Providing safer Virtual Reality experiences with the help of Brain-Computer Interfaces

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Thesis submitted in fulfilment of the requirements for
the degree of

Doctor of Philosophy in Software Engineering

under the supervision of Professor Chin-Teng Lin and Dr. Tim Chen

University of Technology Sydney
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August 2020

CERTIFICATE OF ORIGINAL AUTHORSHIP

I, *Carlos Alfredo Tirado Cortes* declare that this thesis, is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the *School of Computer Science*, *Faculty of Engineering and Information Technology* at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

This research is supported by the Australian Government Research Training Program.

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DATE: 21th August, 2020

PLACE: Sydney, Australia

ACKNOWLEDGMENTS

I want to express my sincere gratitude to my principal supervisor, Profesor CT Lin, for the weekly feedback, guidance, and motivation during these years. Without those, I don't think I would have been able to finish this project. Thank you very much! I would also like to thank my co-supervisor, Dr. Tim Chen. Thanks for the hard work and the long work nights. Thank you for all the help, guidance, and mentoring received during these years. And especially thank you for the support outside the school environment, and to push me to have a work-life balance.

I want to thank all the CIBCI lab members for all the help and knowledge they provided during my years. Special thanks to Tien-Thong Do (THE BEST), Avinash Singh, Howe Zhu, Xiaofei Wang, Jia Liu, Ashlesha Akella, Khuong Tran, and Anna Wunderlich.

I also want to extend my gratitude to the different lecturers I interacted with during my years as a student. Special thanks to Dr. Yu-Kai Wang, Dr. Jaime Garcia, Dr. William Raffe, and all the members of the UTS Games Studio. Thank you guys for sharing your experience, for the collaborations, and thank you for sharing the lab spaces with me, and giving me a place to sit!

I want to thank all my friends outside my lab, who supported me throughout this project. I want to thank all the new friends I met during my stay in Sydney. I also want to thank all those friends who left to follow their paths. And to all those friends who were sending me their support from different parts of the world. Thank you all!

I would like to thank the funding sources that made my research possible. This work was supported in part supported by the Australian Research Council (ARC) under discovery grant DP180100670 and DP180100656. I would also like to thank the UTS International Research Scholarship for covering my tuition fees. I would also like to thank the School of Computer Science and the Australian Artificial Intelligence Institute (AAII) for providing me with financial support for funding my conference travels and publication fees.

Last but not least, I want to thank my family for their constant support. Without their support and motivation, I wouldn't be where I am now. Thank you very much for being my number one fans of whatever craziness I come up with. I love you all!

DEDICATION

To my mom, my dad, and my brother, for their infinite love and support on all my crazy endeavours and ideas. . . .

LIST OF PUBLICATIONS

Journal :

1. **C. A. TIRADO CORTES**, H. CHEN, D. STURNIEKS, J. GARCIA MARIN, S. LORD & CHIN-TENG LIN , *Evaluating Balance Recovery Techniques for Users Wearing Head-Mounted Display in VR*, **IEEE Transactions on Visualization and Computer Graphics**.

2. **C. A. TIRADO CORTES**, H. CHEN, TIEN-THONG NGUYEN DO & CHIN-TENG LIN, *EEG Signals and Body Kinematics During Different Levels of VR Sickness*, **Frontiers in Virtual Reality**. (***under review***).

3. NEGIN HESAM-SHARIATI; TOBY NEWTON-JOHN; AVINASH K. SINGH; **C. A. TIRADO CORTES**; TIEN-THONG NGUYEN DO; ASHLEY CRAIG; JAMES W. MIDDLETON; MARK P. JENSEN; ZINA TROST; CHIN-TENG LIN; SYLVIA M. GUSTIN, *Evaluation of the effectiveness of a novel brain-computer interface neuromodulative intervention to relieve neuropathic pain following spinal cord injury: protocol for a single-case experimental design with multiple baselines*, **JMIR Publications**. (***accepted***).

Conferences :

1. **C. A. TIRADO CORTES**, H. CHEN & CHIN-TENG LIN , *Analysis of VR sickness and gait parameters during non-isometric virtual walking with large translational gain*, Proc. 17th ACM SIGGRAPH International Conference on Virtual-Reality Continuum and its Applications in Industry (**VRCAI 2019**), Article 16, pp. 1 - 10, Brisbane, Australia, November, 2019.

2. **C. A. TIRADO CORTES**, H. CHEN & CHIN-TENG LIN , *Using Support-Vector Machines for the identification of VR sickness and postural instability in Mobile VR setups*. (***drafted***).

3. **C. A. TIRADO CORTES**, H. CHEN & CHIN-TENG LIN , *Closed-loop Brain - Computer Interface to mitigate the effects of VR sickness and postural instability*. (***drafted***).

4. AVINASH K. SINGH, **C. A. TIRADO CORTES** & CHIN-TENG LIN , *Closed-loop Brain-Computer Interface and Augmented Reality Navigation System*. (***drafted***).

5. TIEN-THONG NGUYEN DO, AVINASH K. SINGH, **C. A. TIRADO CORTES** & CHIN-TENG LIN, *Detecting cognitive load in active spatial navigation*. (***drafted***).

Others :

1. **C. A. TIRADO CORTES**, H. CHEN & CHIN-TENG LIN , *Analysis of VR Sickness and Gait Parameters During Non-Isometric Virtual Walking with Large Translational Gain*. **VRST' 19**: 25 th ACM Symposium on Virtual Reality Software and Technology. Article 54, pp. 1 - 2. Sydney, Australia, November 2019.

2. TIEN-THONG NGUYEN DO, CHIN-TENG LIN, **C. A. TIRADO CORTES**, AVINASH K. SINGH, JIA LIU, H. CHEN, KLAUS GRAMANN. *Human brain dynamics during navigation with natural walking under different workload conditions in virtual reality by using the mobile brain/body imaging approach*. Society for Neuroscience 2019.

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ABSTRACT

With the introduction of Virtual Reality (VR) to the mass market, two of the most significant issues affecting its users have come to light: Virtual Reality Sickness and Postural Instability. These issues have lead to a low acceptance rate from consumers towards the VR market, preventing it from growing to its full potential. These issues affect everyone from VR application developers, research projects using VR for different purposes, and the average consumer who wants to use it for recreational purposes. This research project focuses on tackling these issues in two of the most common setups: stationary and non-stationary.

Stationary setups already have a track of works that accurately detect both VR sickness and postural instability. Even VR sickness has a track of different creative methods to mitigate it once detected. Nevertheless, there isn't a clear definition of what can be used to help if a user suffers from postural instability or even a fall. For that reason, this project developed and tested two different methodologies for balance recovery: auditory warning and turning the headset's camera on. Results showed that these techniques activated up to 500 ms before the fall onset is enough to prevent users from losing balance.

For mobile VR setups, it is unclear if the same detection methodologies as in stationary setups. Following previous works that use a combination of electroencephalography (EEG) and full-body motion capture suits, this research project intends to use these technologies to identify VR sickness and postural instability in mobile setups and their difference with stationary setups.

The results confirmed that, on non-stationary setups, users' postural instability could be measured by the changes in their Center of Mass and the changes in EEG signals. Results on VR sickness signals showed that other cognitive processes influence non-stationary VR signals compared to stationary VR signals.

These findings can collectively set the building blocks for developing closed-loop systems that can adequately monitor users, detect the appearance of these issues, and provide a solution to either mitigate or avoid these issues. Ultimately, providing an overall safer VR experience to all VR users.

CHAPTER 1

INTRODUCTION

Virtual Reality Technologies have increased in popularity due to being released to the mass market in March 2016. Virtual Reality (or VR) is the use of a software and hardware environment to simulate a three-dimensional world. These three-dimensional worlds are called Virtual Environments (or VEs), and their design allows users to manipulate them with different interaction devices and techniques [14]. Due to the growth in VR systems' popularity, video game development studios have turned their heads into developing games entitled to work on these devices. Because of this, in 2017, *Upload VR* reported that there were 6.4 million VR devices sold around the world [52]. In 2019, the magazine *Variety* reported that Steam, one of the most influential gaming platforms, has around 90 million users [108]. Out of which, according to *Forbes*, 10% of those users are active VR users [178]. We can see how in a span of two years, the number of active users increased from 6.4 million to 9 million. Moreover, speaking about generated income from this industry, since March of 2016, the VR industry has generated 1.6 billion dollars worldwide. The VR industry is, without a doubt, a very profitable market.

The VR industry's growth is due to the different use-cases that VR technology has. While their main user base is the consumers who use VR as entertainment, many other areas have emerged. Areas like traveling and tourism, psychological research, training, learning, simulations, and rehabilitation use VR technologies for various purposes. These other use cases for VR technologies have pushed the VR headset manufacturers to evolve their VR headset technologies.

All these different uses of VR emerged in the 1990s. These years were defined as the first spike of the popularity of this technology [16, 155]. Researchers at that time categorised the different VR devices on whether they were *high-fidelity* or *low-fidelity* systems [40]. High-fidelity systems involved VR systems that allowed the environment to react to the user's head motion to provide a more realistic interaction. In contrast, low-fidelity systems did not have these capabilities and required keyboard input to move around the VR environment.

In more recent times, VR technologies have evolved to the point where projects like Google Daydream enabled anyone with a smartphone to enjoy a VR experience. This increase in accessibility and improvement in the tracking technologies has led to the change in categorization of VR devices. Now, VR devices are categorized into *desktop VR systems* and *mobile VR systems*.

Desktop VR systems usually provide a more reliable and realistic experience, harnessing the full power of powerful desktop computers with strong graphic cards to provide high fidelity scenarios. These systems harness advanced tracking technologies such as Valve's Lighthouses to provide accurate movement tracking for more advanced interactions. The most significant limitation of these systems is user mobility. Most systems are required to be connected to a computer all the time, and while wireless VR systems exist, they are still an exception rather than a norm.

On the other hand, *mobile VR systems* provide superior mobility since they do not require a connection to a desktop computer. Examples of these systems are Oculus' new Oculus Quest or HTC's Vive Cosmos. Thanks to their affordable 3D position tracking systems, these systems allow users to interact with virtual objects while freely navigating the virtual environment by physically walking. The most significant limitation of these systems is the environments' visual fidelity since these systems rely on mobile graphic chips.

