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# Virtual reality and postural control: The virtual moving room paradigm

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# Virtual reality and postural control: The virtual moving room paradigm

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Virtual reality (VR) is becoming increasingly important in balance training. However, the influence of VR generated visual perturbation, through the novel virtual moving room paradigm, is unknown. Thirty healthy individuals had their static balance assessed on a BTrackS balance plate under eight different conditions: baseline eyes open and eyes closed with and without VR, unexpected toward and away moving VR perturbation, and expected toward and away moving VR perturbation. Multiple statistical analyses were conducted, and the results revealed significantly higher postural sway variables in the unexpected moving toward trials compared to the other moving room conditions; significantly higher postural sway variables in the eyes open no VR compared to VR; and significantly higher postural sway variables in the eyes closed no VR compared to VR. This study provides evidence that VR can be used as a safe and low-cost balance training tool by exposing individuals to fall-prone situations and increasing their balance confidence.

# DEDICATION

I would like to dedicate this research to my parents, Eddie and Tammy Freeman, and my grandparents, James and Sandra Creel and Rebecca Freeman.

# ACKNOWLEDGEMENTS

I would like to acknowledge Dr. Harish Chander for his guidance throughout this entire process and my time at Mississippi State University. Dr. Chander ensured the Neuromechanics Laboratory was equipped with all the tools I needed to successfully complete my research. He was always available to answer any questions, offer advice, and remind me to relax and practice self-care. I would not be the student, educator, or researcher I am without the mentorship of Dr. Chander.

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# CHAPTER I

# INTRODUCTION

According to the U.S. Centers for Disease Control and Prevention and the Bureau of Labor Statistics, falls are the leading cause of fatal and nonfatal injuries among older adults and construction workers and second leading cause of accidental or unintentional injury deaths worldwide. (Bureau of Labor Statistics, 2017; CDC, 2020; WHO, 2018). Additionally, it has been reported that more than one-quarter of sports- and recreation-related injuries occurred due to falls (Sheu et al., 2016). However, falls are preventable and do not have to be an inevitable part of life. Therefore, there is a need to create and evaluate effective balance training programs to reduce the incidence of falls.

Falls can be attributed to postural instability and loss of balance. The sensory information needed to maintain balance is acquired from the visual, vestibular, and somatosensory-proprioceptive systems and alterations to these systems can affect one's ability to maintain postural control, especially when the visual system is manipulated (Horak et al., 1990). Furthermore, erect bilateral standing is marked by the ability to maintain the center of mass (COM) of the body within the base of support (BOS) (Chander et al., 2019). However, maintaining postural stability and balance can be challenging due to the position of the COM in relation to the BOS and influences from environmental or human factors (Chander et al., 2019).

The classical "moving room" experiment is a prime example of what visual perturbations can do to the postural control system (Lee & Aronson, 1974). In this study, participants were asked to stand facing a wall that moved toward them unexpectedly which caused conflict in their visual system. This conflict forced participants to rely on their proprioceptive and vestibular systems in which compensatory postural responses (CPRs) were stimulated to maintain balance. These responses caused the lower extremity muscles to compensate for the disruption in erect standing posture. Researchers also found that when participants expected perturbations, smaller postural instability was seen than with unexpected perturbations due to anticipatory postural responses (APRs). This study manipulated the physical visual environment to disrupt balance, but more recent studies have used virtual reality (VR) to induce visual conflicts by altering the virtual environment (VE) (Chander et al., 2019; Parijat et al., 2015; Prasertsakul et al., 2018). Similar to the moving room experiment, altering a VE provides incongruent visual information forcing increased reliance on the somatosensory and vestibular systems to maintain balance, which is the foundation for VR-based perturbation training (Chander et al., 2019).

The role of VR in rehabilitation and occupational settings is becoming increasingly important. In a VE, individuals can freely move around and interact with various components that may not be feasible to do so in the real world (Kamat et al., 2011). With that, the rise of VR as a tool for balance training introduces the need to understand how CPRs and APRs appear when unexpected and expected visual perturbations are provided in a VE. There has been one study on the usage of the moving wall paradigm in a VE (Chander et al., 2019). In this study, participants wore a head-mounted display (HMD) and were instructed to stand on a force platform as still as possible looking straight ahead. During unexpected trials, the front wall moved toward the participant without their knowledge; but, during expected trials the front wall moved toward the participant after a warning and countdown. The authors concluded there were significant differences between baseline and unexpected trials as well as between baseline and expected trials (Chander et al., 2019). Furthermore, postural sway variables were significantly higher during unexpected trials suggesting decreased postural stability when visual perturbations were unexpected. This study provides evidence that VR can successfully induce postural perturbations and possibly be used as a training program for those at risk of falling, however the effects remain unclear. The proposed study in which a virtual moving room is used to induce visual perturbations had never been done before, hence the reason for first focusing on healthy populations with future research focusing on clinical and geriatric populations. Therefore, the purpose of Specific aim 1: Comparison of VR and no VR in this study was to assess postural stability with the eyes were open and closed with and without the VR HMD. It was hypothesized that the mass of the VR headset and being in a VE would induce greater postural instability compared to no headset and no VE. The purpose of Specific aim 2: Moving room paradigm was to assess postural stability when exposed to an unexpected and expected virtual moving room moving toward versus moving away using VR. Evidence of CPRs and APRs were assessed by measuring postural stability. It was hypothesized that the unexpected virtual moving room moving toward the participants would result in greater postural instability compared to the virtual moving room moving unexpectedly away, expectedly toward, and expectedly away from the participants. The purpose of Specific aim 3: Subjective experience was to subjectively investigate the participants’ simulator sickness, balance confidence, and presence in the VE. It was hypothesized there would be minimal simulator sickness experienced, increased balance confidence, and realistic immersion in the VE.

# CHAPTER II

# REVIEW OF LITERATURE

There is a need to evaluate and create training methods that can reduce the risk of falls and improve balance in various scenarios and populations. Deficits in balance can lead to falls and limitation of activities. It is important to note, falls can occur in people of all ages and are not restricted to the elderly population (Talbot et al., 2005). Due to this, the role of VR in the world around us is becoming increasingly important, especially in rehabilitation. VR provides a synergetic and immersive environment in which a person can move around and interact with various components in the VE (Kamat et al., 2011). Ultimately, VR allows the researcher to have complete control over the environment and task stimuli (Ragan et al., 2015). One of the crucial advantages of using a VR system is that it can easily simulate and repeat scenarios that are not feasible to do so in the real-world.  One researcher believes if postural perturbations are mainly provided to the visual system, such as with a modified "virtual moving room", the difficulties and restraints that exist with physical postural perturbation-based balance training (PBBT) could be minimized and potentially aid in creating a VR technology-based fall prevention intervention (Chander et al., 2020). Thus, the goal of this literature review was to evaluate the potential use of VR as an effective training tool in healthy and clinical populations.

## Immersive versus Non-immersive Virtual Reality

The difference between immersive and non-immersive environments can be better understood through the concept of spatial presence, which is defined as “the sense of being in an environment” (Kennedy et al., 1993). In a non-immersive environment, participants can only see the contents based on how the device is held and moved. This allows the participant to interact with the environment through a mouse or joystick. One advantage of using console-based therapy is that reinforced feedback can be used to prepare the nervous system to regenerate (Kamińska et al., 2018). The prefrontal, parietal cortical areas and other motor cortical networks are activated when VR is used for training; researchers believe these activations may be involved in the reconstruction of neurons in the cerebral cortex (Mao et al., 2014). Non-immersive VR has also shown potential to promote cognitive and motor improvements in advanced stages of different neurological diseases such as Parkinson’s disease (Pelosin et al., 2020). One study examined the effectiveness of VR training through the Xbox 360 Kinect$^{TM}$ on fall prevention in older people (Kamińska et al., 2018). The training portion of this study allowed the participants to be active players in football, skiing, and bowling. This allowed the participants to work their entire body, specifically upper and lower limbs, and stabilizing muscles, in an enjoyable manner. After the training sessions, the study concluded there were significant improvements in gait, static and dynamic balance. This study provides evidence that non-immersive VR training can reduce the risk of falls and improve postural stability (Kamińska et al., 2018).

In an immersive environment, the participants feel as though they are completely submerged in the environment (Ventura et al., 2019). The environment is created by using tools that are connected to the participant’s body which allows them to perform the same motor task that is displayed (Piron et al., 2010). Moreover, a VR environment could be considered immersive when viewed through an HMD to create the illusion of being inside the environment. The real-life visual feedback allows for enjoyable rehabilitation which significantly increases engagement (Shema et al., 2014). A study on the effectiveness of VR training in an immersive VE showed that repeated exposure to VR-induced sensory conflicts produced a training effect in which less stepping responses and improved ability to maintain balance was seen (Bugnariu & Fung, 2007). This training effect led to less stepping responses and improved ability to maintain balance in people who had suffered a spinal cord injury. VR training has also been shown to reduce falls and improve reaction times and functional abilities which will be discussed further in below sections (Parijat et al., 2015; Prasertsakul et al., 2018). Ultimately, VR allows participants to focus less on standing and more on the task at hand in an enjoyable manner.  Lastly, a semi-immersive VR system overlaps virtual images onto real images to increase informative content (Bugnariu & Fung, 2007). Semi-immersive VR allows individualized programs to be provided to patients, and immersion is higher than non-immersive VR in that real images are used in the VE. Additionally, it has fewer side effects such as cybersickness than immersive VR.

## Concern for Cybersickness

There is debate on if, and how much, motion sickness occurs in an immersive environment and the acceptability of VR training in complex populations such as the elderly raises concern for some, specifically in immersive VEs. Interestingly, one researcher among others have reported immersive VR training as being safe and economical even in older adults (Cho et al., 2014). One study reported that older adults tolerated well the use of a HMD with little to mild discomfort in their study (Bugnariu & Fung, 2007). A different study examined the physiological and psychological effects of immersion in a VE (Akizuki et al., 2005). In this study, subjects with an HMD developed some motion sickness after the first VR immersion, which was attributed to the visual scene being slightly delayed after the head movement. However, it was revealed that further VR immersion with additional time lags to the existing delay did not induce additional motion sickness. One possible explanation for this was that repeated exposure was more effective in developing adaptation as compared to prolonged exposure (Akizuki et al., 2005). Furthermore, these findings suggest that exposure and adaptation to certain VEs decrease the contribution of visual inputs to postural control. Additionally, non-immersive environments have shown to be more highly accepted than fully and semi-immersive environments, due to the lowest “cybersickness” symptomatology (Bugnariu & Fung, 2007). Overall, VR has shown to have a positive impact on rehabilitation and fall prevention in older adults, with non-immersive VR being the most effective due to higher acceptability and easier access in complex clinical populations (Bugnariu & Fung, 2007).

## Types of Virtual Reality Programs

There are various ways VR can be used in rehabilitation and fall prevention. VR-based therapy has been used to help stroke victims regain muscle control, reduce falls in the elderly, and improve motor function in people with neurological disorders. VR allows for one’s treatment to be individualized while increasing complexity and decreasing support needed from the clinician (Weiss et al., 2004). The goal of VR training is to simulate an environment that facilitates motor, cognitive or metacognitive abilities to improve functional ability (Weiss et al., 2004).

Various devices can be used to simulate VEs. Examples of these devices include Nintendo Wii Fit (Nintendo Company Ltd., Japan), Microsoft Kinect Sensor (Microsoft Corporation, Redmond, WA, USA), or an HMD such as the HTC Vive Pro (HTC America, Inc., Seattle, WA, USA). These devices can be used to train users with specifics skills and help participants adapt to performances similar to those in the real-word such as meal preparation or crossing a street, which enable clients to participate in real environments in a more independent manner (Ragan et al., 2015; P. L. T. Weiss et al., 2003; Zhang et al., 2001). Other VR programs incorporate exercises and treatment with games such as bowling or skiing (de Vries et al., 2018; Kamińska et al., 2018). These applications target different muscle groups which help with neuromuscular reeducation. Ultimately, VR can be used to focus exercises on dynamic and/or static balance, core control, fine motor control, gait, and trunk support in a more accessible, enjoyable, and safer manner.

