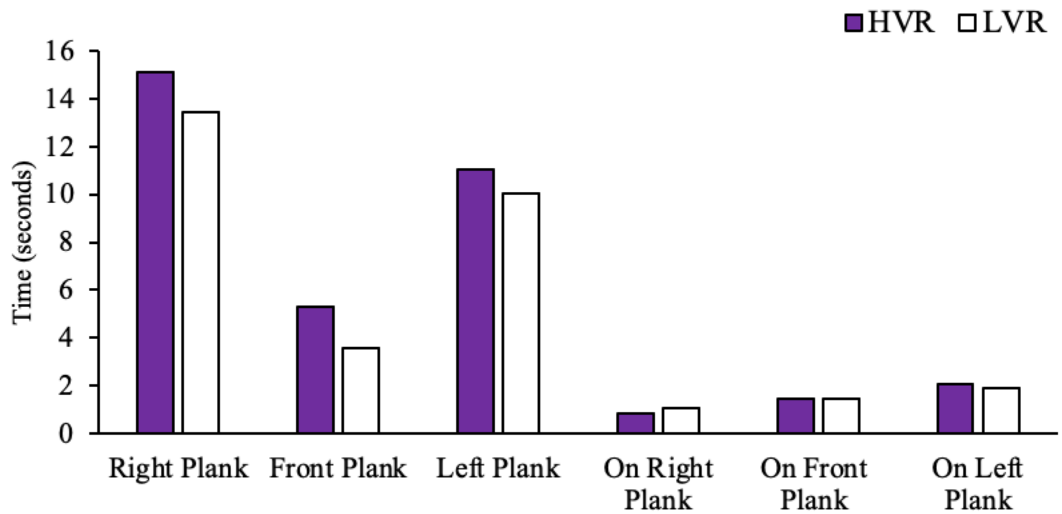

Figure 5. Average time spent viewing AOIs during VR conditions

Heart Rate

Heart rate demonstrated a significant main effect for Condition [F (2, 22) = 20.565; p < 0.001, η_p^2 = 0.65] and for Trial [F (2, 22) = 5.721; p < .05, η_p^2 = 0.342]. Heart rate differed significantly across all conditions (Figure 6). As expected, the NVR condition resulted in the lowest average heart rate (M = 93.15, SD = 12.58) and heart rate steadily increased throughout the LVR (M = 100.9, SD = 17.72) and HVR conditions (M = 104.96, SD = 17.72). The opposite trend was observed for average heart rate across trials. Of the three trials per condition, average heart rate was the highest during trial one (M = 101.99, SD = 17.74) and slightly declined during trial two (M = 98.83, SD = 16.06) and trial three (M = 98.19, SD = 16.67). Pairwise comparisons indicated that differences between trials one and two and one and three were significant (p < 0.05) but that differences between trials two and three were not significant (p > 0.05).