This research project will focus on categorizing the type of VR interactions rather than the type of devices. These categories will be *static VR interactions* and *mobile VR interactions*. Interactions developed for phone-based devices are a great example of *static VR interactions* since the user is required to sit and experience a VR simulation. This research project will refer to *static VR scenarios* as scenarios where participants cannot physically walk from one place to another regardless of the type of headset used. On the other hand, *mobile VR interactions* will be interactions that allow users to walk and move around inside a constrained space.

After its introduction to the consumer market, the VR industry's growth led it to become a powerful medium for content consumption and social interaction. The variety of configurations of VR systems has allowed the industry to increase the number of users wanting to own a VR system. However, despite the number of users and the increasing amount of money the VR industry generates, it is not developing to its full potential. The expanding number of users interacting with these devices has brought to light several safety issues that might occur when a user interacts with a VR system: the sudden loss of balance and the appearance of virtual reality sickness.

1.1 Postural Imbalance, Virtual Reality Sickness, and Brain-Computer Interfaces

In terms of Virtual Reality, we can define a safe experience as a session without having any significant issues related to the interaction with a VR system. These significant accidents can be related to two issues: virtual reality sickness and postural imbalance.

The increase in VR systems has increased the cases of *Virtual Reality Sickness* on users. The symptoms of VR sickness are very similar to those of Motion Sickness, which include headaches, nausea, vomiting, drowsiness, and disorientation [38, 45, 228]. Previous studies show how 80% of the users experience VR Sickness, and 50% of them had to terminate the session due to the intensity of the symptoms [173]. Even though previous work shows how repeated exposure to VR can help increase the resilience to VR sickness[144, 145, 220], experiencing these effects a single time has been enough to keep people from trying VR ever again. What makes things worse, there is an indication that VR sickness could also produce some postural unbalance to the user [175], which can make the interaction with the system more dangerous.

Balancing is the act of controlling the body's Center of Mass (CoM) inside an area called the Base of Support (BoS). The BoS serves as a boundary area around a person's body. The shorter the distance between the CoM and the BoS, the higher the risk from suffering a fall. We can define *Postural Imbalance* as the movements that move the body's CoM closer to the BoS. Previous studies have shown how being able to visualize our posture improves our control over it [197]. However, because VR headsets usually hinder users' views, postural imbalance starts to appear at an increased rate.

Postural Imbalance in VR comes from room-scale VR technologies that enable users to navigate virtual environments by physically walking. Previous studies [145, 220] discuss how the use of a user's body in a virtual environment is a positive feature for VR since it improves the level of comfort and, subjectively, it improves the user's sense of presence and immersion. However, the tradeoff for this freedom of movement can magnify potential hazards regarding falls caused by the disparity between the virtual world and the physical environment. What makes this issue worse is that users are usually wearing a head-mounted display (HMD) while suffering a fall. Because the HMD obscures the user's vision, it can prevent them from normally reacting to the fall or even noticing it, increasing their hazard. A solution to this falling hazard is needed to make VR interactions a much safer experience.

One technology that is gaining strength as a medium to monitor the state of the user is Electroencephalography. Electroencephalography (or EEG) is an electrophysiological method to monitor a human being's brain activity. These devices sometimes come in the form of a cap and implement electrodes to register the brain's activity. The electrodes are placed on a user's scalp (in case it is a non-invasive EEG, which is the most common use of EEG) or on the brain surface (in case of invasive EEG, which is quite uncommon unless stated) to register the brain activity. Every time any action occurs in our body, our neurons fire some electrical activity to connect two or more neurons. The electrodes from the EEG register this change in electrical activity, and the measurement of this activity is on microvolts. Figure 1.1 shows a typical example of an EEG cap.

From the use of EEG caps comes the term of a *Brain-Computer Interface* (or BCI). BCI is a type of interface that allows communication between the brain and an external device, usually a computer or computer software. Commonly, these types of systems involve an EEG device to record brain signals. These signals then get sent to a signal processing software that reads and analyses them. Finally, the processed outcome gets sent to a software product that modifies its contents based on the changes in such brain signals. The use of BCI and EEG as tools to monitor the brain has increased in the past few years. These measurement tools have helped different research projects to identify various states of a human being. Compared to fMRI setups, EEG setups provide a more flexible structure to allow researchers to investigate the brain under different paradigms.

For a long time, EEG has been used in research to monitor different human behaviors. The brain activity changes of a person struggling to maintain balance are among the most notable research lines. Notable examples of this are the works of Mochizuki et al. [136]. The authors of this work try to understand the brain activity changes of a person getting ready to react to a fall. Sipp et al. [190] is another excellent example of this type of research, trying to understand the brain state when a user struggles to maintain balance while walking.

A similar work line is trying to use EEG to understand how our brain patterns change

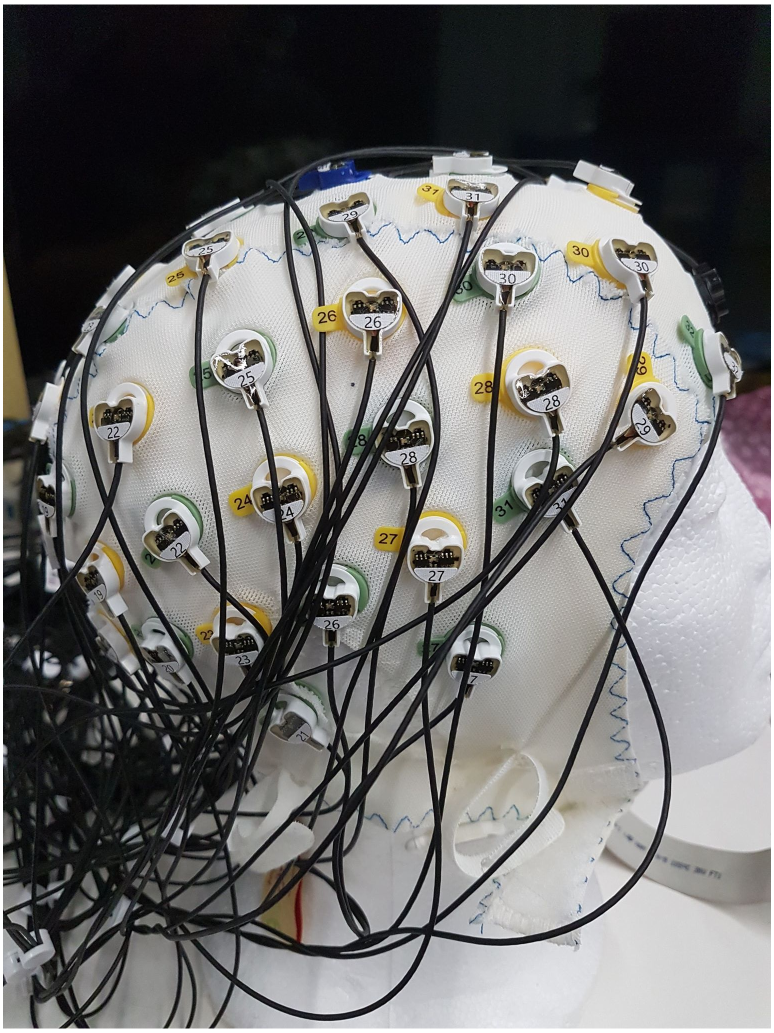

Figure 1.1: The usual setup of a EEG cap.

under different VR sickness levels. The work of Chen et al. [28] compares the changes in different brain regions to the reported changes in VR sickness. The results of Kim et al. [98] tries to compare the changes in the brain signals to the changes in other physiological signals related to VR sickness. These works show how an EEG system is a capable tool to monitor a user's state. This technology can monitor and search for these different events on users interacting with a VR scenario.

This research project will use an EEG device over other physiological recording devices to simplify integrating an EEG device to a VR setup. While other physiological devices will require an additional step of setup and integration to the system, a VR headset with a dry-sensor EEG device seems like a natural step forward for the usual VR setup.

1.2 Background

Current modern VR setups require users to wear a VR HMD. Because the HMD blocks the visual input, users are usually isolated from the real world since the virtual scenario's content replaces their visual feedback. This situation causes inconsistency between the signals from the visual system and the vestibular systems. This signal inconsistency due to the differences in the Virtual Environment and the real-life causes what is called a cognitive conflict [188]. Kennedy et al. [90] reported that this cognitive conflict produced symptoms similar to those from Simulator Sickness and Cybersickness and produced postural instability. Their work showed how participants showed severe postural instability after interacting with a motion simulator. This report is one of the first reports talking about the appearance of the main issues of VR.

Despite the advancement of head-mounted display hardware, many VR users still experience VR sickness symptoms [38, 109]. Among various theories for the cause of VR sickness, two views are the most relevant: the sensory conflict theory and the postural instability theory. The sensory conflict theory has been the most widely accepted theory [89, 109]. The sensory conflict theory argues that the cause of VR sickness is the conflict between sensory input systems engaged in the virtual environment. For example, when experiencing a VR roller coaster in a stationary setup, a sensory conflict arises because the visual system perceives a forward-moving optical flow pattern. In contrast, the vestibular system does not sense a proportional linear or angular motion.

For the postural instability theory, Riccio and Stoffregen [175] first argued that decreased postural stability magnifies cue-conflicts that underlie sickness symptoms. Their work discusses how prolonged exposure to postural unbalance leads a person to suffer from motion sickness. In other works like that of Stoffregen et al. [208], users started to report an increase in the symptoms of motion sickness right after their body showed a rise of postural sway.

To measure the level of sickness in users, researchers use the Simulator Sickness Questionnaire (SSQ). This questionnaire has been the main measurement of VR sickness's severity (and other sickness types). Because the SSQ quantifies the users' symptoms, it provides a secure method to compare different sickness profiles [203]. Since then, various other research projects have developed and used different variations of the SSQ. These different questionnaires try to tackle different types of sickness. The Cybersickness Questionnaire (CSQ) [209] exists to remove those symptoms specific to Motion Sickness and keep those more related to cybersickness. Moreover, Kim et al.

[95] created an improved version of the questionnaire, focusing on users interacting with a VR HMD. Even after developing the different more specific questionnaires and methodologies, the original SSQ stands as the primary tool to measure the different types of sickness.

Using a questionnaire to measure the state of the sickness of a user comes with several drawbacks. Firstly, these questionnaire responses are subject to individual memory bias, sometimes making the users' responses unreliable. Secondly, researchers usually perform the questionnaire at the end of the experiment, making a continuous measure of the sickness level difficult. To detect any symptom's appearance promptly, a measurement that can continuously capture the user's state during an experiment session is needed.