# Physical Postural Perturbation Training

## Physical Postural Perturbation Training with and without Virtual Reality

The treadmill is commonly used to induce a physical postural perturbation and has proven to be effective in various methods of rehabilitation. However, a multitude of studies have shown that treadmill training with the addition of VR is far more effective than traditional methods (Mirelman et al., 2016; Parijat et al., 2015; Shema et al., 2014; Yang et al., 2011). One study showed that in a diverse group of older adults at high risk for falls, treadmill training with non-immersive VR led to significantly lower fall rates compared to treadmill training alone (Mirelman et al., 2016). The treadmill training with non-immersive VR possibly induced changes in cortical cholinergic activity, which has shown to improve gait and lower fall rates compared to traditional methods (Pelosin et al., 2020). Gait training using a treadmill is often applied to children with cerebral palsy. This training helps children to repeat task-centered activities while developing a proper walking pattern (Cernak et al., 2008). However, during this training, it is difficult to keep children’s interest. Therefore, VR-based training is more effective in motivating children. This training provides children the opportunity to safely play, learn, and acquire skills (Cho et al., 2016). A study that investigated this revealed that treadmill training with VR improved muscular strength of the lower limbs, gait velocity, gross motor function and walking endurance to a greater extent than basic treadmill training (Cho et al., 2016). The walking activities of the group who used VR also improved significantly because the skills learned in VR transferred to real walking environments.

Another study revealed that traditional treadmill training failed to improve sit-to-stand performance, while VR-treadmill training improved it significantly (Yang et al., 2011). In this study, VR treadmill training was far more effective by significantly improving balance skills in the medial-lateral direction than traditional training. Overall, treadmill training with VR could be used as a very effective program due to its multifactorial approach that reduces falls by improving gait and cognitive functions.

## Improving Motor and Cognitive Function

A key factor in reducing falls in older adults is to improve motor and cognitive functions because deficits in both of these increase the risk of falls (Shema et al., 2014). Walking and balance are linked to executive functions that are necessary to plan, monitor, and execute goal-directed complex actions (Shema et al., 2014). VR with treadmill training is a great multifactorial approach that can be used to target both motor and cognitive functions. Walking while avoiding obstacles in VR or while performing another task places a greater demand on cognitive resources compared to a single task. A VR system that incorporated treadmill training with virtual obstacle negotiation was developed and tested on patients with Parkinson’s Disease and elderly idiopathic fallers (Shema et al., 2014). This VR system was a task-oriented training approach that required planning, decision making, and motor function. This resulted in improved gait speed, stride length, and cognitive abilities as well as transfer of training and retention. Thus, treadmill training with VR has shown to be more effective at improving motor and cognitive function than traditional therapeutic methods.

A different study examined the effects of a VR training program on motor learning and cognitive function in healthy adults (Prasertsakul et al., 2018). Participants of this study were randomly assigned to the VR exercise group or the conventional balance exercise group. Wilcoxon Signed Ranks Test was used to analyze the postural control of participants in five standing tasks, and data were collected with a force plate. The virtual game design was separated into single- and dual-task training, while the conventional exercise group performed static and dynamic balance exercises. The cognitive-motor training in the VR-based exercise program caused a higher ratio of difficulty when compared to single-task training and encouraged the enhancement of motor learning. Cognitive processes rely heavily on motor learning; furthermore, postural control functions and other cognitive processing must share the same cognitive resources (Prasertsakul et al., 2018). Subsequently, postural control can be impaired by a secondary cognitive task. Due to this, the challenge of balance training with a cognitive task can improve postural control, as demonstrated in this study (Prasertsakul et al., 2018). Overall, the results of this study revealed that the VR program facilitated better postural control and motor learning than the conventional exercise program. Therefore, this program could potentially be used as a training tool to help reduce the incidence of falls in healthy adults and possibly be used with older adults, but this needs to be further investigated.

## Fall Risk and Postural Stability

Postural stability is controlled by the feedback control system that works constantly to maintain an upright vertical body alignment (Horak et al., 1997; Salassa & Zapala, 2009). Postural stability, which is analyzed through postural sway, serves as an indicator for the overall safety status of the postural control system and therefore, an indicator of fall risk. Furthermore, failure to recover from an imbalance has been reported as the primary source for postural instability leading to occupational falls (Redfern & DiPasquale, 1997).

One study examined the effectiveness of VR training through the Xbox 360 Kinect Sensor on fall prevention and stability (Kamińska et al., 2018). The training portion of this study allowed the participants to be active players in football, skiing, and bowling. This allowed the participants to work their entire body, specifically the upper and lower limbs, and stabilizing muscles, in an enjoyable manner. After the training sessions, the study concluded there were significant improvements in gait, static, and dynamic balance (Kamińska et al., 2018). Furthermore, this study provided evidence that VR training can reduce the risk of falls and improve postural stability. While VR training has been reported to minimize falls in the workplace, it has also shown to have detrimental effects on the postural control system (Akizuki et al., 2005; Horlings et al., 2009; Robert et al., 2016). More specifically, it was found that just wearing the HMD and being in a VE caused a decrease in balance (Chander et al., 2020).

The negative effects on the postural control system have been attributed to sensory conflicts between the visual, vestibular, and somatosensory systems (Akizuki et al., 2005; Horlings et al., 2009; Robert et al., 2016). The “moving room” experiment is a popular example of what happens when the visual system is manipulated (Lee & Aronson, 1974). Although this experiment was conducted on infants in the context of motor development, its findings can still be applied to other populations. Participants were asked to stand facing a wall that moves toward them unexpectedly along the anterior-posterior axis. Due to disrupting visual information in relation to the body’s position, the visual information was concealed in favor of vestibular and proprioceptive information. This alteration shifted the COM to the posterior end of the BOS and impaired the erect standing position (Chander et al., 2019). Compensatory postural responses (CPRs) stimulated by sensory feedback were executed by the lower extremity muscles to compensate for the disruption. Interestingly, expected perturbations can cause anticipatory postural responses (APRs) to be executed. The anticipation of disruption allows the central nervous system to adjust responses to the perturbation which can minimize negative consequences associated with loss of balance (Chander et al., 2019). This study revealed when participants anticipated postural perturbations, COP displacement in the anterior-posterior direction was smaller, implying better postural stability compared to unexpected perturbations, which provides evidence that prior knowledge changes postural responses (Lee & Aronson, 1974). Furthermore, these findings call attention to the significance of both APRs and CPRs in maintaining postural stability when exposed to perturbations (Chander et al., 2019).

One study attempted to recreate the “moving room” experiment using a virtual moving wall (Chander et al., 2019). Participants wore an HMD and were asked to stand on a force platform as still as possible with their arms by their side. A lobby VE was used as a transitionary room to the closed room VE that was used for testing. Unexpected perturbation trials were done first, as exposure to the expected perturbations might now allow true unexpected perturbations, which is something that should be further investigated. During these trials, the front wall moved towards the participants at a random time designated by the investigator without warning to the participant. For the expected trials, the front wall was moved toward the participant following a warning and countdown. Participants also completed several rounds of a Simulator Sickness Questionnaire (SSQ) before familiarization, after familiarization, and after testing trials. If any scores were greater than five, the data were excluded from the study. The results concluded there were differences in postural stability parameters between baseline and the unexpected condition as well as between baseline and the expected condition, which suggests there were differences in postural control strategies in unanticipated vs. anticipated visual perturbations (Chander et al., 2019). More specifically, anterior-posterior COP displacement and the 95% ellipsoid sway area was significantly higher in the unexpected condition compared with baseline, suggesting there was decreased postural stability when the postural disruption was unexpected. This study was conducted on healthy individuals; consequently, elderly, and clinical populations may have different responses to the visual perturbations produced by VR. Therefore, the findings of this study should be used with caution due to its early state.

## Virtual Postural Perturbation-based Slip Training

### Effectiveness of Virtual Reality Training in Improving Recovery Reactions

Training programs that help older adults learn movements related to recovery reactions can improve sensory function and muscle coordination which increases their ability to recover from a slip-induced fall (Parijat & Lockhart, 2012). VR training has proven to be very effective in many aspects and especially in improving recovery reactions from slip-induced falls. One study collected kinematic and kinetic data to examine exactly this recovery reaction (Parijat et al., 2015). The VR training group in this study was able to reduce the frequency of falls from 50% in the baseline trial to 0% during the transfer of training trial, while the control group's frequency of falls was only reduced from 50% to 25%. The training group experienced a reduction in slip distance and peak sliding heel velocity; it was noted that reducing the distance traveled by the slipping foot decreases the likelihood of experiencing a fall (Parijat et al., 2015). The training group was also able to quickly reverse their anterior trunk rotations by mid-slip during the final trial. This reduction had a significant effect in bringing the center of mass within the limits of stability (Troy & Grabiner, 2006). Recovery strategies that were learned during VR training transferred to the final trial of the study where the incidence of balance loss decreased significantly compared to the control group. Furthermore, the main effects seen in the training group were reduced time to peak knee coactivity and trunk extension (Parijat et al., 2015). Ultimately, this study supports VR training as an effective way to improve recovery reactions and reduce falls.

### Virtual Reality Training using Perturbations from Moveable Platforms, Waist-pulls, and Slip-belt Treadmills

Repeated perturbation training is a specific training program that is structurally like a slip-induced fall. The study previously mentioned created a program that could produce a training effect for slip-induced falls while walking on a treadmill in a VR environment (Parijat et al., 2015). Each participant wore a head-mounted display that created an environment with buildings, light poles, roads, street signs, etc. The virtual slip consisted of tilts in the pitch plane at random intervals (Parijat et al., 2015). Qualisys was used to record kinematic data and participants wore a full-body harness. This study was composed of three sessions: baseline measure, training acquisition, and transfer of training, all on separate days. During the training session, a perturbation-based slip was induced by tilting the environment from 0 degrees to 25 degrees at 60 degrees per second while the participant was walking on a treadmill. The entire session consisted of about 150 virtual slips. It was found that the time spent in the VE was directly proportional to the reduction in gait variability and instability on the treadmill (Parijat et al., 2015). It took participants 15-20 minutes to adjust to walking on the treadmill with a head-mounted display. Therefore, in future studies, the habituation period should be taken into consideration. Participants did not react to visual perturbations after the initial 2-3 trials; but a training effect was still seen in the final session where the VR training group's falls decreased significantly more than the control group (Parijat et al., 2015).

A different study compared the effects of perturbation-based slips from moveable platforms to slip training in a VE (Parijat, 2009). Both methods proved to be effective as fall frequency and knee coactivation were reduced significantly and early activation of muscles was seen. Overall, significant changes were observed in the lower extremities in the moveable platform group, and the upper body in the VR group (Parijat, 2009). This is likely due to the different types of perturbations produced by the separate groups. This study concluded that VR training could potentially be used as an effective slip-training method.

## Application to Rehabilitation and Clinical Populations

Physical postural perturbation-based balance training (PBBT) has previously been used to reduce falls in older adults (Bieryla & Madigan, 2011). However, there are limitations when using physical postural PBBT. Limitations include difficulty in use among different populations (such as clinical populations) and the inherent physical and fall injury risk, even when strapped into a harness (Chander et al., 2020). However**,** as previously mentioned, VR has shown to potentially be an effective training tool for reducing falls and improving postural stability. VR has shown to enhance the sensorimotor functions of individuals with Down's Syndrome and improve balance and gait after an individual has suffered a stroke making it an effective alternative to physical therapy that can be done at home (Cho et al., 2014). Additionally, by exposing people to fall prone situations it helps them to become more comfortable and aware of the situation, making it easier for their bodies to adequately adapt and possibly prevent a fall. A recent study on older adults revealed that VR positively influenced their attitudes towards VR-based fall prevention and served as an appealing training mode (Dockx et al., 2017). VR training is an accessible, affordable, and safe tool that could be used at rehabilitation facilities, home, schools, or essentially anywhere. Furthermore, home-based VR training could provide and/or prolong the required therapy which could further improve clinical outcomes and compliance to therapy. The  “virtual moving room” paradigms could potentially serve as low-cost and practical fall prevention training programs and be beneficial for all populations when provided with repeated exposure for training and adaptation of control (Chander et al., 2020). The potential differences between a virtual toward-moving room and away-moving should be examined to see if there are differences between the two perturbations and if so, which method would be more effective in preventing falls.