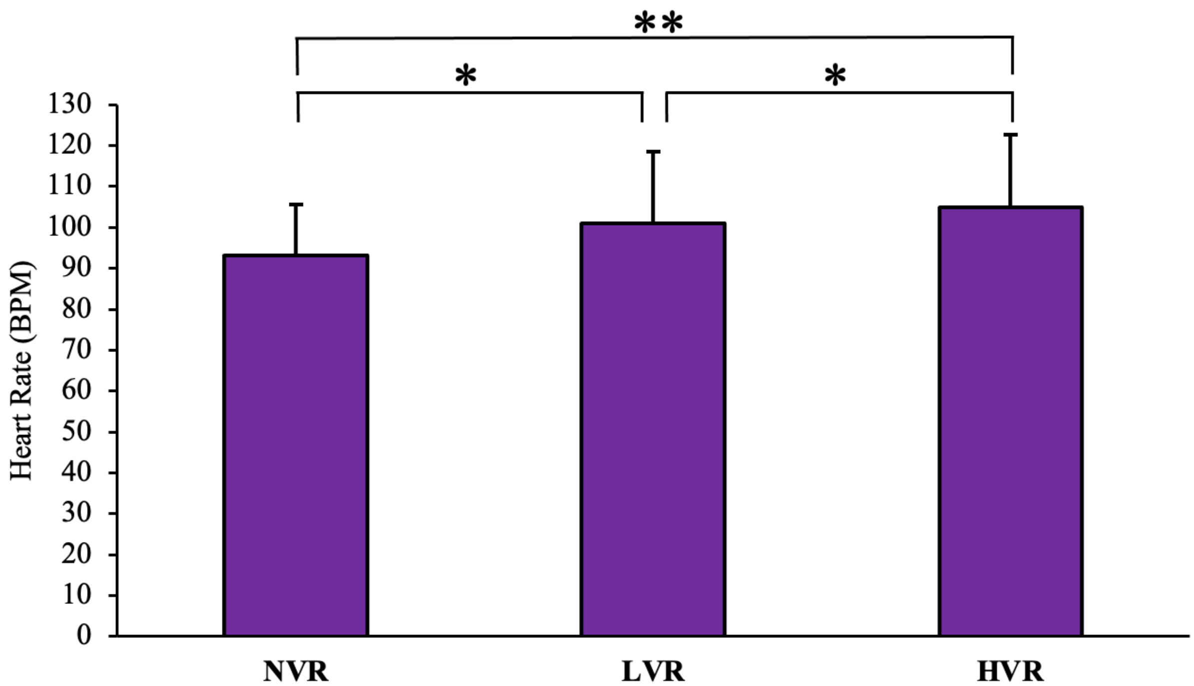

Figure 6. Average heart rate (bpm) across the three walking conditions (* p < 0.05, ** p < 0.001)

EEG

The ANOVA results for Frontal Asymmetry in electrodes F8 and F7 demonstrated a significant main effect for Condition [F (2, 26) = 7.571; p < .05, η_p^2 = 0.368]. Significant differences in frontal alpha asymmetry were found when comparing the NVR condition to the LVR and HVR conditions (p < 0.05), but there was no significant difference for the LVR and HVR comparison (Table 1). Overall, alpha power decreased from the NVR to HVR condition, however there was a slight increase from the LVR to HVR condition (Table 1).

Table 1. Frontal alpha asymmetry comparison of No-VR and VR conditions

Measure	**M**	**SD**	**P-Value**	
Alpha Power				
NVR	0.275	0.187	NVR | LVR	0.006*
LVR	-0.244	0.204	NVR | HVR	0.006*
HVR	-0.100	0.147	LVR | HVR	0.309

* p < 0.05

Event-Related Spectral Perturbation (ERSP) plots (Figure 7) indicated that significant differences in the alpha frequency band (red regions of plots) for the NVR-LVR and NVR-HVR comparisons were prominent during the first 250 ms of the last step participants took before making the first turn in the walkway. Differences in left frontal activity (electrode F7, left ERSP plot) occurred predominantly around 225 ms, while right side activity (electrode F8, right ERSP plot) was more apparent between 200-250 ms and later from 300-350 ms.