The use of physiological signals came as a response to the different limitations of using questionnaires to measure the state of VR sickness. Usual setups involved asking the SSQ to the user several times during the experiment session and compare the final results vs. recorded changes biosignals [131]. The most popular biosignals used to measure VR sickness include heart rate variability using Electrocardiograms (ECG) [242], gastric myoelectric activity using an Electrogastrogram (EGG) [206], skin temperature changes [141], and brain activity using an EEG [156].

In the past few years, EEG has become a relevant device to measure different types of sickness in users. While most of the standard setup studies record the user's state on a 6-DOF virtual car simulation [28, 29, 98, 131, 156], these studies have set up the foundations for future EEG sickness research projects [96, 111, 117]. Nevertheless, all these setups lack two crucial areas: they do not make the user wear the usual HMD, and users usually are sitting. Even the works that use HMD VR technologies [85] require the user to sit still or move the least possible [222].

While some works have focused on detecting the issue of VR sickness, others have turned their attention to reducing its symptoms. The most popular methodology to achieve symptom mitigation has been the dynamic modification of the field of view of the user [2, 56]. Another popular solution has been galvanic vestibular stimulation [57]. Due to the problem's cognitive conflict origins, other works propose allowing the user to walk to eliminate the conflict that causes VR sickness [145, 220]. Moreover, while techniques such as point and teleport work on eliminating the conflict [17], other techniques like redirected walking reintroduced VR sickness in users [229].

Allowing locomotion on users has introduced a whole new set of hazards to the VR interaction. Worse, users wearing a VR HMD are in danger of accidental collisions with physical objects in the surrounding physical environment. Due to users being unaware of the real world, these types of accidents are common. Mismatches between the real world and virtual world produce behaviors that cause loss of balance, such as colliding into physical objects invisible in the virtual world, leaning the bodyweight onto a virtual object that is non-existent in the real world, or tripping over the cables of the VR system.

The loss of balance in VR is sometimes internally triggered. Previous works have suggested that wearing the VR headset produced a postural sway similar to standing with the eyes closed [32, 74, 176]. Vection [91], which is an illusory sensation of the body's movement induced by specific visual field movement patterns, is another notable example. A loss of balance often occurs when a user attempts to accommodate the illusory self-motion with an overly dramatic physical body motion. Multiple online videos show users who lose their balance and even fall from a chair during a virtual roller coaster experience. Some intense VR experiences, such as virtual plank walking, may cause high levels of anxiety and stress, which hinder a user's capability of maintaining posture stability and may cause a loss of balance or even falls [8, 129].

While some works have proposed different types of exercises for fall prevention and fall recovery [59, 110], other works have focused on detecting postural instability to prevent any falls from the users. A notable work that leads us to understand more about falls and postural instability comes from Slobounov et al. [194]. The authors were able to divide a fall into three stages. The first stage is the pre-falling stage, when the user has control of her balance. The second stage is the transition stage, where the user is suffering from postural instability. The third stage is the falling stage, where the user suffers from a fall.

Different works have studied the transition stage in hopes of being able to detect postural instability promptly. Different techniques like tracking the head movements [90], measurement of the Center of Pressure, and the Center of Gravity [26, 194] or calculating the Center of Mass [71] have been useful on understanding more the state of the user when suffering from postural instability.

Besides using kinematic data and other technologies for fall prevention, there is an active community searching for the different brain signals that can describe the different stages of postural instability and loss of balance. The research presented by Wittenberg et al. [231] summarises the different works done to understand the cortical state of different types of falls at different stages, under different setups.

The most common method to use EEG to study postural stability is to combine it with other physiological signals [231]. The main measurements used in conjunction with

EEG are Center of Pressure (CoP) [196], Center of Mass (CoM) [151], Electromyography (EMG) [133], and a variety of gait parameters like Step Distance [20], or Step Reaction Time [121]. These signals help understand the process that happens in all the stages (pre-falling, transition, and falling stages) of a fall [136, 194]. These signals are also useful to understand how a human being reacts during a period of unbalance [78, 190].

While the loss of balance in VR is not a topic with much attention by the research community, many different research projects have leveraged VR to create postural instability and loss of balance of their participants. However, these projects lack that they are not trying to study loss of balance scenarios similar to what everyday VR users experience.

For example, Horlings et al. [74] tried to measure the body sway produced by a VR headset. In their work, they asked the users to stand and watch a virtual movie, which is not a typical posture for users that watch virtual movies. Chiarovano et al. [32] measured the changes in CoP using a Wii balance board. While this method was proven effective, using this device leaves the user with little to no space to interact. Finally, the work of Peterson et al. [164] utilized the pass-through of the frontal camera of the virtual device to create postural unbalance. They did not use a virtual scenario. These works show how VR is used to study controlled instability and falls, not to study VR-caused falls.

One way to prevent postural instability and loss of balance is to eliminate the mismatch between the physical and the virtual worlds. Bringing physical objects into the virtual environment is a methodology used to achieve this. This technique minimizes the disruption to a subject's senses in different methods. Some researchers refer to this approach as *augmented virtuality*. This approach allows for enhancing VR with parts of the physical world [4, 19, 31]. These results allow the experience to be grounded in the virtual world [30, 166, 174].

While these works try to create a blend between VR and the real world, their primary purpose is not to prevent loss of balance or postural instability in users. Worse, these setups do not take into account mobile setups, where the user's environment is continually changing and will require a constant change in the content around users. To help in the problem of postural unbalance in VR reality, a method that aids either regain posture or be better prepared for a fall is needed to aid users.

1.3 VR safety issues and its implications

Different types of sicknesses have been a subject of different studies throughout the years. From its origins when this issue appeared in simulator training for pilots [127], to recent studies focused on the average VR consumer [95]. Even though reports show that the effects are merely symptomatic [38, 45, 228], around half of users that suffer from one of these symptoms loose interest in the technology [202]. Several previous works have discussed how repeated exposure to VR sickness can improve the user's resistance to the issue [144, 145, 220]. Still, just one incidence of these symptoms is enough to keep participants from trying VR again.

Since identifying the issue, many measurements, identification methods, and solutions to the issue have surfaced. Different types of questionnaires [15, 89, 173, 209] have surfaced to measure the issue. Moreover, while they effectively measure the different symptoms of the issue, they are not something the end-user can use in their VR sessions. The use of different types of biosignals to detect the issue [27, 28, 131] in combination with different types of algorithms [85] can help solve this problem. Never the less, there is still a disconnect between the work done to detect the issue and the different solutions available that mitigate the problem [56, 77, 204].

Postural instability follows a similar status as VR sickness. While repeated exposure to a fall has shown to improve the overall fall recovery ability of users [150]. Suffering a fall can lead to hazardous or even fatal accidents. There have been studies that intend to help people (especially older adults) to practice better react to falls [58]. However, requiring fall practice to potential new VR users would obstruct even more potential users from adopting the technology.

What makes the issue worse is the disconnect between the gait, balance, and posture community and the VR community. Postural instability has been studied in the VR community since it started to become a mainstream technology [50, 51, 201, 207]. Furthermore, the gait, balance, and posture community have provided a long list of measurement and detection methods for different types of postural unbalance [39, 71, 231]. While detection of postural instability is possible, there is not a proper mechanism or a line of research that studies how the VR system can help the end-user to avoid a fall or recover from one.

Current numbers show how there are 9 million active VR users. While this number of users shows how many people are in danger of potentially suffering from an accident in VR, they are not the only stakeholders in danger. The increase in popularity of this technology increased its use for different purposes than just entertainment. One critical example of this is the rehabilitation community [62, 192, 231]. They require their patients to do specific movements or interact meticulously with their virtual scenarios to ensure maximum recovery. For patients suffering from any unsafe event during their session, their recovery might suffer to the point where it gets delayed or even worsened.

1.4 Research Stakeholders

In this thesis's context, the term stakeholders will refer to the group of people that can benefit from the results of this research project. This group consists mainly of the VR community, which itself is composed of 4 different subgroups. The first group is the VR consumers, or the *VR users*. Each of the 9 million active VR users makes up this group.

The second group is the VR content producers or *VR developers*. Developers and companies that develop VR experiences make up this group. Usually, *VR developers* get to follow development guidelines (such as the Oculus Submission Guidelines) if they want their app published in the different available VR stores. While these standards attempt to prevent any accident happening to VR users, following them does guarantee the avoidance of these issues. Providing an API or SDK that allows developers to access the user's state can provide *VR Developers* with enough tools to come up with new creative ways to mitigate or prevent these issues.

The third group consists of the VR hardware developers or *VR manufacturers*. Companies such as Oculus, HTC, or Valve are companies that profit from developing VR hardware. All consumer-available devices already provide some security system that leverages their tracking system to avoid collisions with external objects. Providing *VR manufacturers* with a new methodology to avoid more issues can help them provide a safer product for the average consumer.

The final group of stakeholders consists of the *VR researchers*. These groups of people use VR technologies to push forward their area of research. Some examples of this type of research are different types of rehabilitation [62], phobia treatment [60], learning applications in VR [171], data visualization [23], among others. Some of these research groups face considerable setbacks when their participants suffer from VR sickness or postural instability during their experiments. Providing a way to ensure VR users will not suffer from any issue can help *VR researchers* to accomplish their goals more efficiently.

1.5 Research Aims and Objectives

This research project's primary goal is to provide a safer VR experience to anyone interested in VR technology. This project consists of two research aims. These aims focus on helping the VR community obtain safer VR experiences. This project also consists of several research objectives. These objectives will set the path that fulfills the aims that will benefit the research stakeholders.

The current research state has identified specific cortical state for users suffering from both VR sickness and postural instability in different static scenarios. Furthermore, on the VR sickness side, several proven techniques can mitigate or decrease the feeling of sickness on users [2, 163]. Nevertheless, there is no clear definition of techniques that could help mitigate a fall when detected. The first part of the research will focus on finding which techniques are useful so that a VR device can help the user recover from a fall. Testing those techniques against each other will help to understand which technique is more useful for the user.

On mobile VR scenarios, it is unsure if the VR sickness cortical signals will be the same compared to those previously recorded on static scenarios. While there are already works that look at postural instability on mobile VR setups [164, 165], it is unclear how much VR sickness will affect these signals if both these issues appear simultaneously. The second part of this research project will try to fill that gap.