## Conclusion

It is critical that we address the incidence of falls in clinical populations and decrease fatal and nonfatal injuries related to falls. Furthermore, there is a need to assess and create training programs for people who are at risk of falling. VR is a new tool that can be used to do just that. VR has shown to decrease falls by improving postural stability, motor, and cognitive functions in various populations (Kamińska et al., 2018; Mirelman et al., 2016; Parijat et al., 2015; Prasertsakul et al., 2018). Although VR has shown to induce greater postural instability than no VR, especially at heights, it is believed with more familiarization and exposure to VEs effects can be minimized (Chander et al., 2020). Upon reviewing the literature, it was found there is a lack of research on using VR as a tool to assess fall risk and create safe training programs in clinical populations. It is important to note, the complications and limitations that exist with physical postural perturbation-based balance training could be minimized when using VR (Chander et al., 2020). Consequently, the effects of VR on postural control and its potential use as a tool to assess fall risk and create fall prevention training programs is an area that needs to be further investigated in healthy and clinical populations.

# CHAPTER III

# METHODOLOGY

## Overview

The below measures were performed in an open room (the University's Neuromechanics Laboratory) with social distancing and no contact with human subjects, except to ensure fit of the VR HMD. The methodology was similar to a previous study conducted in the University's Neuromechanics Laboratory with the exception of different virtual environments (Chander et al., 2019). Most researchers were more than 10 ft away from the participant (using a wireless mouse, keyboard, and laptops connected to big screen TVs) in a large indoor environment and only one participant came in at a time. However, one to two researchers alone were near the participant to prevent them from falling, if the participant lost balance. Participants only came in one time for familiarization and testing. The study was approved by the University's Institutional Review Board (IRB).

## Participants

A total of 31 healthy male and female collegiate students were recruited for the study (age: 20.7 ± 1.2 years; height: 166.5 ± 7.3 cm; mass: 71.7 ± 16.2 kg; gender: 26 females and 5 males). One female participant's participation was terminated after the expected conditions due to an SSQ > 5; hence, 30 participants successfully completed the study, and their data were used for analyses. The inclusion criteria consisted of a physically active status based on the American College of Sports Medicine criteria for physical activity, which included a minimum of 3-5 days of aerobic exercise per week and 2 days of resistance training per week for at least the past 3 months (American College of Sports Medicine, 2018). The exclusion criteria consisted of the presence of any recent visual, vestibular, neurological, or musculoskeletal disorders. Participants also completed a physical activity readiness questionnaire (PAR-Q) and a simulation sickness questionnaire (SSQ) in response to VE exposure.

## Instrumentation

Participants' static postural stability and fall risk were measured with a BTrackS$^{TM}$ (Balance Tracking Systems, Inc., San Diego, CA, USA). Required VEs were developed with Unity 3D and were delivered via an HTC Vive Pro (HTC America, Inc. Seattle, WA, USA) head-mounted display. A lobby environment and a closed-room environment were the two VEs used in the study.

## Study Design

The experimental procedures followed a repeated-measures design, in which each participant served as their own control and were tested at baseline (no visual perturbation) and were followed by unexpected and expected visual perturbations. The order in which the conditions (toward-moving room versus away-moving room) were administered was randomized to eliminate any training effects.

## Experimental Procedures

Upon arriving at the laboratory, the study protocol was explained to the participants, and written consent to participate in the study was obtained. To assess eligibility for the study, a PAR-Q and SSQ was given. Any participant with risk factors in the PAR-Q and/or SSQ score > 5 were excluded from the study. The BTrackS$^{TM}$ software performed an automatic selfcalibration of its sensors at the beginning of each testing session, and a sampling rate of 25 Hz and duration of 20 s was set. The VR system was calibrated using the hand-held sensors to ensure the VE was oriented in the correct direction and with the correct dimensions and boundaries of the room. After collecting anthropometric data (age, height, and mass), participants were familiarized with the examination protocol. Participants were barefoot for all familiarization trials. Initial familiarization was done with the BTrackS$^{TM}$; then, participants were provided the VR headset. Participants were first exposed to the lobby area VE, which was used to familiarize them with VE as well as to practice their ability to use their gaze to complete given tasks. During each VR task, corresponding instructions appeared on the screen and additional verbal commands were given. The instructions were to look at each red square until it disappeared. Immediately following familiarization, the participants completed a second round of SSQ to assess their experience with VR exposure, and if the SSQ score was > 5, the study was withheld.

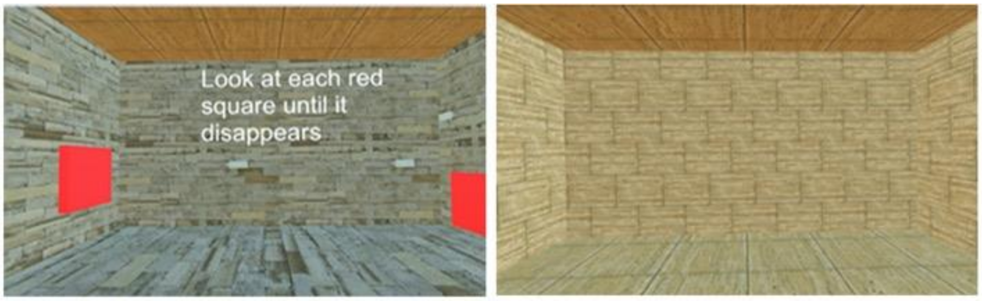


*Figure 1.* *Virtual Environments*

Left: lobby and transition environment, right: closed room testing environment

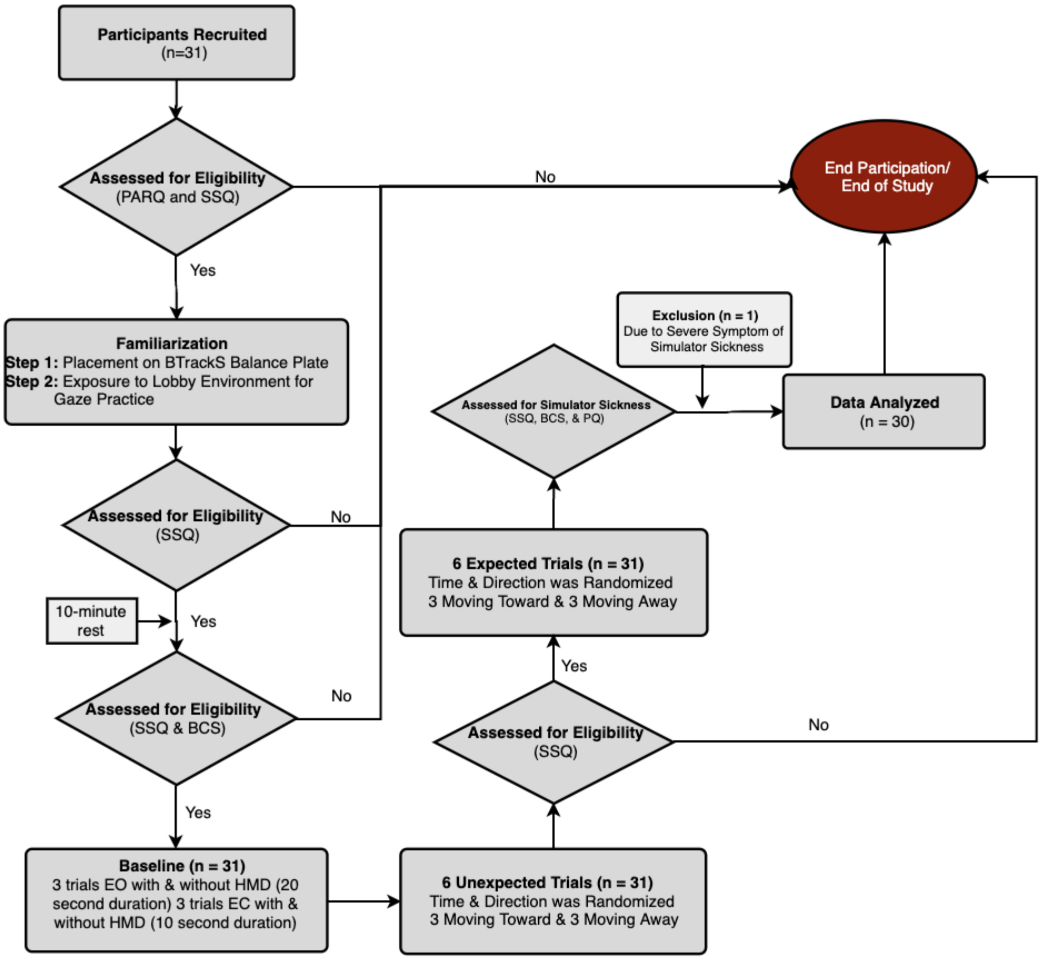


*Figure 2.* *Flowchart of Experimental Procedures*

Participants were given a 10-minute break between familiarization and initiation of testing. Participants completed an SSQ and an adapted Balance Confidence Scale (BCS) before beginning any testing trials (Nandi et al., 2019). All participants underwent testing barefoot due to its rehabilitation and disability applications. Three 20 s trials of baseline bilateral static postural stability were recorded in the eyes open condition with quiet standing, arms by the side, eyes fixed at a specific point, and without the VR headset. Upon completion, participants completed three 10 s baseline trials in the eyes closed condition with quiet standing and arms by side without the VR headset. Participants were then provided with the VR headset and completed three 10 s baseline trials with their eyes closed with quiet standing and arms by side with the headset on. Participants also completed three 20 s baseline trials with their eyes open with quiet standing and arms by side with the headset on in the lobby environment. Testing trials with eyes open then began and participants were first exposed to the lobby area VE, which was used as a transitionary environment before moving onto the testing VE. Transitioning to the testing VE was accomplished by participants using their gaze to make a box disappear, which was practiced during familiarization. Once the box disappeared in the lobby area, participants were exposed to the new testing VE, which involved a closed room VE. Participants were advised to stand as erect as possible without moving and to look straight at the front wall of the room. Participants then completed three trials of an unexpected toward-moving room, expected toward-moving room, unexpected away-moving room, and expected away-moving room. The three trials of each condition were completed within a total of 5 s. The velocity of the virtual moving rooms was preset to 6 m/s. Participants first underwent three unexpected trials in each direction during a 5 s time window. As previously mentioned, the order of testing was randomized for the virtual environments (toward-moving room and away-moving room). For unexpected testing trials, the same investigator attempted to move the room at one random time within a 5 s time window to minimize anticipation by participants. The initiation of the moving room was based on a random time decided by the same investigator, and the result was that the front and two side walls of the testing VE were moved towards or away from the participant without a warning. Upon completion, participants were provided with a fourth round of SSQ. Participants then underwent expected trials in which they were exposed to three movement trials of each virtual environment (toward-moving room versus away-moving room) within a 5 s time window, where the room was moved following a warning and a countdown. The participants were not told if the virtual moving room was moving toward or away from them, and the order was randomized. The warning statement that was issued to all participants for the expected moving room conditions was that the room will start to move on the “go” signal, which was provided as a three-second countdown of three, two, one and “go”. This marked the end of the study and participants were provided with a fifth round of SSQ and second round of BCS. In the event of an SSQ score > 5, the participants were monitored in the laboratory until they felt comfortable and were then allowed to leave.

*Figure 3. Participant Wearing the HTC Vive Pro*

Participant’s postural stability is being tested with the BTrackS balance plate while wearing the VR headset looking straight ahead at the VE.