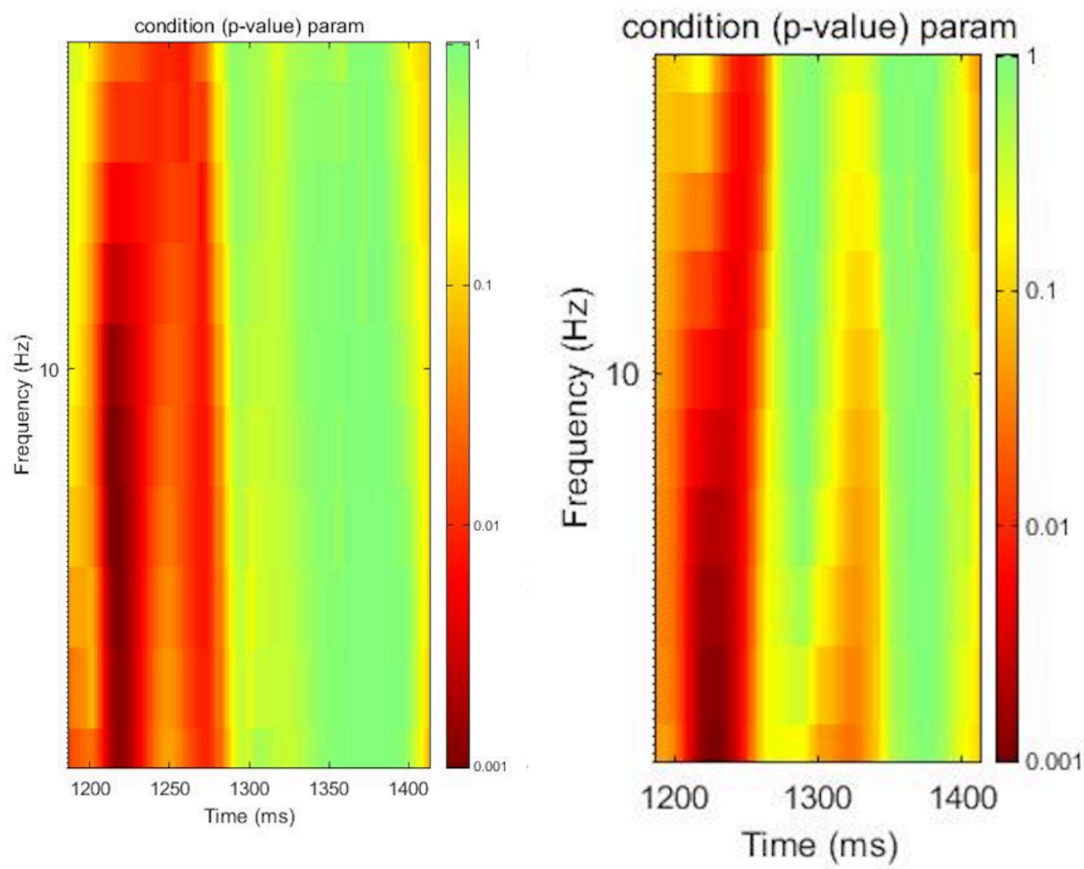

Figure 7. Event-Related Spectral Perturbation (ERSP) alpha band plot for electrode pair F7/F8

ERSP full spectrum plots (4-30 Hz) of the F7/F8 electrode pair revealed significant activity in the theta frequency band (4-8 Hz) between the three conditions throughout the initial 500 ms of the last step before making the first turn in the walkway (Figure 9). Similar to the alpha frequency, the most significant differences occurred primarily during the first 300 ms of the step.