Given the current state of VR, the first aim is to *provide a safer VR interaction to VR users*. VR sickness and loss of balance in VR are the two main issues affecting VR consumers. Being able to detect them and mitigate them will surely provide a safer VR interaction environment. The second research aim of this project is to *propose a system capable of continually monitoring the user's state during their interaction with a VR scenario*. The system should monitor the state of the user continuously and modify the content if necessary.

The first research objective will help achieve the first aim. This first objective will focus on **using the VR system to help users that suffer from postural instability and fall to recover from the fall**. This objective is to help users recover from a fall suffered during interaction with a VR headset. This objective intends to propose a method that, similar to reducing FOV for VR sickness, can be implemented in any VR device.

The second objective is to **understand the cortical state of VR sickness and postural instability in mobile VR setups.** By analyzing EEG and kinematic data of users suffering from VR sickness under a mobile setup, this objective intends to understand more about these problems on VR users. These results intend to help both aims 1 and 2. Understanding more about this issue can lead to provide a safer VR environment (Aim 1). The results from this research objective can contribute to the monitoring system proposed for Aim 2.

The final research objective intends to **propose a system capable of monitoring the user state during an interaction with VR**. This system should monitor, detect any issue with the VR experience, and react to the problem. This objective intends to be continually monitoring the user in search of the cortical signals that represent both VR sickness and postural instability and modify the content in VR to mitigate these issues. This research objective will address both aims.

1.6 Research Significance

Aim 1 intends to benefit all stakeholders. In the case of *VR users*, the appearance of postural imbalance or VR sickness prevents them from trying these experiences again, or new users to even try it for the first time. Providing a safer experience can help current users enjoy longer VR experiences while helping new VR users adapt faster to these systems. The same type of benefits applies for *VR researchers*, a safety system for VR will allow them to prolong their VR sessions or provide safer rehabilitation sessions in case of rehabilitation. *VR developers* and *VR manufacturers* can benefit from an increase in the adoption of the technology. This increase in adoption can lead to an increase in their income.

Aim 2 intends to benefit *VR users*, *developers* and *researchers*. A system that is constantly monitoring the user's state can be beneficial for *VR developers*. Having access to the user's state could help developers improve the user experience, adapting the content based on the user status. *VR researchers*, on the other hand, can benefit from the physiological signal recording to introduce new paradigms for research. A system the easily implements a BCI into the VR experience can help improve gait research[164, 165], psychological research [60], or other types of research that use VR as a tool. Finally, the *VR user* will be the most benefited of all the stakeholders. In the end, this improvement will help to provide them a better, more enjoyable VR experience.

Based on the current state of research, Figure 1.2 shows the first two research objectives' contributions. The first research objective tries to find a method to help users suffering from postural instability while interacting with their VR scenario. Because this methodology intends to improve the user's security if she is in danger of suffering a fall,

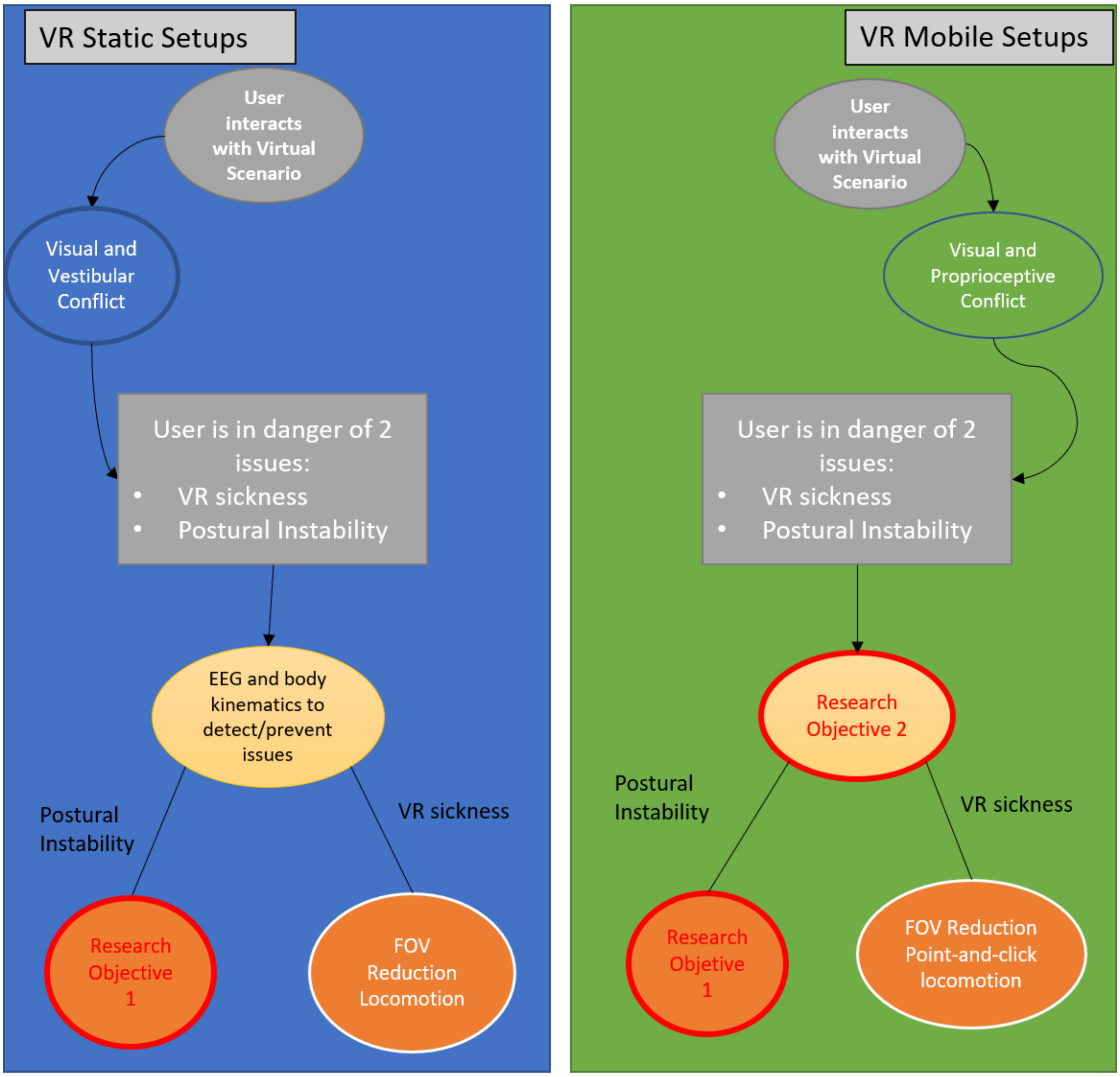

Figure 1.2: The current state of research in safety for VR users in both static and mobile setups and the research gaps that this research project will address to provide a safer VR interaction.

this objective focuses on Aim 1.

The second research objective Intends to help users interacting with mobile setups. Figure 1.2 shows how for static setups, there are already methodologies to promptly detect postural instability and VR sickness with the help of EEG devices and body kinematics. RO2 intends to do something similar, but for mobile VR setups. Because this objective tries to find the issues of users, use an EEG headset to build a BCI method and could be part of a monitoring system, this objective focuses on Aims 1 and 2.

The final research objective that intends to propose a system capable of following

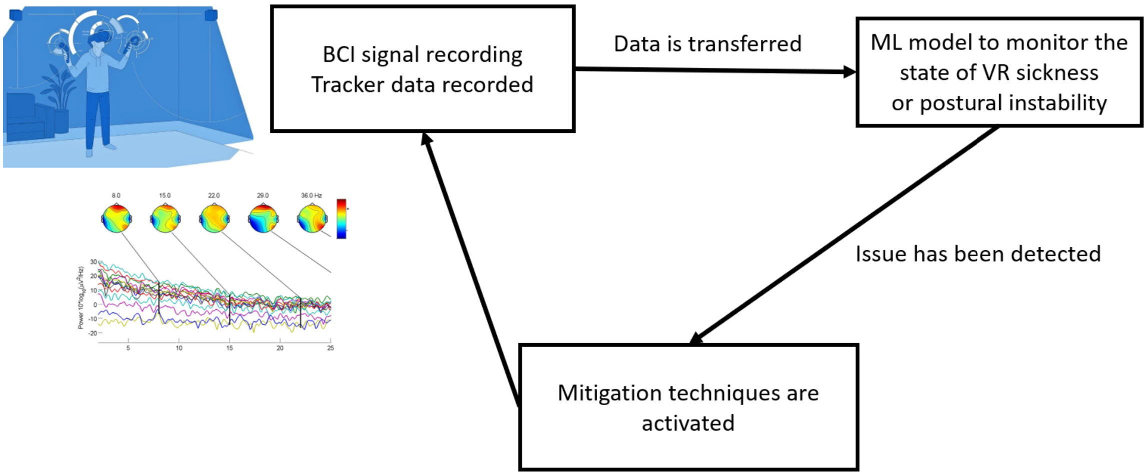

Figure 1.3: Graphical representation of the end goal of Research Objective 3.

the steps on Figure 1.2. This system should be capable of monitoring the user while interacting with the VR scenario (Aim 2). The system should detect the cortical changes that represent VR sickness and postural instability through the use of a BCI headset. If any of these issues are detected, the system should be able to react to improve the user's safety (Aim 1). Figure 1.3 shows the optimal functionality of this system.

1.7 Approach

The methodology of this project will follow a combination of Qualitative and Quantitative Methods. This project will implement EEG brain signals and kinematic behavior signals such as Center of Mass (CoM), Stepping Distance, and Time to Complete Trials for the quantitative methods. For Qualitative measurements, this project will use the Simulator Sickness Questionnaire (SSQ) [203], and informal questionnaires and interviews about each user's experience.

Electroencephalography Signals (or EEG signals) are signals produced by the different connections our neurons make. When compared to other behavior measurements, these signals allow us to understand the cognitive state of different groups of people [36]. This research project will use EEG signals to measure posture instability and VR sickness. The users of this research project will get their EEG signals monitored while they experience different types of virtual scenarios. Previous work already identified different brain regions related to postural instability [196] and related to VR sickness [29]. This project will focus on monitoring those brain regions to find any differences in similarities to previous work.

The most significant risk of this methodology is the quality of data and possible loss of data. For the experiments of this research project, users will have to wear currently commercially available VR headsets, which are not yet compatible with various EEG and BCI systems. For that reason, the combination of these two devices might at first be uncomfortable for the users, leading them into scratching or moving the devices, tampering with the EEG information. Other risks from this measurement are the loss of data due to device malfunction. These devices rely heavily on Bluetooth connections to transmit data. Because this technology is such an unreliable technology, there will be instances where there will be some data loss.