## Data Analyses

The BtrackS$^{TM}$ explore balance software was used to analyze and filter the postural sway variables. Voltages were sampled from the top-right, bottom-right, bottom-left, and top-left force transducers. Voltage samples were calibrated and passed through a Butterworth filter with frequency cutoff set to 4 Hz. Participants' weights were calculated by summing the top-right, bottom-right, bottom-left, and top-left voltages. From that the Center of Pressure (COP) along the x- and y-axes were calculated which were then used to calculate the balance metrics and analyze postural stability. Medial-lateral excursion, anterior-posterior excursion, 95% ellipsoid area, average sway velocity, total sway, root mean square in the medial-lateral and anterior-posterior directions were calculated and considered the outcome variables of interest. Total sway was the total COP trajectory length. Average COP sway excursions in the medial-lateral (M/L), and anterior-posterior (A/P) directions were calculated by subtracting the minimum values from the maximum values along the x (M/L) or y (A/P) axes. The average COP sway velocity was calculated by dividing the total length of the COP path by the number of data points multiplied by the change in time over the duration of each postural stability testing trial. The 95% ellipsoid area (cm2) represented an area of the ellipsoid based on the COP shifts such that 95% of the data is within the ellipsoid and 5% is outside it. Root mean square was the square root of the average of the squares of the difference between mean COP and COP in the medial-lateral and anterior-posterior directions. Furthermore, greater sway excursion, velocity, and area represented decreased balance and postural stability. Lastly, the participant's responses to SSQ and BCS were calculated and an SSQ score > 5 after VE exposure resulted in exclusion from data analyses.

## Statistical Analyses

All postural sway variables were analyzed using a repeated-measures analysis of variance (RM ANOVA). Specific aim 1: Comparison of VR and no VR in the eyes open conditions were analyzed using a one-way [1x2 RM ANOVA (Eyes Open No-HMD vs. Eyes Open HMD)]. Specific aim 1: Comparison of VR and no VR in the eyes closed conditions were analyzed using a one-way [1x2 RM ANOVA (Eyes Closed No-HMD vs. Eyes Closed HMD)]. Specific aim 2: Moving room paradigm was analyzed using a one-way [1x4 RM ANOVA (Eyes Open Unexpected Toward-Moving Room vs. Expected Toward-Moving Room vs. Unexpected Away-Moving Room vs. Expected Away-Moving Room)]. Specific aim 3: Subjective experience with SSQ was analyzed using a one-way [1x3 RM ANOVA (Pre-testing vs. Post-Unexpected vs. Post-Expected)]. If a significant main effect was found, follow-up post-hoc pairwise comparisons were performed using a Bonferroni correction. If a significant interaction was found, main effects were ignored and simple effects were analyzed. Specific aim 3: Subjective experience with the BCS was analyzed using a Paired Samples T-Test to compare pre- and post-VR exposure scores. All statistical analyses were performed using SPSS software v.27 (IBM SPSS, Armonk, NY, USA) with an a priori alpha level of 0.05.

# CHAPTER IV

# RESULTS

Based on the results from the SSQ, testing was terminated, and data were excluded from one participant. Thirty-one participants were recruited but only thirty were tested and analyzed, this consisted of twenty-five females and five males (age: 20.7 ± 1.2 years; height: 166.46 ± 7.3 cm; weight: 71.68 ± 16.23 kg). The main effects were analyzed for the repeated-measures ANOVA analyzed, and if a significant main effect was found the pairwise post-hoc analyses were performed with a Bonferroni correction. All results are summarized in Table 1 and significant findings are elaborated under each of the specific aim's results.

## Specific Aim 1: Comparison of VR and No VR

The repeated-measures ANOVA revealed a significant main effect between baseline eyes open conditions for the postural sway variables of medial-lateral root mean square (F (1,29) = 17.455, $p < 0.001$, pȠ2 = 0.376) and medial-lateral sway excursion (F (1,29) = 14.213, $p = 0.001$, pȠ2 = 0.329), but not total sway, sway velocity, sway distance, anterior-posterior root mean square, 95% ellipsoid area, or anterior-posterior sway excursion. Pairwise comparisons of significant main effects revealed that for both medial-lateral root mean square and medial-lateral sway excursion, eyes open without the VR HMD induced greater postural sway than eyes open with the VR HMD in the lobby environment. The repeated-measures ANOVA revealed a significant main effect between baseline eyes closed conditions for the postural sway variables of total sway (F (1,29) = 20.512, $p < 0.0001$, pȠ2 = 0.414); sway velocity (F (1,29) = 20.497, p <

0.0001, pƞ2 = 0.414); 95% ellipsoid area (F (1,29) = 4.480, p = 0.036, pƞ2 = 0.143); and anterior-posterior sway excursion (F (1,29) = 4.407, p = 0.045, pƞ2 = 0.132), but not sway distance, medial-lateral root mean square, anterior-posterior root mean square, or medial-lateral sway excursion. Pairwise comparisons of significant main effects revealed that for total sway, sway velocity, 95% ellipsoid area, and anterior-posterior excursion, eyes closed with no VR HMD induced greater postural sway than eyes closed with the VR HMD.

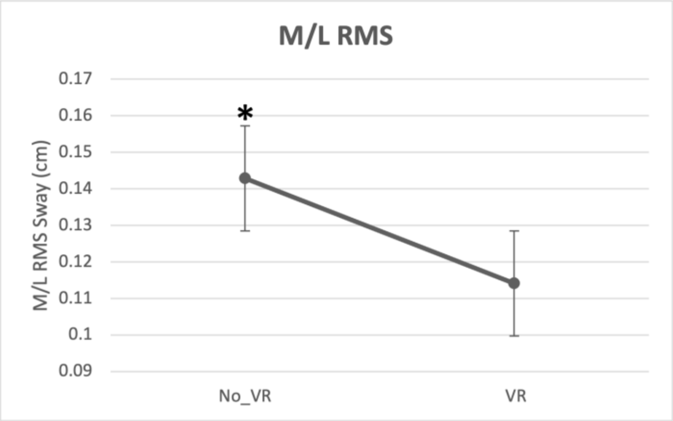


*Figure 4. Medial-Lateral Root Mean Square Sway During Eyes Open Conditions*

Center of pressure medial-lateral root mean square (cm) during eyes open no virtual reality (No_VR) and eyes open with virtual reality (VR) conditions. Bars represent standard errors. * Represents a significant difference at $p < 0.05$ compared to the VR condition.

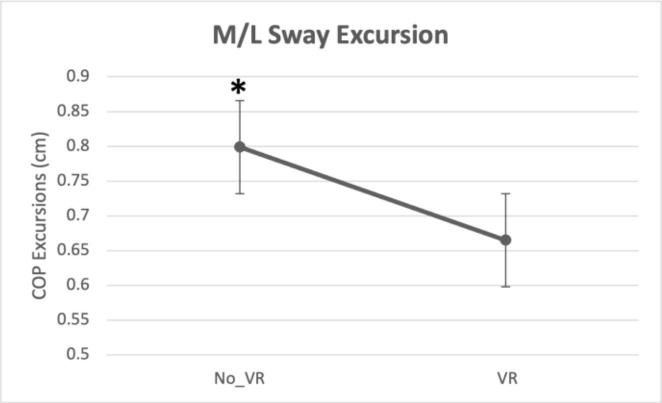


*Figure 5.* *COP Medial-Lateral Sway Excursions During Eyes Open Conditions*

Center of pressure medial-lateral sway excursion (cm) during eyes open no virtual reality (No_VR) and eyes open with virtual reality (VR) conditions. Bars represent standard errors. * Represents a significant difference at $p < 0.05$ compared to the VR condition.

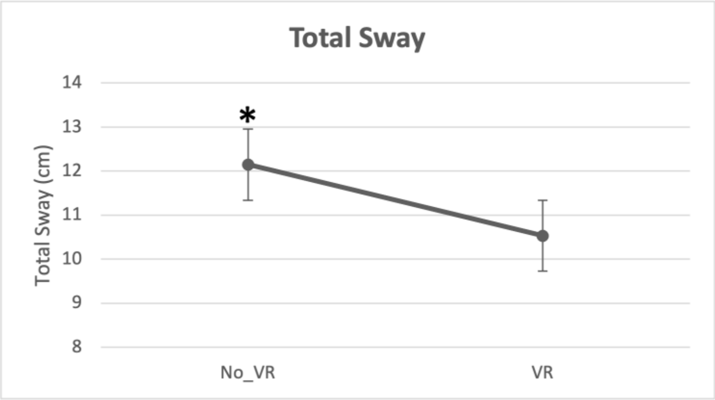


*Figure 6.* *Total Sway During Eyes Closed Conditions*

Center of pressure total sway (cm) during eyes closed no virtual reality (No_VR) and eyes closed with virtual reality (VR) conditions. Bars represent standard errors. * Represents a significant difference at $p < 0.05$ compared to the VR condition.

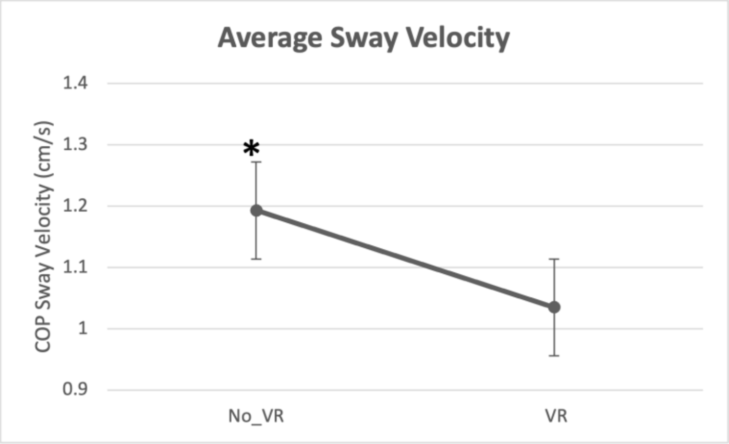


*Figure 7.* *Average Sway Velocity During Eyes Closed Conditions*

Center of pressure average sway velocity (cm/s) during eyes closed no virtual reality (No_VR) and eyes closed with virtual reality (VR) conditions. Bars represent standard errors. * Represents a significant difference at $p < 0.05$ compared to the VR condition.

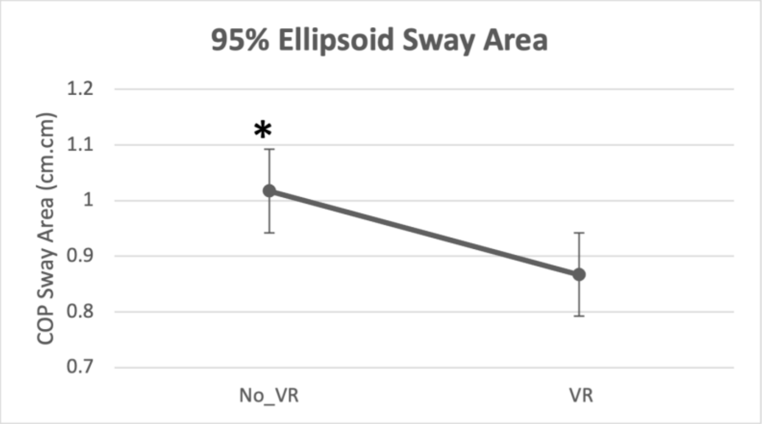


*Figure 8.* *95 % Ellipsoid Sway Area During Eyes Closed Conditions*

Center of pressure 95% ellipsoid area (cm.cm) during eyes closed no virtual reality (No_VR) and eyes closed with virtual reality (VR) conditions. Bars represent standard errors. * Represents a significant difference at $p < 0.05$ compared to the VR condition.