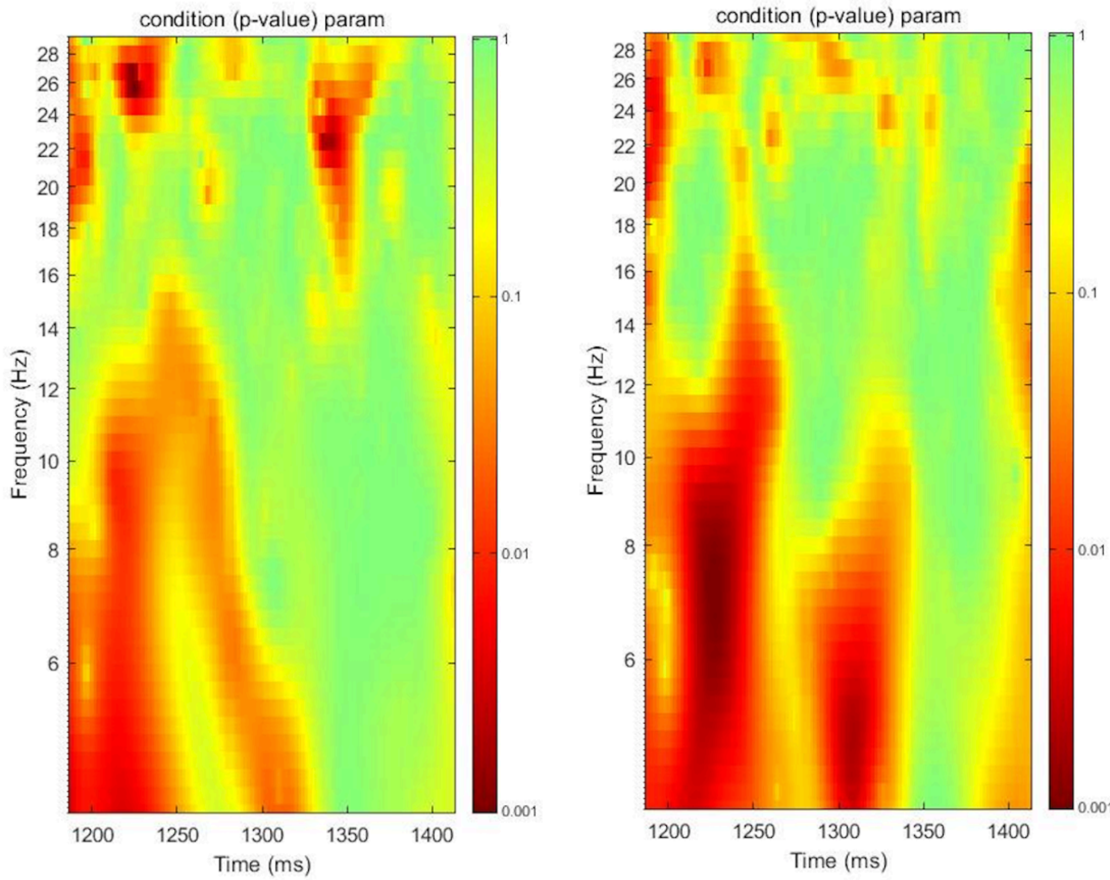

Figure 8. Event-Related Spectral Perturbation (ERSP) full spectrum plot for electrode pair F7/F8

Figure 9 below serves as a visual representation of the frontal alpha asymmetry patterns across the three experimental conditions for all participants.

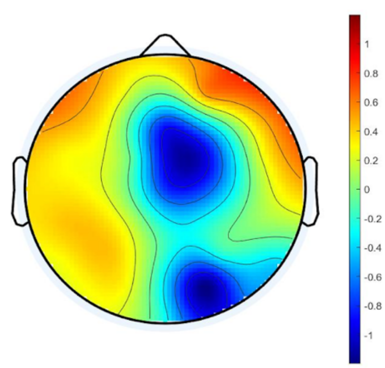

Figure 9. Representative heat map of frontal alpha asymmetry across the three conditions

Balance Performance

There was a significant main effect for failures per minute for Condition [F (2, 24) = 20.883; $p < .001$, $\eta_p^2 = 0.635$]. Failures per minute significantly increased from NVR to LVR ($p < 0.001$) and between NVR and HVR ($p < 0.05$). In contrast, failures per minute significantly decreased from LVR to HVR ($p < 0.05$) (Table 2).

Table 2. Comparison of failures per minute per condition

Measure	M	SD	P-Value	
Failures per Minute (count/min)				
NVR	0.002	0.007	NVR | LVR	<0.001**
LVR	0.075	0.051	NVR | HVR	0.003*
HVR	0.045	0.053	LVR | HVR	0.028*

* $p < 0.05$, ** $p < 0.001$

For the step-off analysis, another significant main effect was found for Condition [F (2, 22) = 12.006; $p < .001$, $\eta_p^2 = 0.522$]. The average number of step-offs significantly increased from NVR to LVR ($p < 0.001$) and between the NVR and HVR conditions ($p < 0.05$), while average step-offs decreased from LVR to HVR ($p > 0.05$) (Table 3).

Table 3. Comparison of average step-offs per condition

Measure	M	SD	P-Value	
Step-Offs				
NVR	0.028	0.096	NVR | LVR	<0.001**
LVR	1.722	1.425	NVR | HVR	0.007*
HVR	1.306	1.598	LVR | HVR	0.275

* $p < 0.05$, ** $p < 0.001$

Chapter V. Discussion

The purpose of this study was to observe how virtual reality height exposure induced stress and impacted balance performance, visual processing, and cognitive effort during beam walking. As expected, dynamic balance performance declined with the incorporation of VR, yet performance slightly improved from the LVR to HVR condition, offering partial support for the balance control hypothesis. Participants displayed restrictive visual search patterns in both VR conditions, thereby refuting the visual processing hypothesis. Frontal alpha spectral power followed the same trend as the balance performance data and therefore only partially supported the hypothesis pertaining to cognition. The observed physiological stress responses supported the fourth hypothesis which predicted heart rate would increase and remain elevated across all three conditions.

Failures per minute were significantly lower for the NVR condition when compared to both VR conditions, indicating that motor performance and motor acquisition were impaired by virtual reality use. Since virtual reality has been shown to hinder balance performance and lead to stability patterns comparable to being blindfolded (Akizuki et al, 2005, Horlings et al, 2009), participants may have initially struggled with adapting to the virtual environment. Interestingly, balance performance slightly improved from the LVR to HVR condition. This improvement is unique from other studies involving VR height exposure in that most found no differences in balance performance between low and high height conditions or performance deteriorated from low to high height exposure (Kisker et al, 2019, Peterson et al, 2018). Wuehr et al (2019) specifically evaluated changes in center of pressure (COP), body sway amplitudes and sway velocities with respect to various levels of virtual elevation. Their findings indicated that virtual height exposure led to increased body sway amplitudes and higher sway velocities in the mediolateral (ML) and anterior-posterior (AP) directions. Likewise, COP trajectories fluctuated more in the ML and AP directions at 40 meters above ground when compared to ground level measurements. Ultimately, increases in sway amplitudes, sway velocities, and COP trajectories led to participants experiencing unstable stance and gait during virtual elevation. Electing not to include these advanced balance metrics in the initial data analysis for this study may have limited the ability to explain why balance performance declined and then improved throughout the three conditions. Therefore, including more advanced balance metrics in subsequent analyses of this data set may offer specific insight on how the underlying mechanisms of balance control contribute to balance maintenance and performance during beam walking and virtual height exposure (see Appendix B). Despite not including specific anatomical measures of balance performance, trial time and gross dynamic performance metrics (step-offs and failures per minute) still offered an adequate evaluation of beam walking performance across the three experimental conditions.