After a data recording session, the first small step towards success is that the data's quality is good. Once the data quality is proven, another step towards success is seeing changes in the different brain regions and frequencies related to the issues in this project.

In this research project, Kinematic Behaviour data describes all the data produced by movement in the human body. A critical example of this type of measurement is the Center of Mass (CoM). The CoM's location is usually calculated based on the human skeleton's bones, and it is usually used to evaluate postural control of a person [107]. Another important kinematic measurement used in this research project is Step Distance and Step Strategy. After a human body reacts to a strong postural unbalance, the first instinct will be to use a reactive step to prevent the body from losing balance. The number of steps and distance between each step is reliable measurements to understand how well or how bad the user is reacting to postural unbalances.

The most significant risk to this methodology is recording faulty data. Because these recordings require complex camera systems, any malfunction on the system can produce erroneous data that can cause the entire data set's discarding. Because the users have to wear different markers around their bodies, issues like them accidentally moving the markers from their place might also end up with incorrect data.

The successful application of these methodologies will help this project in categorizing its users. Different variances in the CoM might help in categorizing how strong the unbalance is on each user. The stepping strategy might also help categorize users into three different groups and see the differences between each group.

The Simulator Sickness Questionnaire (or SSQ) is a questionnaire of different symptoms and quantifies simulator sickness after a user interacts with a scenario. The questionnaire is generally applied after a user finishes interacting with a virtual simulation and asks users to quantify their feeling of a particular set of symptoms. These values undergo a final calculation that produces a final score representing the experience. The questionnaire's scores are then compared against other scores to measure how good or bad the experience was.

The most significant risk of this measurement is the individual bias of the user. If they cannot express their personal feelings or do not answer the questionnaire truthfully, there is a significant risk of working with incorrect data about their status. These incorrect data sets could lead to an incorrect interpretation of the other measurements.

Successful collection of SSQ questionnaire data can help to have a decent idea of the user's status during the simulation. Accurately knowing the status of the user is key to this research project. Comparing these data points and others, i.e., EEG, will be the foundation of understanding VR sickness on participants.

This research project will also use informal, self-developed, open-ended questionnaires at the end of each experiment. The reasoning behind each of the questionnaires is to motivate the participants to think aloud about their experience interacting with this project's VR scenarios.

The most significant risk of these questionnaires is having participants being dishonest during the interview. If the participants are not completely honest during the interviews, the conclusions this research projects draw will be inaccurate.

Successful questionnaire interviews will show a relationship between the user's responses and their behavior during the experiment. Because the questions will be oriented to understand their behavior, if there is a coherent relationship between the responses and their behavior, the questionnaire answers will be considered valid.

1.8 Major Findings

This thesis's significant findings include the proposal to use auditory aids and the VR headset's frontal camera as recovery techniques for the loss of balance in VR. These techniques were tested by simulating a loss of balance on a static VR setup. This experiment showed how these techniques work before the onset of the fall.

On mobile setups, a visual-proprioceptive conflict was introduced to users using redirected walking. The results showed that people who suffered from VR sickness during the experiment also suffered from more significant postural instability than those who did not suffer from it.

From mobile setups, another group of findings comes from the participant's cortical activity. Results concluded how the visual-proprioceptive conflict was strong enough that the lower frequencies (delta, theta) seemed to be affected by it. Results showed how decreased delta frequency could indicate an increase in the VR sickness symptoms in mobile VR users. The cortical activity of postural instability appeared in different cortical state changes, such as the decrease in the power of the alpha, beta, and gamma frequencies.

These results can help design and develop a closed-loop biofeedback system. This system can have different inputs such as the EEG and kinematic signals and user preferences for system intervention. The output that the system offers could vary depending on the type of issue detected. It could be an activation of the video-see-through camera or an auditory warning in postural instability. Alternatively, it could reduce the user's field of view for motion sickness problems.

1.9 Structure of this Dissertation

Chapter 2 starts with a comprehensive literature review about the problems of VR sickness, postural instability, how to detect them, and what works have tried to find solutions to these problems.

Next, Chapter 3 of this thesis will explain the different experiment designs used for this research project. This chapter will explain the experiment design and explain in depth the software and hardware used for this project and the decision behind choosing these technologies. This chapter will also describe the different processes for data analysis used for this project.

Chapter 4 will focus on the results of the static VR experiment. The results of the mobile VR experiment appear in two chapters. Chapter 5 will focus on behavioral results from the experiment, while Chapter 6 will focus on the cortical results of the experiment. All chapters contain a discussion section that explains how the results from the experiments fit this research project's objectives.

To conclude this thesis, Chapter 7 will describe a closed-loop design, explaining how the acquired results fit into a possible closed-loop system. This chapter will also discuss the limitations of each of the experiments and their results. Finally, this chapter will provide some concluding statements of this thesis and several future works. Hopefully, the discussion of future work will motivate the reader further to study the line of research on VR safety.

CHAPTER 2

LITERATURE REVIEW: THE SAFETY ISSUES OF VR

2.1 Virtual Reality

As defined by Berntsen et al. [14], Virtual Reality is the combination of software and hardware to create 3D interactive worlds. The user then interacts and manipulates these worlds through different input devices and techniques. Some of the first VR systems involved a configuration of 2D screens to feel immersed in the virtual environments. These systems are called cave systems and require a room filled with different screens to create a virtual environment. This type of cave system was the most common VR configuration [44] before introducing the Head-Mounted Displays (or HMD). Low-cost HMD devices' introduction increased this technology's reachability and made VR easily accessible to the mainstream consumer market.

2.1.1 VR applications

The introduction of VR to the mainstream consumer market created a significant impact in many areas of VR. Other than entertainment, VR disrupted into different fields. Science and Education, Physical Training, Social and Cultural Experiences, Moral Behaviors, and Traveling and Teleconferencing are major groups where VR has made a significant impact, according to Slater & Sanchez-Vives [192].

Researchers and developers have worked in different ways to improve the VR experience in different VR areas. These ways include user input [118, 137], humans-virtual agent interaction [67], knowledge acquisition in VR [105, 168]. Others are trying to differentiate behavior from regular gaming sessions to that in VR [214]. When the newest advances in VR tracking became available, other works focused on improving the VR walking experience [145]. Overall, these works have been working towards the same goal: improving the VR experience by improving users' overall sense of immersion.

2.1.2 The importance of Immersion in VR

Improving the sense of immersion of VR users became an important area of research in recent years. The sense of "self" inside VR is the most common definition of sense of immersion. It is feeling "inside" a body and feeling that the body is "ours" [94]. Different projects worked with these ideas to understand the sense of self in VR and improve the immersive experience.

Besides using questionnaires to measure immersion [14, 94, 192, 226], some works tried to measure body ownership based on human behavior inside a VE [9, 63, 102, 160, 169, 191]. Other works correlated the results from immersion questionnaires with physiological signals to measure the sense of immersion with the user's physiological state [84, 237]. These physiological signals included eye-tracking [84], brain signals [63], heart rate variability [131] among others.

While testing for immersion in users, Weech et al. [226] found that a decrease in the sense of immersion of users leads to them suffering from unpleasant symptoms like nausea, discomfort, or fatigue. The less the immersion perceived by the users, the more the intensity of these symptoms. These results showed how critical the sense of immersion is for the user, not only in the aspects of enjoyability but also in user safety. Other projects realized that changes in the user's immersion lead to cognitive conflicts between different users' input systems, leading them to suffer from different issues during their VR interaction [186–189].

2.2 Cognitive Conflicts in VR

As humans, we are used to the certainty that whatever event our eyes are witnessing and whatever object we can see occupies a physical space. After introducing VR, this technology created a new paradigm in our lives: what we see may not be what is happening. A sensory conflict happens when there is a "conflict" between our sensory inputs [189]. Due to the nature of VR, people wearing VR headsets are at risk of suffering them [109]. An example of such conflict is when a user tries to interact with a virtual object, and the given object behaves differently than expected [188]. The consequences of such conflict can be as minor as a decrease in performance on specific tasks [187], but other conflicts have shown to have more dangerous consequences.

The most notable conflict suffered by VR users happens between the visual and proprioceptive systems [91]. This conflict derives from users visualizing movement while they remained static in their position. An example of this conflict appeared when users had to traverse VEs using game controllers, joysticks, or mouse and keyboard [143]. The appearance of this conflict can create several hazards for VR users that put them in danger during their VR interaction.

2.2.1 Dangers of Cognitive Conflicts

Previous reports show how a cognitive conflict between the visual and vestibular systems cause VR sickness in users [89, 106, 109]. The issue of VR sickness is dangerous for the well-being of VR users [202]. Even if repeated exposure to this conflict minimizes the appearance of VR sickness [144, 145, 220], the fact that these symptoms can persist for up to three hours after interacting with a virtual environment [203] has prevented some users from coming back to or even trying, these technologies.

The appearance of Vection, a consequence of a cognitive conflict between the visual and vestibular systems, has been reported to produce not only VR sickness but also postural instability that can later lead to falls [91]. This conflict causes an illusory sensation of the body's movement induced by specific visual field movement patterns. Loss of balance often occurs when a user attempts to accommodate the illusory self-motion with dramatic physical body motion. Multiple online videos show users who lose their balance and even fall from a chair during a virtual roller coaster experience. Some intense VR experiences, such as virtual plank walking, may cause high levels of anxiety and stress, which hinder a user's capability of maintaining posture stability and may cause a postural unbalance or even falls [8, 129].

2.2.2 VR Locomotion: A solution to the cognitive conflict

One of the most prominent solutions to the visual-vestibular conflict is locomotion in VR. VR locomotion consists of either allowing users to move physically within the limited space of the VR setup or implementing different redirection techniques to simulate movement within the limited space. Walking in virtual environments naturally provides a superior VR experience by making it feel closer to a real-life activity. While this type of locomotion provides a better user experience by removing the visual-vestibular conflict [70, 83, 145], VR systems have a significant disadvantage when allowing users to walk naturally: the size of the traversable area.