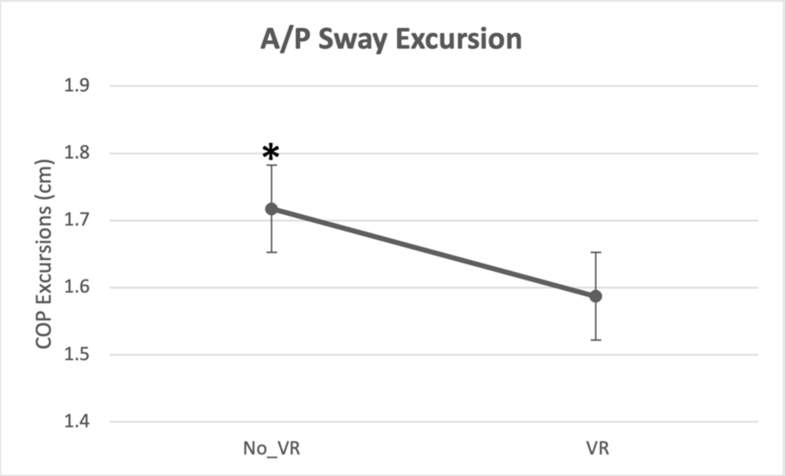


*Figure 9. COP Anterior-Posterior Sway Excursions During Eyes Closed Conditions*

Center of pressure anterior-posterior sway excursion (cm) during eyes closed no virtual reality (No_VR) and eyes closed with virtual reality (VR) conditions. Bars represent standard errors. * Represents a significant difference at $p < 0.05$ compared to the VR condition.

## Specific Aim 2: Moving Room Paradigm

The repeated-measures ANOVA revealed a significant main effect between moving room conditions for the postural sway variables of total sway (F (3,87) = 10.232, p < 0.0001, pƞ2 = 0.261) and sway velocity (F (3,87) = 10.149, p < 0.0001, pƞ2 = 0.259), but not sway distance, medial-lateral root mean square, anterior-posterior root mean square, 95% ellipsoid area, medial-lateral sway excursion, or anterior-posterior sway excursion. Pairwise comparisons of significant main effects revealed that for both total sway and sway velocity, the unexpected toward moving room induced significantly greater postural sway compared to the unexpected away moving room, expected toward moving room, and expected away moving room.

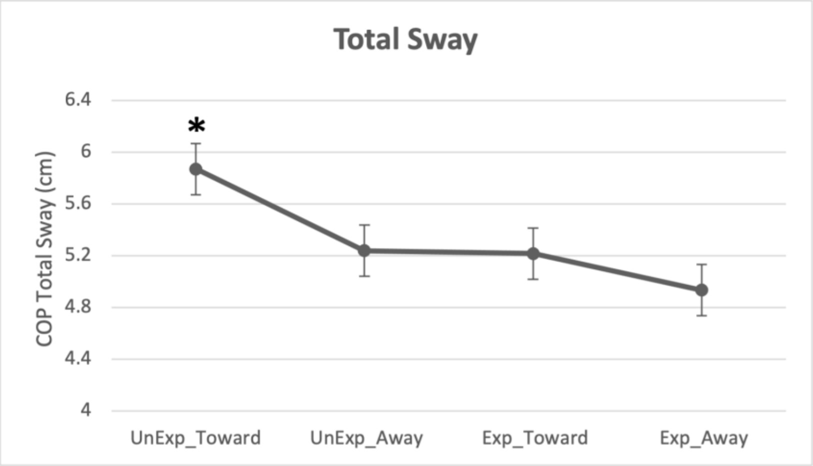


*Figure 10.* *Total Sway During Moving Room Conditions*

Center of pressure total sway (cm) during unexpected toward-moving room (UnExp_Toward), unexpected away-moving room (UnExp_Away), expected toward-moving room (Exp_Toward), and expected away-moving room (Exp_Away) conditions. Bars represent standard errors. * Represents a significant difference at $p < 0.05$ compared to UnExp_Away, Exp_Toward, and Exp_Away conditions.

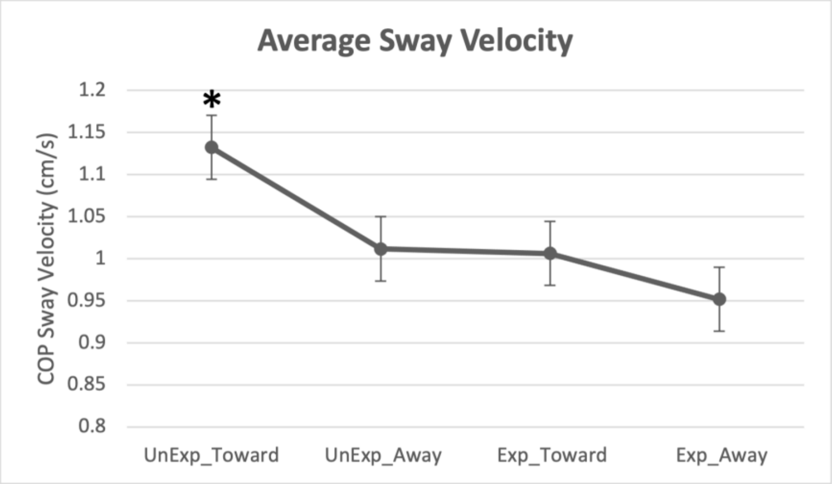


*Figure 11.* *Average Sway Velocity During Moving Room Conditions*

Center of pressure average sway velocity (cm/s) during unexpected toward-moving room (UnExp_Toward), unexpected away-moving room (UnExp_Away), expected toward-moving room (Exp_Toward), and expected away-moving room (Exp_Away) conditions. Bars represent standard errors. * Represents a significant difference at $p < 0.05$ compared to UnExp_Away, Exp_Toward, and Exp_Away conditions.

## Specific Aim 3: Subjective Experience

The repeated-measures ANOVA revealed a significant main effect between the SSQ responses of pre-testing, post-unexpected, and post-expected (F (2,58) = 5.524, p = 0.006, pƞ2 = 0.160). Pairwise comparisons of significant main effects revealed the post-expected SSQ responses were significantly greater than the pre-testing SSQ responses, but not the post-unexpected SSQ responses. The average score for the PQ was 94.4 with a standard deviation of +/- 12.21, maximum score of 113, and minimum score of 67. The average score for the pre-testing BCS was 42.90 with a standard deviation 12.72, maximum of 67, and minimum of 10 out of 80 possible points, which comes out to the average balance confidence being 53.6%. The average score for post-testing (moving-room trials) was 45.77 with a standard deviation of 12.40, maximum of 72, and minimum of 11 out of 80 possible points, which comes out to the average balance confidence being 57.2%. The Paired Samples T-Test revealed pre- and post-testing scores were strongly and positively correlated (r = 0.943, p < 0.001). Additionally, it revealed there was a significant difference between pre- and post-testing scores ($t_{29}$ = -3.70, p = 0.001), where post-testing scores were significantly higher than pre-testing.

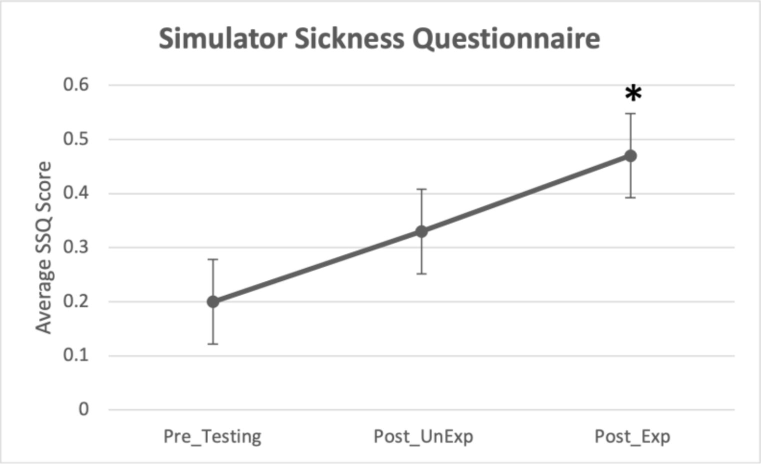


*Figure 12.* *Simulator Sickness Questionnaire*

Simulator Sickness Questionnaire scores pre-testing (Pre_Testing), post-unexpected (Post_UnExp), and post-expected (Post_Exp) trials. Bars represent standard errors. * Represents a significant difference at $p < 0.05$ compared to Pre_Testing.

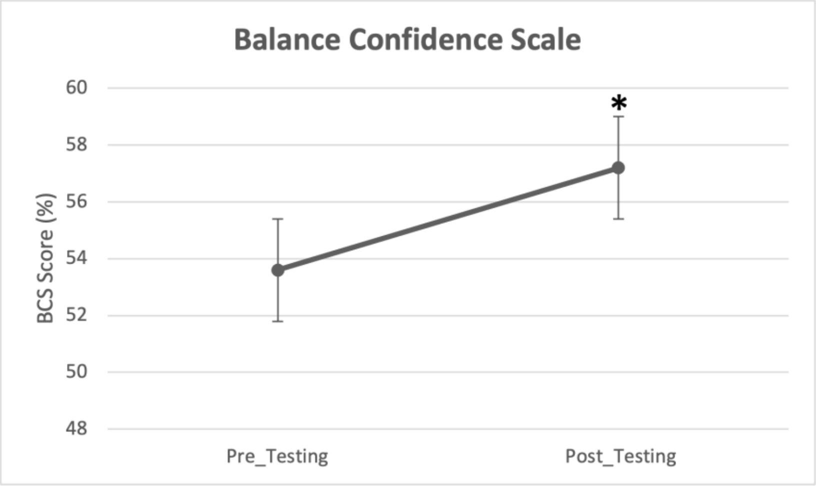
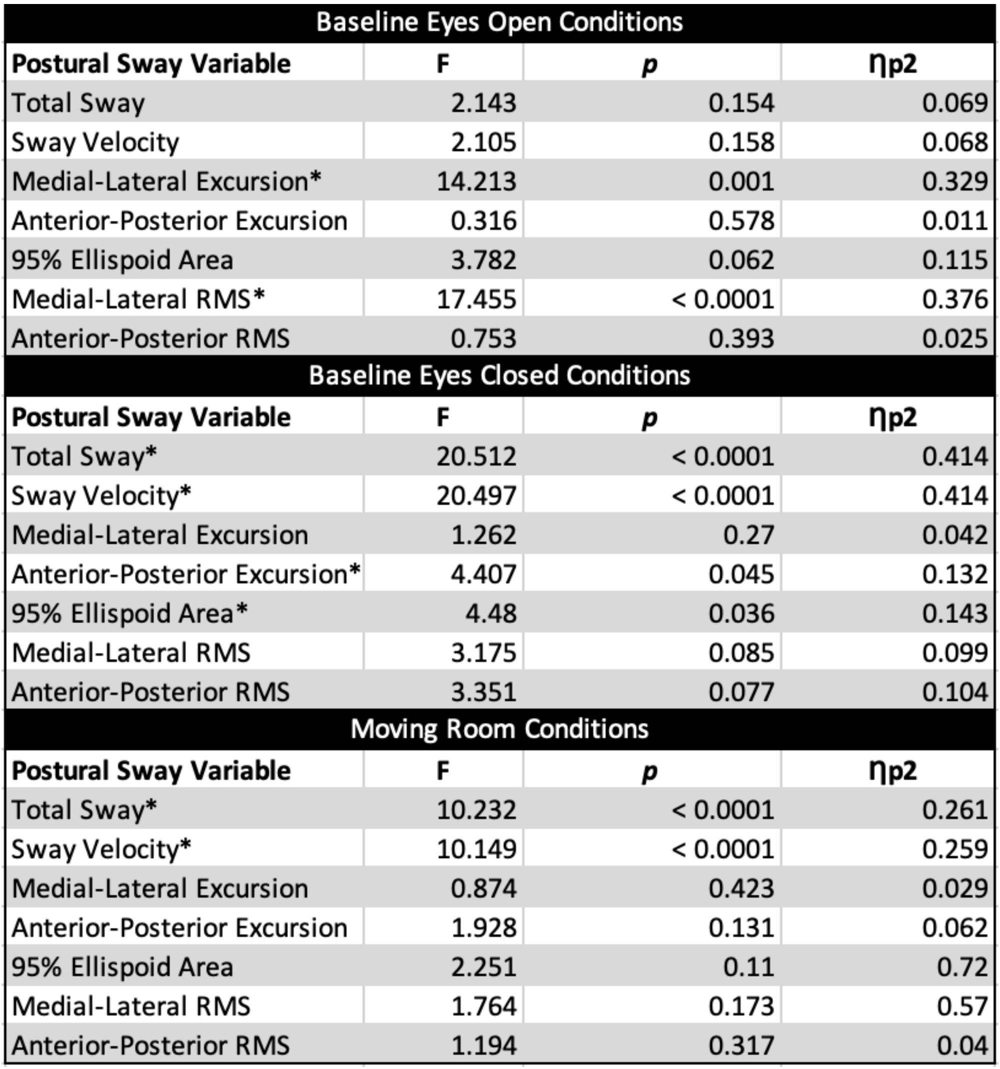


*Figure 13.* *Balance Confidence Scale*

Balance Confidence Scale scores pre-testing (Pre_Testing) and post-testing (Post_Testing). Bars represent standard errors. * Represents a significant difference at $p < 0.05$ compared to Pre_Testing.