Previous investigations into the effects of height exposure, in both VR and real-life settings, have shown that individuals take longer to navigate walkways in high height situations and display anxiety-related behaviors (Tersteeg et al, 2012, Kugler et al, 2014, Kisker et al, 2019). These behavior patterns include slower and more cautious gait as well as limited visual exploration in the surrounding environment. Hence, better balance performance could be a result of participants spending more time on the walkway during the HVR condition. VR trial completion time significantly increased from the LVR to HVR condition by roughly seven seconds. Despite participants being aware that they were in a safe environment and would not fall to the virtual ground, their behavior during the HVR simulation still reflected patterns observed when individuals believe that a misstep will lead to severe injuries. Thus, spending more time on the walkway in the HVR condition enabled participants to maintain motor control and minimize the perceived risk of stepping off the beam and falling to the ground below.

Since the VR conditions were completed in the same order by all participants, it can be speculated that better balance performance may have stemmed from a learning effect. However, had a learning effect occurred, participants would have completed the HVR condition in less time than the LVR condition. Fitts' law offers an explanation for the relationship between trial time and balance performance observed during the HVR condition. According to Fitts' law, movement time is dependent on the accuracy requirement of a task (Fitts, 1954). Consequently, movement time increases as a task becomes more difficult. Based on this relationship, it can be inferred that participants perceived the HVR condition as a more difficult task and ultimately traded movement speed for accuracy in order to successfully navigate the walkway while subject to high height exposure. In addition to the evidence of a speed-accuracy trade-off, visual search patterns observed in this study further refuted the possibility of a learning effect. Participants demonstrated restrictive visual exploration patterns in both VR conditions, indicating that task familiarity may not have influenced walkway navigation. Again, if learning had taken place, participants would have navigated the walkway more quickly and also demonstrated greater visual exploration into the surrounding environment (Kugler et al, 2014).

Due to the lack of significant differences in the number of AOI viewed and viewing times between the LVR and HVR simulations, the visual processing hypothesis in this study was not supported. In fact, participants spent significant amounts of time viewing the three walkway planks and the areas just below or around the planks during both VR conditions. Despite the lack of statistical significance, there was a large effect size ($\eta_p^2 \geq 0.14$) (Richardson, 2011) for AOI viewing time between the LVR and HVR scenes (η_p^2 = .220). Participants spent the most time viewing the right plank (start plank). The second most frequently viewed AOI was the left plank (end plank), yet participants spent less time viewing this in comparison to the right plank, despite them being the same length and width. A slight shift in search patterns was observed as participants tended to expand their gaze just beyond the virtual beams by the time they reached the end of the walkway (Figure 7). This shift could be attributed to participants becoming more familiar with navigating the virtual walkway as they transitioned from the right to left plank.