Many research works have come up with different VR locomotion techniques to overcome the space problem. Nilsson et al. [145] categorized these techniques into three classes: repositioning, proxy gestures, and redirection techniques. Repositioning techniques leverage different treadmill systems [80, 213] to offset the user's forward movement and keep the user in the same position. Proxy gestures, on the other hand, are techniques that drive movements in the virtual environment through proxy gestures resembling real walking, such as upper arm-waving [128, 143], head tilt [217], and walk-in-place [193, 218]. All these methods improve the user experience and eliminate the visual-vestibular conflict [125].

The third group of techniques is called redirection techniques. They allow users to walk inside a VE physically [145]. These techniques manipulate the user's actual walking path in the real world, without being perceived by the user, to exploit the limited physical space. The path manipulation of these techniques is achieved by dynamically scaling user motion [205, 229], or updating the virtual environment [13, 61, 185, 210, 212]. An issue with these techniques is that the manipulation of user movement introduces another type of conflict: a visual-proprioceptive conflict [229]. Previous works talk on how this conflict causes postural adjustment issues in their users [123, 164], and following the conflict theory [89, 106, 109], it may also cause VR sickness.

2.2.3 Other Popular Solutions to Cognitive Conflict Issues

Besides locomotion, many other research projects have proposed different methodologies and techniques to eliminate any potential cognitive conflict that VR users might suffer. The work of Ng et al. [142] showed how the visual-vestibular synchronization using external movements significantly reduced the level of the conflict, increasing the user's enjoyment of the environment. Other works have tried the approach of *augmented virtuality* to solve the issue. These works attempt to blend the virtual environment with the real world, enhancing the virtual environment with different real-world elements [19, 166, 174]. Some relevant projects in this space are those that provide different types of haptic feedback to their users. This type of feedback has decreased the different conflicts the user suffers, increasing the sense of immersion [4, 30, 31].

2.2.4 Cognitive Conflict Implications

VR users will be in constant interaction with different cognitive conflicts during their interactions with VR systems. While some of them are not even noticeable by users [186–188], others provide hazardous reactions from the users like VR sickness and loss of balance. Even if repeated exposure to these conflicts might train some users to adapt to them, users who cannot adapt are in danger of suffering either VR sickness or postural instability. If cognitive conflicts are inevitable, it is essential to understand and solve the hazardous outcomes of suffering these conflicts to provide a safer experience for VR users.

Note that this research project's primary purpose is not to find a solution to the different cognitive conflicts that VR users suffer. As stated before, these conflicts' constant repetition will train VR users to handle the conflict better. This research project intends to provide aid to better deal with some of the consequences of these conflicts. By dealing with these issues, VR users can enjoy returning to this technology. If the user is continuously in contact with VR, these symptoms will decrease until they stop appearing.

2.3 VR Sickness

Despite the advancements of VR devices, the issue of VR sickness is still prevalent among VR users. The most common symptoms are similar to those of motion sickness, such as headaches, nausea, vomiting, drowsiness, and disorientation [38, 45, 109, 159, 228]. This issue worsens with reports stating that VR sickness can be three times more severe with different symptom profiles than in regular motion sickness [203].

2.3.1 Causes of VR Sickness

Many theories explore the causes of VR sickness [109]. Based on the research by Rebenitsch and Owen [173], the theories of what causes VR sickness fall into three categories: sensory conflict theory, postural instability theory, or issues with the VR setup.

- **Sensory Conflict Theory**. This is the most widely accepted VR sickness theory [89, 106, 109]. It suggests that VR sickness arises when the user perceives inconsistent inputs among different sensory systems, such as visual and vestibular systems. La Viola [109] explains how the inability of the human body to process the conflict between systems is what causes it to suffer from different sickness symptoms.

- **Postural Instability Theory**. This is the second most widely accepted theory for VR sickness. The early work of Riccio and Stoffregen [175] has suggested that postural instability is the cause of the symptoms of motion sickness. The authors stated that prolonged exposure to postural instability causes motion sickness. Later, Smart et al. [201] found that producing postural instability in users leads them to suffer Vection [206], which leads to the start of VR sickness symptoms. Since then, many different works have discussed and tested this theory in different ways [27, 103, 104, 140, 208].
- **Device Malfunction**. Other proven reasons for VR sickness are malfunctions with the VR scenario or the VR hardware. One example of issues caused by the VR headset is flicker. La Viola [109] reported that this malfunction was one of the leading causes of VR sickness symptoms on users. Other works concluded that delay in image rendering causes VR sickness [47, 138]. Jitter produced by the VR headset is another common cause of VR sickness[204]. Other reports studied the length of the VR session [219] or the level of immersion [226] as influences in the intensity of VR sickness symptoms.

While one of the primary purposes of this research project is to study VR sickness's appearance, it is not under the scope of this project to identify which VR sickness theory is the most accurate. At most, the sensory conflict theory will be used to elicit VR sickness. However, it will not be compared to the other theories to measure which theory produces the most VR sickness cases.

Previous works showed how there is an ability to identify the different symptoms of VR sickness. Nevertheless, it is essential to complement this knowledge with methodologies to quantify the levels of VR sickness. Some measurement is needed to be able to compare the symptoms appearing in different users. We need to understand which types of users are affected more by these symptoms and why.

2.3.2 VR Sickness Measurement And Detection

The Simulator Sickness Questionnaire (or SSQ) is a standard tool to record the perceived level of simulator sickness [89, 203]. However, the questionnaire responses are subject to individual memory bias, and the questionnaire session usually happens at the end of the experiment. It cannot continuously capture the change of sickness level throughout the experiment. Previous works have discussed how VR sickness symptoms differ in intensity to Simulator Sickness or Motion Sickness [38, 203]. This difference in the symptom profile has lead other works to develop different measurements to quantify VR sickness [95, 183, 209]. Some works even suggested applying an SSQ at a specific rate during a session [98, 156, 181] as a useful solution. However, the VR session needs to stop and can only continue after the user successfully answers the questionnaire.

Many previous works explored using physiological and neurophysiological signals acquired from wearables as an objective and continuous measurement to detect and predict VR sickness. Results from this methodology have shown how a simulated roller coaster can increase finger temperature and create prolonged reaction times on participants [141]. Vection [206] induced an increase of gastric myoelectric activity. The low-frequency band of heart rate variability (HRV) gradually increased during the development of cybersickness [141, 149]. Kim et al. [98], and Dennison et al. [45] employed a polygraph to associated a range of physiological signals with different levels of cybersickness. These methods are useful in accurately measuring VR sickness.

Electroencephalogram (EEG) is a promising emerging technology for the detection of VR sickness. Several studies have tried to identify which brain region-frequency pair gets activated when a user is suffering from VR sickness. For example, Kim et al. [98] reported an increase in Delta power related to the increase in sickness reported. Alternatively, other works like that of Chen et al. [29], focused on identifying which brain regions get activated when a person suffers from VR sickness, reporting that the Alpha rhythm in Parieto-Occipital areas of the brain should increase when the user reports an increase in VR sickness.

Table 2.1 presents a summary of results from different relevant works in the area of EEG and VR sickness. Table 2.1's last column explains the relationship between the changes in the signal and the sickness reported by users in the experiments. A positive relationship means an increase in power of the signals as the level of VR sickness increased. In contrast, a negative relationship means a decrease in power as the level of reported sickness increases.

Table 2.1 shows that most previous works focused on using driving simulators. Participants had to be in a sitting position during the duration of the simulation. Even with the introduction of modern VR headsets, projects still look at sitting driving setups to measure VR sickness in users [222]. This project focuses on use-cases where the user has to be actively moving and walking and wearing a consumer-available VR headset. This project tries to understand whether the VR sickness signals from static setups will translate to more mobile, interactive setups.

Author, year	**Experiment Setup**	**Spatial Location**	**Relationship**
Min et al. 2004 [131]	Projector-based driving simulator	Fz and Cz channels	δ Positive θ, α, β Negative
Lin et al. 2007 [113]	6-DOF driving simulator	Parietal	β Positive
Park et al. 2008 [156]	2 Screen driving simulator	Fz and Cz channels	δ Positive θ, α, β Negative
Chen et al. 2010 [28]	6-DOF driving simulator	Left Motor	θ, α, β Positive
		Parietal	θ, α Positive β Negative
		Right Motor	$\delta, \theta, \alpha, \beta$ Positive
		Occipital	δ, θ, α Positive
		Occipital Midline	$\delta, \theta, \alpha, \beta$ Positive
Kim et al. 2019 [97]	Smartphone-based VR with a video	Occipital	α Positive

Table 2.1: Different relevant EEG-based works that studied VR sickness. This table shows what type of experiment setup induced VR sickness, what brain regions and frequencies were studied, and the relationship between the signals and the reported VR sickness. δ stands for the delta frequency. θ stands for the theta frequency. α stands for the alpha frequency. β stands for the beta frequency. γ stands for the gamma frequency.

2.3.3 Mitigation Methods for VR sickness

The research community has long been aware of VR sickness [38, 53, 173], and has proposed a stream of creative methods to reduce the sickness symptoms [2, 5, 17, 56, 154, 163, 211, 218]. Applying blurring [158] and vignetting [56] in peripheral vision, which has high motion sensitivity, to reduce the perceived visual motion has been an exciting approach. Dynamically modifying the field of view of the user [2, 56] or applying vibratory feedback to the VR headset [163] have shown a reduction of VR sickness by reducing the level of conflict perceived by the user.

Other techniques include Galvanic Vestibular Stimulation (GVS), which applies an electrical current to stimulate vestibular afferent nerves and recouple visual and vestibular cue [24, 57]. Notably, most of these previous works focused on stationary VR setups. The users usually remained relatively stationary on a seat where visual motion patterns on 2D displays or head-mounted displays created sensory conflicts.

While allowing users to move physically reduces the visual and vestibular conflict, the virtual movement generated a conflict between the visual and vestibular systems. The simplest way of tackling this issue was allowing users to use the point and teleport locomotion technique to traverse large virtual spaces [17]. Other more creative options involved redirecting users during eye saccades [211] to redirect users and avoid any conflict caused by redirection techniques.

Previous works showed different solutions to solve the VR sickness issue when it appears on static and non-static setups. However, these techniques still lack a detection method to trigger these solutions. Combining one of the different methodologies for VR sickness detection with one of these methodologies could provide a safe solution for VR sickness in VR scenarios.

2.4 Postural Instability in Virtual Reality

Different studies have tried to understand more about why VR users suffer from postural instability. Different works have shown how a combination between the type of interaction and the user focus [51], or the field of view of the users [50] heavily influenced the level of instability of VR users. These results correlate with other studies that mention how an increased complexity of the virtual environment increases the postural instability of VR users [207]. These works described different research projects from the VR community that did some useful work to understand postural instability in VR. However, some other research communities have an overlap of research topics that could help understand more about postural instability in VR.