Table 1

*Statistical Analyses*



**Baseline Eyes Open Conditions**

| Postural Sway Variable | F | *p* | ηp2 |
|---|---|---|---|
| Total Sway | 2.143 | 0.154 | 0.069 |
| Sway Velocity | 2.105 | 0.158 | 0.068 |
| Medial-Lateral Excursion* | 14.213 | 0.001 | 0.329 |
| Anterior-Posterior Excursion | 0.316 | 0.578 | 0.011 |
| 95% Ellispoid Area | 3.782 | 0.062 | 0.115 |
| Medial-Lateral RMS* | 17.455 | < 0.0001 | 0.376 |
| Anterior-Posterior RMS | 0.753 | 0.393 | 0.025 |

**Baseline Eyes Closed Conditions**

| Postural Sway Variable | F | *p* | ηp2 |
|---|---|---|---|
| Total Sway* | 20.512 | < 0.0001 | 0.414 |
| Sway Velocity* | 20.497 | < 0.0001 | 0.414 |
| Medial-Lateral Excursion | 1.262 | 0.27 | 0.042 |
| Anterior-Posterior Excursion* | 4.407 | 0.045 | 0.132 |
| 95% Ellispoid Area* | 4.48 | 0.036 | 0.143 |
| Medial-Lateral RMS | 3.175 | 0.085 | 0.099 |
| Anterior-Posterior RMS | 3.351 | 0.077 | 0.104 |

**Moving Room Conditions**

| Postural Sway Variable | F | *p* | ηp2 |
|---|---|---|---|
| Total Sway* | 10.232 | < 0.0001 | 0.261 |
| Sway Velocity* | 10.149 | < 0.0001 | 0.259 |
| Medial-Lateral Excursion | 0.874 | 0.423 | 0.029 |
| Anterior-Posterior Excursion | 1.928 | 0.131 | 0.062 |
| 95% Ellispoid Area | 2.251 | 0.11 | 0.72 |
| Medial-Lateral RMS | 1.764 | 0.173 | 0.57 |
| Anterior-Posterior RMS | 1.194 | 0.317 | 0.04 |

Statistical analyses for all postural sway variables during all conditions. * Represents a significant difference at $p < 0.05$

# CHAPTER V

# DISCUSSION

The purpose of this study was to assess postural stability and fall risk when exposed to fall-prone situations. More specifically, the purpose of specific aim 1 was to compare the effect of wearing a virtual headset compared to no headset during baseline eyes closed conditions as well as the effect of being in a confined VE compared to no VE in baseline eyes open conditions. The purpose of specific aim 2 was to investigate the effect of a virtual moving room when it was unexpectedly and expectedly moving toward and away from participants. The final purpose of the study was to investigate participants' subjective experience through various questionnaires about simulator sickness, presence, and balance confidence.

## Comparison of Baseline Conditions

The current study found significant differences in postural sway parameters between eyes open without the VR HMD and eyes open with the VR HMD in the virtual lobby environment. More specifically, the postural sway variables of medial-lateral root mean square and medial-lateral sway excursion were significantly higher when the participants were not wearing the VR HMD compared to wearing the VR HMD in the virtual lobby environment. In other words, wearing the VR HMD significantly lowered postural sway. This finding suggests decreased postural stability when participants are standing with their eyes open, arms by their side, looking straight ahead compared to wearing the HMD looking straight ahead at the virtual lobby environment. This finding is opposite of the hypothesis that being in a VE would induce greater postural instability compared to not being in a VE.  Additionally, this study found significant differences in postural sway parameters between eyes closed without the VR HMD and eyes closed with the VR HMD. More specifically, the postural sway variables of total sway, sway velocity, 95% ellipsoid area, and anterior-posterior sway excursion were significantly higher when the participants were not wearing the VR HMD compared to wearing the VR HMD. This finding suggests decreased postural stability when participants are standing erect with their eyes closed versus standing erect with their eyes closed while wearing the HMD. This finding is opposite of the hypothesis that the weight of the HMD would induce greater postural instability compared to not wearing the HMD. Contrastingly, Chander et al., (2020) found significantly greater postural instability in VR conditions compared to no VR conditions. The findings from the baseline eyes open and eyes closed conditions can be better understood through the concept of external and internal attentional focus. Attentional focus refers to the location in which individuals pay attention to while performing a task (Park et al., 2015). Internal focus is when individuals concentrate on the inside of the body while performing a task and external focus is when individuals concentrate on the outside of the body while performing a task. Multiple studies have shown that external focus was more effective than internal focus in performance and balance (Jeong et al., 2020; Wulf et al., 2001, 2001, 2003). Although the instructions were the same for all tasks, to stand erect as possible looking straight at the wall in front of them, the VE was more controlled compared to the lab environment. More specifically, during eyes open with VR, the participants were externally focused on the center point of the controlled VE; whereas during eyes open no VR the participants were in an open uncontrolled environment where they may have received extra feedback that elicited greater postural sway. Proprioception plays a vital role in postural control and increased proprioception has been shown to improve postural stability by increasing one's awareness to their body position in space (Gur et al., 2015). The increased proprioception from the HMD provided more feedback to the participants' central nervous system thereby increasing their awareness of their body's position in space. This phenomenon is likely what prompted the participants to stand more stable with less postural sway, especially during the eyes closed with VR conditions. The HMD could also be viewed as an external attention of focus since it is on the outside of the body. Therefore, it is also likely participants externally focused on the HMD during the baseline VR conditions which contributed to the increased postural stability compared to no HMD.

## Comparison of Moving Room Conditions

In the current study, significant differences in postural sway parameters were found between unexpected and expected moving room conditions as well as between the virtual room moving toward and away from the participants. More specifically, the postural sway variables of total sway and sway velocity were significantly higher in the unexpected toward-moving room compared to the unexpected away-moving room, expected toward-moving room, and expected away-moving room. This finding suggests decreased postural stability when the perturbations were unanticipated and the virtual moving room was moving toward the participants. The roles of APRs and CPRs are important to consider when comparing unexpected and expected perturbations. In expected perturbations, the participants' postural control system anticipates the perturbation which could be the reason for the lower postural sway compared to the unexpected perturbations (Horak et al., 1989; Santos & Aruin, 2008). Whereas in unexpected perturbations, the participant's postural control system is forced to compensate for the unanticipated perturbation which is likely the reason for the higher postural sway compared to expected perturbations (Horak et al., 1989). More specifically, not only did the perturbation being unexpected or expected matter; rather the virtual moving room was moving toward or away also played a role in the postural sway variables. In the current study, the unexpected toward-moving room condition elicited significantly higher total sway and sway velocity compared to the other three conditions. It is known that participants tend to sway in the direction of the perturbation (Lee & Aronson, 1974). It is also known the degree of limits of stability (LOS) in the posterior direction (4.5 degrees) is less than in the anterior direction (8 degrees) (Ganesan et al., 2015). Therefore, one can interpret when the virtual moving room perturbation is moving towards the participant causing the participant to sway posteriorly, and subsequently, there is little room for error which results in the participant needing to quickly shift anteriorly to prevent themselves from falling. Hence, the significantly greater sway velocity and total sway when the visual perturbation is unexpectedly moving toward the participant. Furthermore, when the virtual moving room was moving toward the participants the visual perturbation was more pronounced compared to moving away. The reason for lower postural sway during expected conditions can be understood through APRs. Anticipation of a perturbation allows time for the body to make the appropriate adjustments prior to the perturbation. In the current study, participants were told when the virtual moving room was going to begin moving which allowed their postural control system to prepare for the perturbation and properly respond. Unexpected trials were always conducted first to get "true" unexpected perturbations followed by expected trials, but the order in which participants experienced a virtual moving room moving toward or away from them was completely random to eliminate any learning effects. A similar study was conducted in the Neuromechanics Laboratory in which the front wall moved toward the participants unexpectedly and expectedly (Chander et al., 2019). In the current study, medial-lateral and anterior-posterior sway excursions were higher compared to the previous study indicating greater postural instability in the current study when considering COP excursions. Factors such as a different force platform and the visual perturbation being a virtual moving wall should be considered when comparing the results from the two studies. More specifically, the previous study used a virtual moving wall that attempted to trick only the central vision which allowed the participants to rely on their peripheral vision as the two side walls remained stationary. However, in the current study, both the front and two side virtual walls moved toward and away from the participants which attempted to trick not only the participants' central vision but also their peripheral vision.

## Questionnaires

The surveys conducted revealed participants felt a strong sense of immersion, experienced little simulator sickness, and had greater balance confidence post-exposure to the virtual environments. A previous study validated four VEs using the PQ scores with a standard mean score of 98.11 and a standard deviation of +/- 15.78 (Witmer & Singer, 1998). Although the average score was lower in this study, the standard deviation was also lower compared to the findings of the previously mentioned study (M = 94.4, SD = 12.21, Min = 67, Max = 113). Based on these numbers, one can confirm the participants' perception of successful and realistic immersion in the developed VEs. The BCS was used to test the participants' perception of their balance confidence. The BCS was previously validated on healthy young adults with their scores ranging from 34 to 79.6%, with a mean score of 56 and standard deviation of +/- 12.5% (Nandi et al., 2019). The total score obtained by summing responses to all questions (maximum 80), was expressed as a percentage with from 0-100 with 0 reflecting "not confident at all" and 100 reflecting "extremely confident". In the current study, scores ranged from 10 to 67 with a mean score of 42.9 (53.6 %) for pre-testing and 11 to 72 with a mean score of 45.77 (57.2%) for post-testing. These findings suggest the unexpected and expected visual perturbations resulted in the participants' balance confidence increasing significantly compared to the pre-testing scores which provides evidence that VR could be used as a balance training tool. More specifically, it supports the hypothesis that balance confidence would increase after being exposed to the visual perturbations because of learning how to respond to the fall-prone situations. Furthermore, findings from the SSQ revealed post-expected scores were significantly higher compared to pre-testing scores. This suggests the longer one is in a VE, the more likely simulator sickness will be experienced; but the mean scores for all conditions were significantly lower than five. There was one outlier in which one participant was forced to end testing and data were excluded due to experiencing an SSQ > 5. This participant reported they get motion sickness very easily. This is something to consider for future studies in which screening for individuals who are prone to motion sickness should be conducted.

## Limitations

There are many potential limitations to consider with this study. First, the study was conducted on healthy individuals with no pre-existing conditions. We know postural responses are different for elderly and clinical populations; therefore, the results may look different if this study was conducted in a different population. However, future studies using VR in elderly and clinical populations should be conducted with caution as there is a slight risk for falls and simulator sickness. Another limitation to consider is that the preset order of baseline, unexpected, and expected trials could potentially cause a learning effect. However, if expected trials are conducted first there would be no true unexpected trials. During both unexpected and expected trials participants did not know if the virtual moving room was going to be moving toward or away and the order of direction was randomized, which potentially minimized any learning effects. Other limitations to consider is the preset velocity of the virtual moving room, as faster or slower velocities could cause different postural stability behaviors. This study was also conducted during the COVID-19 pandemic; therefore, facemasks were required to conduct research. The wearing of facemasks could potentially cause different postural stability behaviors due to disruption of peripheral vision. However, the participants were always instructed to look straight ahead, and the HMD fully covered their eyes with no visual disruption from the facemask.