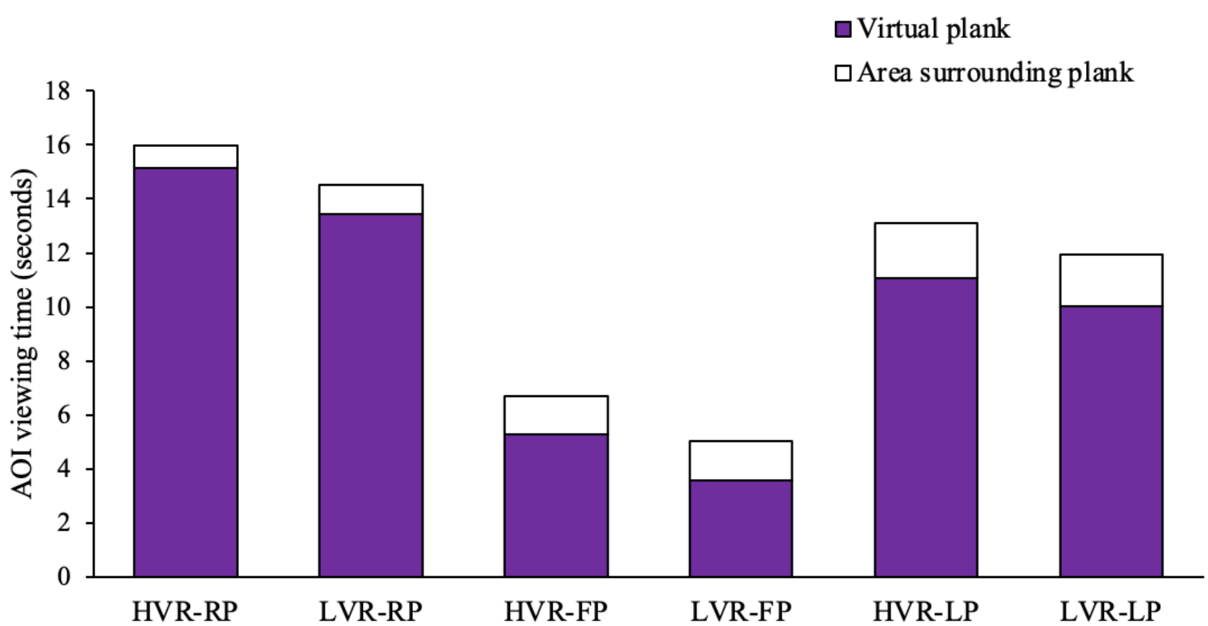

Figure 10. Comparison of search patterns during virtual walkway navigation

These results are in line with those of Kugler et al (2014) that showed individuals who respond negatively to height exposure walk slower and primarily fixate on the path beneath their feet, while individuals without a height intolerance walk at natural paces and freely explore their surrounding environment. Kugler et al (2014) also determined that gaze restriction was especially prominent during the initial phases of walking. Consequently, restrictive gaze patterns and higher initial AOI viewing times led to slower trial completion times. Other studies assessing how fixation location impacts walking performance have indicated that fixating on task relevant cues can improve locomotion (Hollands et al, 1995, Hollands, & Marple-Horvat, 2001, Hollands et al, 2002, Zito et al, 2015). Therefore, it can be inferred that participants spent the majority of their time viewing the virtual walkway in order to successfully traverse the physical walkway.

In addition to restrictive gaze patterns, frontal alpha asymmetry indicated that participants demonstrated greater external attentional focus during virtual reality usage. Generally, a decrease in frontal lobe alpha power represents an increase in cognitive activity (Pfurtscheller et al, 1996, Klimesch, 1999). More recently, alpha decrease (Event-Related Desynchronization, ERD) has been associated with externally directed attention whereas increases in alpha have been related to internal focus (Magosso et al, 2019). Frontal alpha power significantly decreased between the NVR and LVR and NVR and HVR conditions, confirming the third hypothesis for this study. For the LVR and HVR comparison, frontal alpha power slightly increased between the conditions, but the HVR alpha power value remained negative. Numerous studies have shown alpha desynchronization is associated with tasks requiring processing of relevant information in a variety of cognitive domains, especially with visual perception (Klimesch, 1996, Babiloni et al, 2004, Min et al, 2008). Therefore, the decrease in alpha power observed during LVR could be attributed to participants focusing their gaze on the virtual walkway in order to simultaneously navigate the physical walkway. Alpha power is an inverse index of cortical activity (Cook et al, 1998). Reductions in right frontal alpha power compared to left frontal sites indicate greater right-sided activity, which has been associated with withdrawal motivation behavior and negative affect (Sutton & Davidson, 1997). Alternatively, increases in right frontal alpha power when compared to left frontal sites signify greater left-sided activity and have been linked to approach behavior. Based on the relationship between alpha power and negative affect, participants may have experienced greater right-sided activity as a result of the initial exposure to the virtual environment. The right-prefrontal cortex mediates vigilance for threat (Sutton & Davidson, 1997), so experiencing difficulty in adjusting to VR while trying to navigate the walkway may have caused temporary feelings of distress and anxiety, which was reflected in balance performance and elevated heart rate. On the contrary, the small increase in alpha power during HVR could be the result of participants experiencing a higher level of motivation to safely complete the walking task since there was a perceived risk of falling from the high-rise building. The shift to approach behavior may have led to higher HVR trial completion times and ultimately, fewer beam step-offs. Because HVR trials were completed after the LVR condition, participants may have experienced positive affect after adjusting to immersion in the virtual world.