2.4.1 Using VR to Study Postural Instability

The areas of gait, balance, neuroscience, and medical rehabilitation communities also have a long track of research on fall prevention, prediction, and recovery combined with VR technologies. These areas try to understand how the body behaves when it is suffering from postural unbalance. Therefore, there has been a significant overlap of studies between these communities and the VR community. Thanks to these communities' studies, more and more information about how the body reacts to postural instability have become available, allowing our community to understand more about postural instability in VR.

These communities have used different VR technologies to simulate fall scenarios. These VR technologies can go from the now consumer-available HMD displays [176] to other configurations like cave systems [198], projector-based VR [200, 215], 2D screen-based [132], or even the development of an ad-hoc VR system [74].

These works leverage the cognitive conflict produced by interacting with a VR scenario to induce postural unbalance (and sometimes even falls) on their users. These scenarios are very controlled scenarios, where the user usually starts from a standing position and is asked to move as little as possible [135]. In these works, the combination of scenario and user posture is not a realistic combination of how falls happen from VR users [74]. These works focus on studying the body reactions to fall, not how VR induces falls in users.

When a user interacts with a VR scenario, the HMD blocks her sight. This lack of visual input prevents users from being aware of their posture, making it easier for them to lose balance or even suffer from a fall [152]. Robert et al. [176] tested to what extent an HMD introduces postural instability on users. Their results showed that merely standing does not introduce any changes to instability. However, after asking the user to perform specific simple tasks like reaching or sitting, users' instability started to increase.

Worse are scenarios that involve some level of walking. These setups have a higher chance of inducing postural unbalance than their static counterparts [164]. The next section will discuss the characteristics of postural instability in VR, the measurement of postural instability, and the role of users' visual input in posture.

2.4.2 Measuring the Different Stages of Postural Instability in VR

Different body kinematics can help measure the level of imbalance that a human body is suffering. Very early works [34, 230] stated that changes in the Center of Mass (CoM), Center of Pressure (CoP), and Center of Gravity (CoG) reflect the level of instability that the user is suffering. Later works translated these results to be usable in modern motion capture technologies to be used in modern postural unbalance studies [75, 107].

After establishing methodologies to measure postural instability, many works focused on studying the type of changes leading to postural instability [71, 73, 93, 151, 194]. All

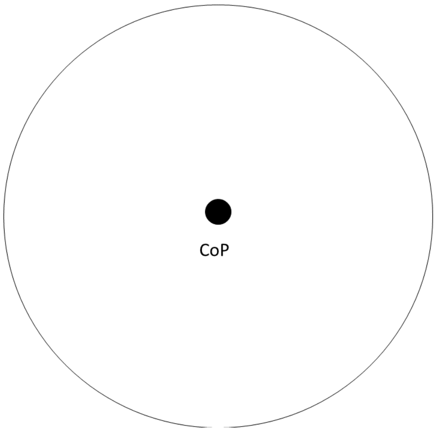

Figure 2.1: Simplistic representation of the relationship between the Boundary of Stability and the Center of Pressure.

these works established that a person has a boundary of stability, an imaginary circle around the user. The location of the center of this boundary is where the CoP would is when the user is standing straight [92].

Figure 2.1 shows a simplistic representation of the boundary of stability (black-lined circle) and the CoP (black dot in the center). When the CoP moves towards the boundary of stability, the user suffers from postural unbalance. Furthermore, when the CoP crosses the boundary of stability, the user will inevitably suffer from a fall.

Based on the boundary of stability methodology, Slobounov et al. [194] divided the falls into three stages: The first stage is the pre-falling stage when the user has no changes to her posture. The second stage is the transition-to-fall stage. In this stage, the user is suffering from postural instability and has a risk of suffering from a fall. The last stage, the falling stage, happens when the user cannot maintain balance and suffers a fall.

The use of CoP and CoM helped several projects understand postural instability on VR setups. One example is Chardonnet et al. [27], which observed the changes of CoP before and after interacting with VR and found how post-VR CoG movements were different from pre-VR movements. However, the mainline of work focused on studying the changes of these measurements during interaction with VR [32, 74, 152, 176]. The overall conclusion was that a user wearing a VR headset suffers from the same level of postural instability as a person standing with their eyes closed [32, 74]. Moreover, the instability level will undoubtedly increase due to the complexity of the task or the virtual environment's virtual movements.

This research project will focus on using the changes in CoM to measure the level of postural instability on VR users. Because CoP requires complex pressure boards that limit the user's mobility [32], it is hard to imagine the average VR user to purchase these boards to measure for postural instability. However, technologies like the HTC Vive trackers can accurately record CoM and are more accessible for the average VR consumer.

2.4.3 Fall Recovery

Another line of research in the community of Balance and Posture is understanding how people react after they suffer a fall [10, 20, 21, 64, 120, 121]. After the postural instability reaches a level where the user will suffer from a fall, several measurements can be studied to understand the user's status before the fall.

Fall recovery techniques should help the user mitigate any potential harm caused by a fall if the loss of balance is inevitable. The research area of fall recovery aims to understand the relationship between postural control and attentional demands and how to react after a person fails to control their posture and loses balance [232]. Researchers have developed different paradigms to induce loss of balance for subjects in a lab setup. Each setup intends to emulate a real-life loss of balance.

2.4.3.1 Fall Recovery Paradigms

Conventional paradigms involve a single leg stand [78, 194], artificial slipping tiles [233], changing the level of stability of the walking surface [78], and a tether-release protocol [20, 21]. These systems induce loss of balance so that researchers can measure the different responses to these systems and label how "well" or how "dangerous" is the response to each of the different types of falls. These paradigms, applied to VR, can be useful to measure how dangerous a fall can be while interacting with a VR scenario.

One of the most popular protocols to study loss of balance is the lean-and-release protocol for controlled falls in users [20, 48, 76]. The lean-and-release protocol for controlled falls provided a leap in understanding the variables around recovery steps used by users. Hsiao-Wecksler [76] found that the step length is not the only variable to study, but the reaction time after the fall is also helping to understand the readiness for the fall [76].

Out of the previously described loss of balance paradigms, lean-and-release is the one closest to a fall induced by interacting with a VR scenario. Many internet videos display forward loss of balance as the most common fall by VR users (for example, see this video).

Figure 2.2: Model of a single step reaction.

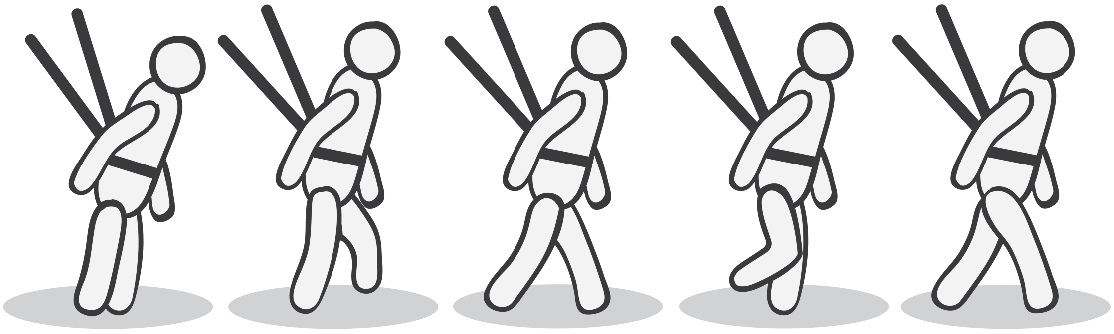

Figure 2.3: Model of a multiple step reaction.

If this project wants to understand better how to aid VR users in recovering from a fall, using the lean-and-release paradigm will be the best option. Using this paradigm to study VR falls will cover the most common type of fall in the average VR consumer.

2.4.3.2 Fall Recovery Techniques

When a person suffers a fall, the best-case scenario is that she will use a reactive step to prevent the body from completely falling to the floor [21, 99, 151]. Several theories indicate that this reactive step of a person is part of a central postural control system on the human body [126, 194–200]. This reactive step increases the radius of the boundary of stability [21]. Increasing the boundary of stability intends to maintain the CoM and CoP inside the boundary [151].

The reactive step of a user provides beneficial information to understand the severity of the fall and the user's preparedness for it. Carty et al. [20] identified three common reactive strategies after a person suffers from a fall: No- Steps, Single Step, and Multiple Steps. The no-step response is the best. It means that the struggle of the fall was not considerable enough for the user to require a recovery step.

The single-step response intends to increase the radius of the boundary of stability [21]. The smaller the distance of the step, the better prepared was the user for the fall [99]. If a single step is not enough to increase the area of the boundary of stability, a user might use multiple steps [21]. This response is the worst technique used, and the bigger the number of steps and distance covered, the worse prepared was the user for the fall. A visual representation of the recovery techniques can be visualised at Figures 2.2 and 2.3.

After suffering a fall while interacting with a VR scenario, measuring a user's fall recovery technique seems like the best approach to measure their state previous to the fall. Combined with the lean-and-release paradigm, a fall in VR can be simulated and measured. These recovery techniques can be useful to test potential fall mitigation methods for VR users. Comparing what type of recovery techniques get used on each mitigation method can help understand which technique better helps the users recover.

2.4.4 Balance recovery in VR

As previously stated, introducing VR into the mix increases the instability of a user [32, 74]. Wearing a VR headset and interacting with a VR scenario can make a possible fall even more dangerous than an average fall. Lord et al. [121] discussed that the process of reacting to a fall involves several visual and cognitive processes. Their work discusses how adding additional cognitive processes (like interacting with a VR scenario) can make users' cognitive load higher, tampering with their reaction to a possible fall.

The work of Zettel et al. [240] further discusses the use of cognitive resources to react to a fall. Their work discusses that both cognitive resources and visual input are essential to react to a fall adequately. However, when a user interacts with a VR scenario, her cognitive resources focus on the task in the scenario, causing her visual input to be distracted by the immersive nature of VR. Research that looks into fall reactions when users interact with VR will be needed to understand more about how VR affects the performance in step reaction.

Previous works show how the VR headset's introduction to a loss of balance scenario adds more cognitive load that needs to be processed. If this project aims to aid people in fall recovery, the technique must use something relevant to shift the user's full attention to the fall recovery.