## Conclusions

In conclusion, this study revealed decreased postural stability when the visual perturbation provided through the virtual moving room was unexpected and moving toward the participant compared to unexpected moving away, expected moving toward, and expected moving away. It also builds upon the body of literature that increased proprioception and external attentional focus, such as focus on the HMD and center point of the front wall of the virtual moving room, demonstrates better postural stability. Future studies like the current one should provide varying instructions on where to focus (internally or externally) to determine if external focus is the reason we saw increased postural stability with the HMD compared to no HMD. Furthermore, future studies should consider incorporating electromyography, 3D motion capture, and electroencephalography to better understand what is happening to the postural control system during visual perturbations. Overall, realistic immersion, decreased postural stability, and increased balance confidence was seen which provides evidence that VR can be used as a proper balance training program.

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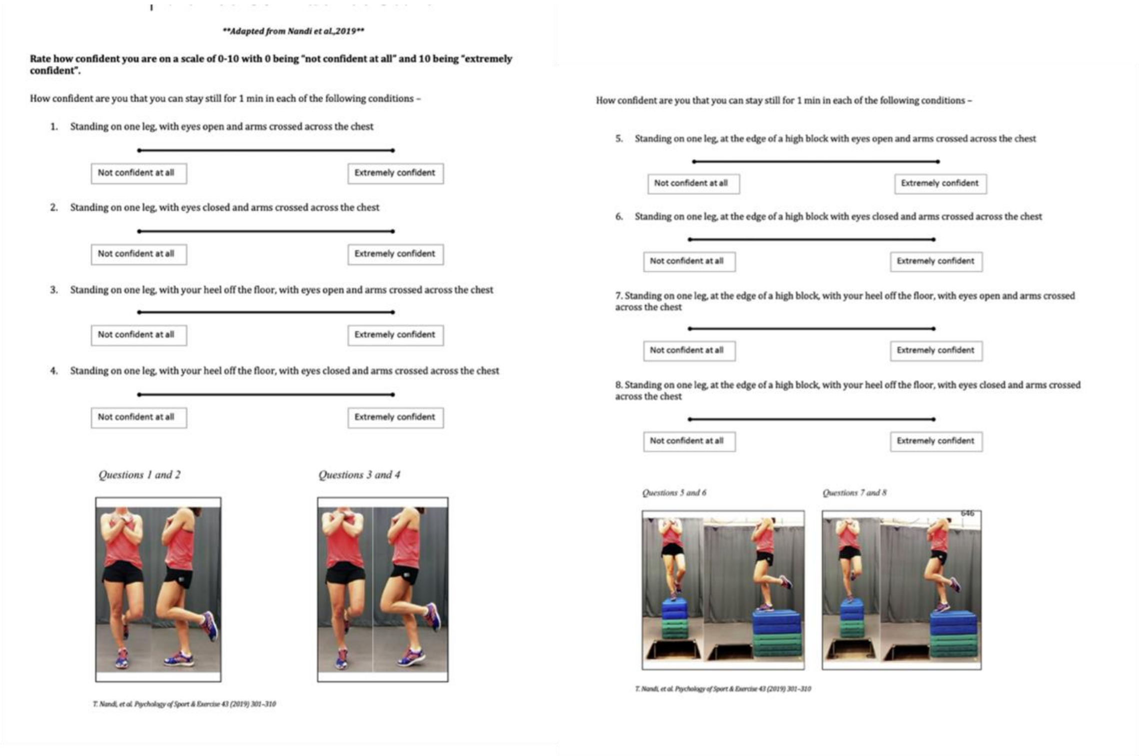
# APPENDIX A

# QUESTIONNAIRES

# Balance Confidence Scale



***Adapted from Nandi et al.,2019***

**Rate how confident you are on a scale of 0-10 with 0 being "not confident at all" and 10 being "extremely confident".**

How confident are you that you can stay still for 1 min in each of the following conditions –

1. Standing on one leg, with eyes open and arms crossed across the chest

Not confident at all
Extremely confident

2. Standing on one leg, with eyes closed and arms crossed across the chest

Not confident at all
Extremely confident

3. Standing on one leg, with your heel off the floor, with eyes open and arms crossed across the chest

Not confident at all
Extremely confident

4. Standing on one leg, with your heel off the floor, with eyes closed and arms crossed across the chest

Not confident at all
Extremely confident

*Questions 1 and 2*

*Questions 3 and 4*

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How confident are you that you can stay still for 1 min in each of the following conditions –

5. Standing on one leg, at the edge of a high block with eyes open and arms crossed across the chest

Not confident at all
Extremely confident

6. Standing on one leg, at the edge of a high block with eyes closed and arms crossed across the chest

Not confident at all
Extremely confident

7. Standing on one leg, at the edge of a high block, with your heel off the floor, with eyes open and arms crossed across the chest

Not confident at all
Extremely confident

8. Standing on one leg, at the edge of a high block, with your heel off the floor, with eyes closed and arms crossed across the chest

Not confident at all
Extremely confident

*Questions 5 and 6*

*Questions 7 and 8*

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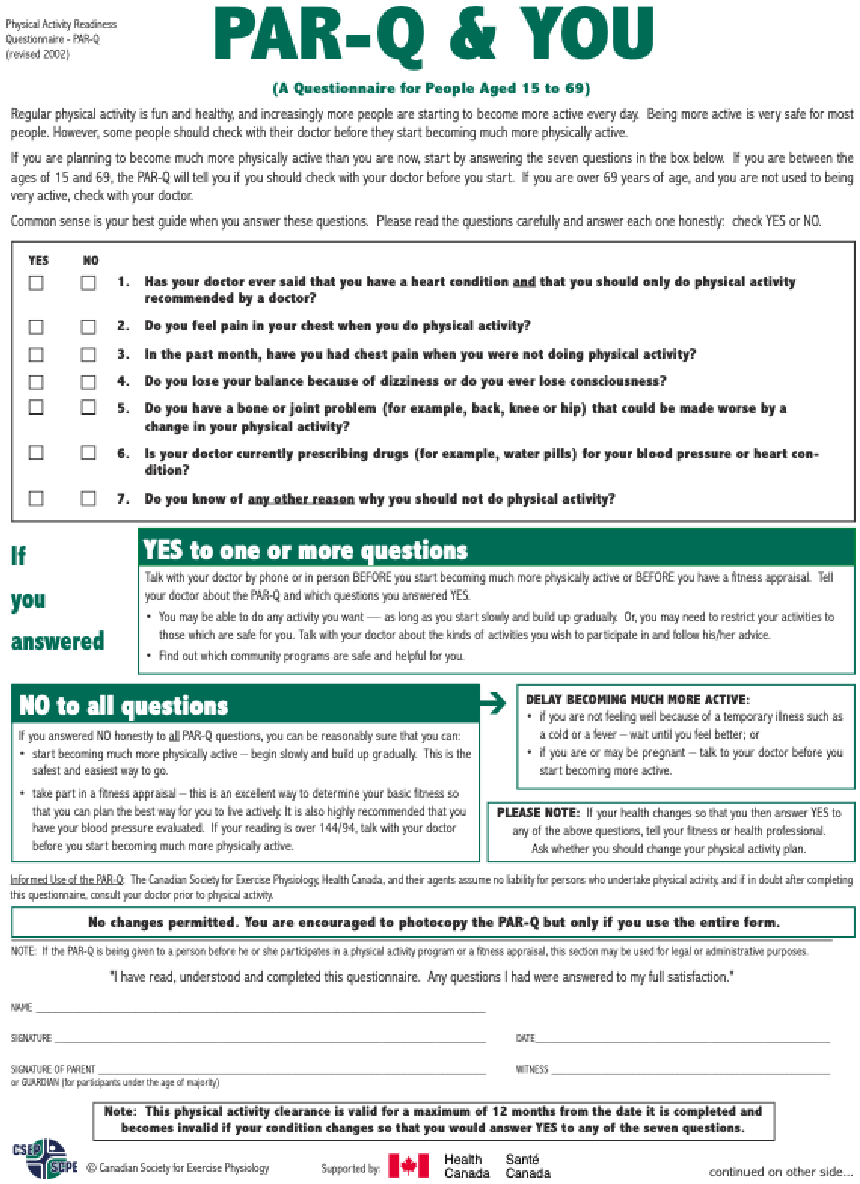
The below adapted Balance Confidence Scale was used to test pre- and post- balance confidence scale scores (Nandi et al., 2019).

*Figure A1.* *BCS Form*

## Physical Activity Readiness Questionnaire

The below PAR-Q was used to assess if participants were cleared for physical activity before participating in the study.



Physical Activity Readiness
Questionnaire - PAR-Q
(revised 2002)

# PAR-Q & YOU

**(A Questionnaire for People Aged 15 to 69)**

Regular physical activity is fun and healthy, and increasingly more people are starting to become more active every day. Being more active is very safe for most people. However, some people should check with their doctor before they start becoming much more physically active.

If you are planning to become much more physically active than you are now, start by answering the seven questions in the box below. If you are between the ages of 15 and 69, the PAR-Q will tell you if you should check with your doctor before you start. If you are over 69 years of age, and you are not used to being very active, check with your doctor.

Common sense is your best guide when you answer these questions. Please read the questions carefully and answer each one honestly: check YES or NO.

| YES | NO | | |
|---|---|---|---|
| ☐ | ☐ | 1. | **Has your doctor ever said that you have a heart condition and that you should only do physical activity recommended by a doctor?** |
| ☐ | ☐ | 2. | **Do you feel pain in your chest when you do physical activity?** |
| ☐ | ☐ | 3. | **In the past month, have you had chest pain when you were not doing physical activity?** |
| ☐ | ☐ | 4. | **Do you lose your balance because of dizziness or do you ever lose consciousness?** |
| ☐ | ☐ | 5. | **Do you have a bone or joint problem (for example, back, knee or hip) that could be made worse by a change in your physical activity?** |
| ☐ | ☐ | 6. | **Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition?** |
| ☐ | ☐ | 7. | **Do you know of any other reason why you should not do physical activity?** |

**If you answered**

**YES to one or more questions**

Talk with your doctor by phone or in person BEFORE you start becoming much more physically active or BEFORE you have a fitness appraisal. Tell your doctor about the PAR-Q and which questions you answered YES.

- You may be able to do any activity you want — as long as you start slowly and build up gradually. Or, you may need to restrict your activities to those which are safe for you. Talk with your doctor about the kinds of activities you wish to participate in and follow his/her advice.
- Find out which community programs are safe and helpful for you.

**NO to all questions**

If you answered NO honestly to all PAR-Q questions, you can be reasonably sure that you can:

- start becoming much more physically active – begin slowly and build up gradually. This is the safest and easiest way to go.
- take part in a fitness appraisal – this is an excellent way to determine your basic fitness so that you can plan the best way for you to live actively. It is also highly recommended that you have your blood pressure evaluated. If your reading is over 144/94, talk with your doctor before you start becoming much more physically active.

→

**DELAY BECOMING MUCH MORE ACTIVE:**

- if you are not feeling well because of a temporary illness such as a cold or a fever – wait until you feel better; or
- if you are or may be pregnant – talk to your doctor before you start becoming more active.

**PLEASE NOTE:** If your health changes so that you then answer YES to any of the above questions, tell your fitness or health professional. Ask whether you should change your physical activity plan.

Informed Use of the PAR-Q: The Canadian Society for Exercise Physiology, Health Canada, and their agents assume no liability for persons who undertake physical activity, and if in doubt after completing this questionnaire, consult your doctor prior to physical activity.

**No changes permitted. You are encouraged to photocopy the PAR-Q but only if you use the entire form.**

NOTE: If the PAR-Q is being given to a person before he or she participates in a physical activity program or a fitness appraisal, this section may be used for legal or administrative purposes.

"I have read, understood and completed this questionnaire. Any questions I had were answered to my full satisfaction."