Lastly, the fourth hypothesis that stated heart rate would increase with HVR in comparison to LVR, was supported by the significant increase in heart rate from LVR to HVR (approximately 4%, 4 bpm). In addition to the differences observed between the VR conditions, heart rate significantly increased from the NVR to LVR condition by approximately 8% (7.75 bpm) and by 11.3% (11.81 bpm) between NVR and HVR. This elevated response from NVR to LVR was the most prominent change when heart rate was compared in the order of which conditions were completed. As mentioned earlier, this more pronounced response for the LVR condition could have been due to the initial adaptation to VR. These heart rate trends are consistent with previous studies that also assessed how VR height exposure impacted physiological stress responses (Peterson et al, 2018, Kisker et al, 2019, Martens et al, 2019). Furthermore, the elevated heart rate response across all three conditions can in part be credited to the realism of the virtual environment and the nature of the physical task. Peterson et al (2018) only used a single balance beam and adjusted the depth of a bottomless space below the virtual beam. As a result, their heart rate data only demonstrated significant differences between unaltered and low VR viewing conditions. In contrast, Kisker et al (2019) and Martens et al (2019) both found that heart rate significantly increased during low and high virtual height exposure when participants were immersed in realistic city landscapes. Kisker et al (2019) also used physical and virtual walkways that consisted of multiple beams. Based on the similarities between the current methodology and those of other VR height exposure studies, the complexity of the physical task and realistic nature of the virtual environment appeared to play a role in the effectiveness of VR induced stress responses.

Overall, the results gathered from this study indicate that VR height exposure can impact balance performance, visual processing, and cognition. Average step-offs and failures per minute indicated that even low virtual height exposure can lead to significant changes in balance control. Gaze behavior data showed that participants utilized task relevant information when navigating virtual and physical walkways. When compared to unaltered viewing (NVR), LVR and HVR conditions led to elevated heart rate and decreased right frontal alpha power, showing that immersive VR can elicit psychophysiological stress responses. Finally, balance beam walking cam offer an adequate challenge for dynamic balance in healthy young adults.

Limitations

When interpreting the present findings, certain limitations need to be considered. First, the small sample size could have impacted the level of significance found or not found during the data analysis. Due to restricted laboratory protocols and social distancing guidelines imposed by the COVID-19 pandemic, participant recruitment methods were limited. Second, the VR conditions were completed in the same order by all participants. This methodology was chosen in the attempt to prevent exaggerated responses to the HVR condition first or blunted responses to the LVR condition had it been completed second. However, the effects of VR height exposure may have been slightly diminished due to a practice effect. Third, though the physical walkway offered a sufficient dynamic balance challenge for healthy young adults, the difficulty in navigating both the physical and virtual walkways may have contributed to the restricted gaze patterns. Previous studies have utilized wider physical walkways or stationary tasks to observe how height exposure impacts gait, vision, and cognition (Kugler et al, 2014, Kisker et al, 2019, Martens et al, 2019). Nonetheless, building a challenging physical walkway and developing a virtual environment that contained that same walkway allowed us to further test the realism of VR manipulation. Fourth, although the data processing and analysis methods utilized in this study were validated in previous work, the conclusions drawn may benefit from a more robust analysis. Some analyses were simplified due to project timeline limitations (see Appendix B).

Future Directions

In the event this protocol was replicated or expanded upon in the future, including a separate eye tracking device during the NVR condition may offer more insight on visual processing during beam walking as well as how gaze behavior may change in response to virtual immersion. In addition to observing physiological responses to VR, including a post-testing survey that assesses a participant's sense of presence and subjective feelings towards virtual height exposure may help further validate the realistic nature of the virtual environment. Combining objective and subjective assessments of VR could lead to a more inclusive interpretation of the effects of immersive VR.

Conclusions

Collectively, these findings offer a more comprehensive understanding of the impact VR has on balance control and information processing systems. With VR technology gaining greater attention in the realms of research and rehabilitation, it is important to first develop a strong base of knowledge on not only the effects of VR, but also the magnitude of those effects in healthy individuals. Establishing how immersive VR induces stress and taxes balance control and information processing among healthy participants allows researchers and clinicians to tailor their applications of VR to fit a diverse range of populations.