NAME ______________________________

SIGNATURE ______________________________ DATE ______________________________

SIGNATURE OF PARENT ______________________________ WITNESS ______________________________
or GUARDIAN (for participants under the age of majority)

**Note: This physical activity clearance is valid for a maximum of 12 months from the date it is completed and becomes invalid if your condition changes so that you would answer YES to any of the seven questions.**

CSEP SCPE © Canadian Society for Exercise Physiology

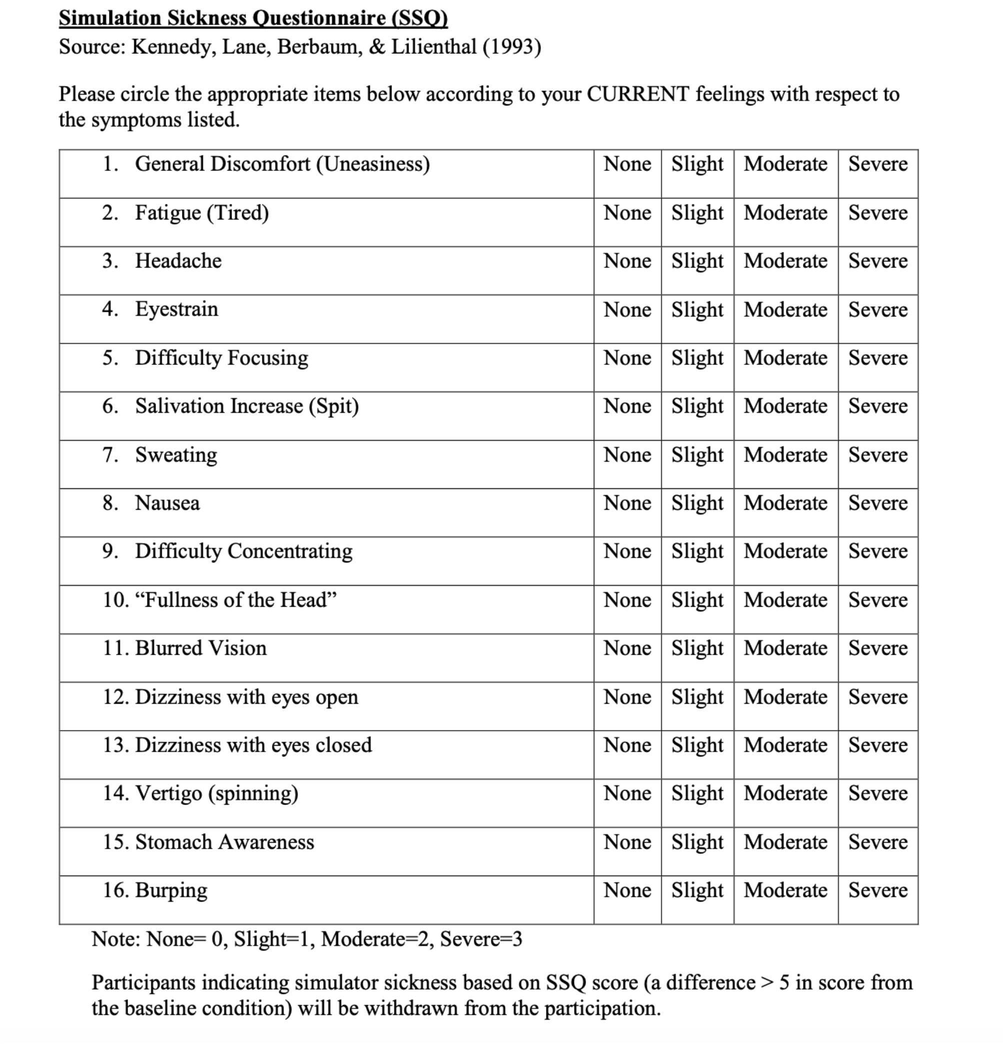
Supported by: Health Canada Santé Canada

continued on other side...

*Figure A2.* *PAR-Q Form*

## Simulator Sickness Questionnaire

The below questions were used to assess participants' eligibility to continue participating at various points in the study. If a score > 5 was experienced, testing was terminated, participants were monitored, and data was excluded.



**Simulation Sickness Questionnaire (SSQ)**
Source: Kennedy, Lane, Berbaum, & Lilienthal (1993)

Please circle the appropriate items below according to your CURRENT feelings with respect to the symptoms listed.

| | | | | |
|---|---|---|---|---|
| 1. General Discomfort (Uneasiness) | None | Slight | Moderate | Severe |
| 2. Fatigue (Tired) | None | Slight | Moderate | Severe |
| 3. Headache | None | Slight | Moderate | Severe |
| 4. Eyestrain | None | Slight | Moderate | Severe |
| 5. Difficulty Focusing | None | Slight | Moderate | Severe |
| 6. Salivation Increase (Spit) | None | Slight | Moderate | Severe |
| 7. Sweating | None | Slight | Moderate | Severe |
| 8. Nausea | None | Slight | Moderate | Severe |
| 9. Difficulty Concentrating | None | Slight | Moderate | Severe |
| 10. "Fullness of the Head" | None | Slight | Moderate | Severe |
| 11. Blurred Vision | None | Slight | Moderate | Severe |
| 12. Dizziness with eyes open | None | Slight | Moderate | Severe |
| 13. Dizziness with eyes closed | None | Slight | Moderate | Severe |
| 14. Vertigo (spinning) | None | Slight | Moderate | Severe |
| 15. Stomach Awareness | None | Slight | Moderate | Severe |
| 16. Burping | None | Slight | Moderate | Severe |

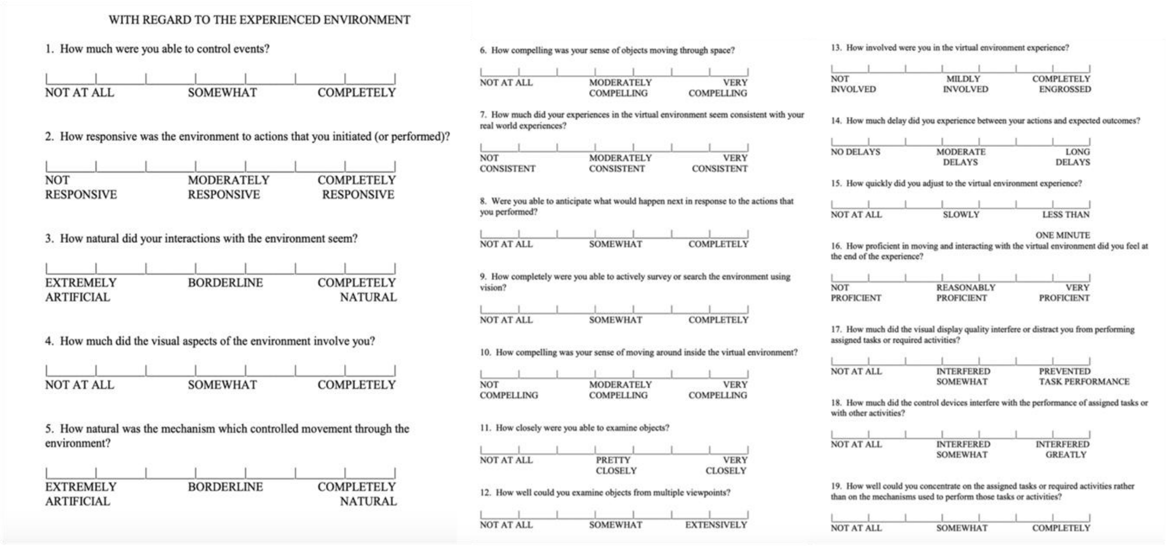
Note: None= 0, Slight=1, Moderate=2, Severe=3

Participants indicating simulator sickness based on SSQ score (a difference > 5 in score from the baseline condition) will be withdrawn from the participation.

*Figure A3. SSQ Form*

## Presence Questionnaire

The below PQ was administered after all testing was completed to assess the participants' experience in the virtual environment.



WITH REGARD TO THE EXPERIENCED ENVIRONMENT

1. How much were you able to control events?

| | | |
|---|---|---|
| NOT AT ALL | SOMEWHAT | COMPLETELY |

2. How responsive was the environment to actions that you initiated (or performed)?

| | | |
|---|---|---|
| NOT<br>RESPONSIVE | MODERATELY<br>RESPONSIVE | COMPLETELY<br>RESPONSIVE |

3. How natural did your interactions with the environment seem?

| | | |
|---|---|---|
| EXTREMELY<br>ARTIFICIAL | BORDERLINE | COMPLETELY<br>NATURAL |

4. How much did the visual aspects of the environment involve you?

| | | |
|---|---|---|
| NOT AT ALL | SOMEWHAT | COMPLETELY |

5. How natural was the mechanism which controlled movement through the environment?

| | | |
|---|---|---|
| EXTREMELY<br>ARTIFICIAL | BORDERLINE | COMPLETELY<br>NATURAL |

6. How compelling was your sense of objects moving through space?

| | | |
|---|---|---|
| NOT AT ALL | MODERATELY<br>COMPELLING | VERY<br>COMPELLING |

7. How much did your experiences in the virtual environment seem consistent with your real world experiences?

| | | |
|---|---|---|
| NOT<br>CONSISTENT | MODERATELY<br>CONSISTENT | VERY<br>CONSISTENT |

8. Were you able to anticipate what would happen next in response to the actions that you performed?

| | | |
|---|---|---|
| NOT AT ALL | SOMEWHAT | COMPLETELY |

9. How completely were you able to actively survey or search the environment using vision?

| | | |
|---|---|---|
| NOT AT ALL | SOMEWHAT | COMPLETELY |

10. How compelling was your sense of moving around inside the virtual environment?

| | | |
|---|---|---|
| NOT<br>COMPELLING | MODERATELY<br>COMPELLING | VERY<br>COMPELLING |

11. How closely were you able to examine objects?

| | | |
|---|---|---|
| NOT AT ALL | PRETTY<br>CLOSELY | VERY<br>CLOSELY |

12. How well could you examine objects from multiple viewpoints?

| | | |
|---|---|---|
| NOT AT ALL | SOMEWHAT | EXTENSIVELY |

13. How involved were you in the virtual environment experience?

| | | |
|---|---|---|
| NOT<br>INVOLVED | MILDLY<br>INVOLVED | COMPLETELY<br>ENGROSSED |

14. How much delay did you experience between your actions and expected outcomes?

| | | |
|---|---|---|
| NO DELAYS | MODERATE<br>DELAYS | LONG<br>DELAYS |

15. How quickly did you adjust to the virtual environment experience?

| | | |
|---|---|---|
| NOT AT ALL | SLOWLY | LESS THAN<br>ONE MINUTE |

16. How proficient in moving and interacting with the virtual environment did you feel at the end of the experience?

| | | |
|---|---|---|
| NOT<br>PROFICIENT | REASONABLY<br>PROFICIENT | VERY<br>PROFICIENT |

17. How much did the visual display quality interfere or distract you from performing assigned tasks or required activities?

| | | |
|---|---|---|
| NOT AT ALL | INTERFERED<br>SOMEWHAT | PREVENTED<br>TASK PERFORMANCE |

18. How much did the control devices interfere with the performance of assigned tasks or with other activities?

| | | |
|---|---|---|
| NOT AT ALL | INTERFERED<br>SOMEWHAT | INTERFERED<br>GREATLY |

19. How well could you concentrate on the assigned tasks or required activities rather than on the mechanisms used to perform those tasks or activities?

| | | |
|---|---|---|
| NOT AT ALL | SOMEWHAT | COMPLETELY |

*Figure A4.* *PQ Form*

# APPENDIX B

# NOMENCLATURE

## Common Abbreviations

- VR = Virtual Reality
- VE = Virtual Environment
- HMD = Head-mounted Display
- BCS = Balance Confidence Scale
- SSQ = Simulator Sickness Questionnaire
- PAR-Q = Physical Activity Readiness Questionnaire
- COP = Center of Pressure
- COM = Center of Mass
- BOS = Base of Support
- CPR = Compensatory Postural Response
- APR = Anticipatory Postural Response
- PBBT = Perturbation-based Balance Training