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APPENDIX A

EAST CAROLINA UNIVERSITY
University & Medical Center Institutional Review Board
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Office **252-744-2914** · Fax **252-744-2284** · **rede.ecu.edu/umcirb/**

Notification of Initial Approval: Expedited

From: Biomedical IRB
To: Callie Herman
CC: Nicholas Murray
Date: 1/21/2021
Re: UMCIRB 20-002864
Influence of virtual reality height exposure on cognitive load and visual processing during balance beam walking

I am pleased to inform you that your Expedited Application was approved. Approval of the study and any consent form(s) occurred on 1/19/2021. The research study is eligible for review under expedited category # 4,6,7. The Chairperson (or designee) deemed this study no more than minimal risk.

As the Principal Investigator you are explicitly responsible for the conduct of all aspects of this study and must adhere to all reporting requirements for the study. Your responsibilities include but are not limited to:

1. Ensuring changes to the approved research (including the UMCIRB approved consent document) are initiated only after UMCIRB review and approval except when necessary to eliminate an apparent immediate hazard to the participant. All changes (e.g. a change in procedure, number of participants, personnel, study locations, new recruitment materials, study instruments, etc.) must be prospectively reviewed and approved by the UMCIRB before they are implemented;

2. Where informed consent has not been waived by the UMCIRB, ensuring that only valid versions of the UMCIRB approved, date-stamped informed consent document(s) are used for

obtaining informed consent (consent documents with the IRB approval date stamp are found under the Documents tab in the ePIRATE study workspace).

3. Promptly reporting to the UMCIRB all unanticipated problems involving risks to participants and others;

4. Submission of a final report application to the UMICRB prior to the expected end date provided in the IRB application in order to document human research activity has ended and to provide a timepoint in which to base document retention; and

5. Submission of an amendment to extend the expected end date if the study is not expected to be completed by that date. The amendment should be submitted 30 days prior to the UMCIRB approved expected end date or as soon as the Investigator is aware that the study will not be completed by that date.

The approval includes the following items:

Name	Description
Informed Consent	Consent Forms
lower extremity injury questionnaire	Surveys and Questionnaires
neurological questionnaire	Surveys and Questionnaires
Protocol	Study Protocol or Grant Application
Recruitment Flyer	Recruitment Documents/Scripts
Social Media Language	Recruitment Documents/Scripts

For research studies where a waiver or alteration of HIPAA Authorization has been approved, the IRB states that each of the waiver criteria in 45 CFR 164.512(i)(1)(i)(A) and (2)(i) through (v) have been met. Additionally, the elements of PHI to be collected as described in items 1 and 2 of the Application for Waiver of Authorization have been determined to be the minimal necessary for the specified research.

The Chairperson (or designee) does not have a potential for conflict of interest on this study.

IRB00000705 East Carolina U IRB #1 (Biomedical) IORG0000418
IRB00003781 East Carolina U IRB #2 (Behavioral/SS) IORG0000418

APPENDIX B

As mentioned in the discussion of results and study limitations, certain analyses were simplified due to project timeline restrictions. The initial plan for the balance performance analysis included calculating virtual time-to contact (VTC) for each participant's first step onto the embedded force plate (i.e., last step before making the first turn in the walkway). VTC is a relatively new metric that incorporates instantaneous position, velocity and acceleration of COP to predict how long it will take the COP to reach the BOS boundary (Whittier et al, 2020). Determining VTC during beam walking may have further contributed to the understanding of how balance control fluctuates in response to challenging dynamic tasks during virtual height exposure. This in turn could have offered further explanation for why balance performance worsened then improved during the two VR conditions. Had the project timeline permitted, VTC would have been determined by isolating the first full step onto the force plate for all trials of each condition using QTM software. These files would have then been exported as MAT files to be further analyzed with a custom VTC MATLAB code. In addition to time constraints, the custom code presented another set of challenges due to it being primarily developed for static measurements and data files that included a third foot marker to create the BOS boundary. Thus, we were unable to adequately tailor the VTC code to analyze the data collected in this study. Future analysis could include creating a rectangular BOS boundary (using the two foot markers from the current protocol) in relation to foot placement on the balance beam. Seeing that VR height exposure during beam walking is a relatively new research topic, establishing what constitutes a successful or failed step via VTC and changes in COP may help further determine the effectiveness of using beam walking to challenge dynamic balance during VR reality use.