2.4.5 The role of Visual Input in Postural Instability

Different works have studied how visual feedback of a person's posture affects their posture management. Several works have studied different methods to measure the involvement of the visual system in postural management [126, 152, 215]. Other works have looked at different visual feedback methodologies about a person's posture [87, 215], and how they affect a person's posture management. These works found that factors such as the feedback display distance [87] or the visualization method [215] influence the user's postural response.

There have been several studies in the VR community that looked at creating postural instability using VR's visual feedback [32, 165]. The results from Peterson et al. [165] are particularly interesting. Their work measured the instability caused by visual perturbations on VR. Compared to physical perturbations, visual perturbations created similar kinematic and cortical responses from users [164, 165].

Undoubtedly, if a VR system wants to take care of the user's posture, visual feedback can be a solution to improve the balance of users. Never the less, there is not yet a system that cheaply gives postural feedback to a user. The closest tool to provide users with postural feedback is the Wii balance board, as Chiarovano and colleagues [32] proposed. However, this system requires the user to remain in a static posture for the VR session duration.

2.4.6 Postural Instability Measurement and Detection

Falls are the leading cause of severe injuries in older adults [120]. Preventing falls has been an active research topic for decades [68, 177]. In addition to the traditional exercise programs [184], practitioners and researchers leverage emerging technologies for fall prevention and fall risk assessment. For example, the iStoppFalls system [148] demonstrated how integrating information and communication technology into older adults' daily lives helped them better prevent falls. Research by Mirelman et al. [132] suggested that combining traditional treadmill training and a virtual training environment on display in front of the treadmill reduced older adults' fall rates at high risk for falls.

The Balance and Posture community has long studied different ways to measure and predict postural instability on users. Usually, research works use VR to produce postural unbalance on a participant [164, 165, 200, 224]. The projects that study instability in VR either use VR setups that are inferior to the commercially available devices [26, 27, 74] or ask the participant to perform tasks that an average VR user will not perform [32].

Even though postural instability research is still limited, there are several detection techniques from postural instability that can transfer to VR.

2.4.6.1 Postural Instability Detection Through Body Kinematics

Measurement of postural instability through body kinematics has been the standard measurement in the Balance and Posture community [34, 71, 73, 75, 93, 107, 151, 194, 230]. Combining some of these measurements helped develop methodologies able to detect and predict postural instability [233]. The early work of Kennedy et al. [90] used the changes in the variation in head movement as a predictor of postural instability. Other works focused on studying the shape of the movement of the CoG [26] and found that a circular shape means postural instability and an increased danger of suffering a fall [26, 27].

Later works used the variation of the CoP, and the CoM as an indication of a user suffering from a bad posture [71, 194]. This popular technique is called Virtual Time to Collision (or VTC). VTC is used to estimate the time taken for the CoP to collision with the boundary of stability [199]. This methodology became so popular and accurate in predicting the loss of balance during postural imbalance that other projects start to improve it by applying the same methodology to the CoM [71]. These works used the variation of the CoM to predict whether the user will need a step recovery in case of the fall [71], or thoroughly estimate the time remaining for a user to lose balance [194].

Even though previous works successfully predict postural instability on users or even successfully predict the time of a fall, the setups used by these works are too complex to be used by the average VR consumer. These studies leverage the use of pressure plates [26, 27, 71, 194] that are difficult to acquire, or body motion capture suits [71, 194] that are expensive to afford. The work of Chiarovano et al. [32] tried to reduce the cost of such measurements by combining the use of a Wii balance board (Nintendo, Kyoto, Japan), which is commercially available and affordable by an average consumer, with a VR system. Unfortunately, this device allows a minimal movement space for a user to enjoy a VR experience altogether. VR systems require a cheaper, better adaptable system that allows monitoring users to prevent the danger of postural instability.

2.4.6.2 Cortical Measurement of Loss of Balance

Brain-Computer Interfaces are another technology that is becoming commercially available to the average consumer. The Balance and Posture community has a sub-group of research dedicated to studying the cortical activity produced by postural instability.

Several studies have used EEG to measure and understand the brain's involvement in postural control [135, 136, 196]. Still, EEG signals have also been used, in combination with other measurements, to predict postural unbalance on users [194].

Because there are different scenarios where a regular person might suffer from postural imbalance and even fall, different research projects focus on studying different fall scenarios and how the brain signals from these scenarios differ. Each research project exposes its users to different balance challenges to understand these different types of falls. The research done by Wittenberg et al. [231] identified the most popular balance challenges to be erroneous posture identification [197], self-initiated postural movements [195, 196], the lean-and-release set up for forward and sideways falls [133–135, 221], unstable surface conditions [81], unipedal standing [54, 78, 194], or walking with different balance challenges [170, 180, 190, 223, 234].

A theory exists stating that visually identifying an unstable posture might cause postural instability [215]. Slobounov et al. [197] tried to see if there was a brain mechanism activated when a user visualized an uncomfortable posture. Their results showed an increase in Gamma activity at the Frontal and Central brain regions whenever their participants visualized a challenging posture.

Later works then tried to understand the neural basis of self-initiated movements that move the body towards uncomfortable postures. The work of Slobounov et al. [196] found that when self-initiated movement leads their participants to lose balance, there was an increase in Gamma activity before falling, following their previous work [197]. Further studies from these same authors later found that self-initiated instability and falls created a decrease in Central Alpha, Beta, and Gamma frequencies after the person suffered from a fall [195]. These different research works agreed that Gamma activity is a reliable feature to describe postural instability when the user movements were self-initiated.

If self-initiated movements already showed promising results in detecting postural instability, different research projects then tried to tackle postural instability and loss of balance coming from uncomfortable postures [54, 78, 194]. Solbounov et al. [194] were able to divide a fall into three stages: stable, transition to fall, and falling. This division allowed them to understand the cortical changes during each stage and found that during the transition to fall, Theta and Alpha bands increased in power in the Frontal brain region, to later suffer a considerable decrease during the falling stage. This finding was similar to other works that found increases in Central and Frontal brain regions when a user is under challenging postures that lead to falls [54, 78].

Previous experiments so far asked the users to voluntarily move to uncomfortable postures to later suffer from a fall. Still, other research projects tried to understand the cortical changes of externally triggered loss of balance. Works like that of Jacobs et al. [81] tested users by putting them under a surface that caused instability on users that later might lead to falls. They also tested if there was a difference in brain signals between knowing that instability was coming versus not knowing that instability will occur. Their results showed that knowing about future instability generated a decrease in brain power versus trials where participants did not know about instability.

Other works tried similarly predictable vs. non-predictable falls but under a different mechanism. The lean-and-release mechanism, a standard mechanism used for different postural instability and loss of balance research projects [10, 20, 21, 64], was used to induce loss of balance in users externally. The results of Mochizuki et al. [133] found differences in signal amplitude based on the "readiness" of users towards a fall. Based on this work, Varghese et al. [221] found an increase in power in the Frontal region after the loss of balance. Following these results, Mochizuki et al. 2017 [134] found how cognitive tasks affect the increase rate of the previously discovered power increase after a user loses balance.

So far, the previously mentioned works focus on understanding cortical changes when a user suffers from postural imbalance or a fall from a static position. However, another set of works look at postural unbalance while participants are doing different types of walking activities [170, 180, 190, 223, 234]. These works looked at how adding cognitive challenges while walking can change the output of a person's gait parameters [180, 234], and how changing the gait parameters involves changes at different frequencies in the Central-Frontal brain regions [170]. More specifically, the Frontal Alpha and Beta frequencies suffer decreases in power when modifying the gait due to postural unbalances [190, 223].

Once VR became commercially available, some research projects tried to use the technology to perform different postural instability and loss of balance studies using different cognitive conflicts to create postural instability while walking [164, 200, 224]. The studies tried to see the differences between walking with and without VR headset [224], predictable vs. unpredictable visual shifts [200], and suffering different visual shifts while walking with a VR headset [164, 165].

Most of these works agreed that Frontal, Central, and Occipital brain regions were key in understanding postural instability. Reporting decreases in Theta [164, 165, 200], Alpha and Beta [164] frequencies for different brain regions. Even if these works corroborate the findings from previous cortical related findings, they still have several limitations. These VR projects would not let users naturally walk in the VR scenario [224]. If they are naturally walking, the VR headset displays a see-through from the frontal camera, not a proper virtual environment [164, 165].

2.4.6.3 Postural Instability Monitoring

The previous sections discuss the many different works on how to detect postural unbalance on users. While these works' results can guarantee a reliable detection of the issue, there is little to no work that uses these results to prevent loss of balance, especially on VR users.

Most systems implement other types of monitoring systems [46, 146] that focus on monitoring the user on their everyday life and involve a complex combination of hardware and software. In contrast, this research project focuses on a more niche group of people, VR users. Compared to previous works that focus on the elderly or the general population.

This research project intends to find how these results could help the VR user by communicating with a VR headset. Reporting this is information to the VR headset is an essential process to aid in fall recovery. Once the headset is "aware" of this information, it should help the VR user recover.

2.4.7 Preventing Postural Instability and Balance Recovery

Different previous works have tried to prevent loss of balance with different solutions. One solution could be eliminating the conflict between the real world and the virtual world by adding elements of the real world into the virtual environment [19]. Other works have proposed visualizing their posture [197, 215], or the position of the CoM and CoP relative to the boundary of stability [93]. Even if the user ends up suffering a fall, different research papers have focused on how training on different fall mechanisms allow users to better react to a fall [76, 132, 150].

While eliminating the conflict and visualizing the posture could work as solutions to the postural instability problem, they still interrupt the user's immersion in the virtual environment. Worse, it will require them to wear different complex motion capture suits to accurately visualize the position of the CoM and CoG relative to the boundary of stability. Worse, fall reaction training requires users to repeatedly suffer from a fall to learn to react to one. This research study intends to develop a mitigation method for postural unbalance once the issue is detected. Most works focus on preventing loss of balance from happening but do not propose any solution of what to do once it happens. This research will propose several alternatives on what to do once a user is suffering from postural imbalance.

2.5 Relationship between VR sickness and Postural Unbalance

As previously mentioned, there is an influential theory that suggests a relationship between postural instability and VR sickness in VR users. This theory goes back to 1991, were Riccio and Stoffregen [175] proposed that the postural sway caused by postural instability initiates the symptoms that later develop to *Motion Sickness*. This theory gained strength after later fighter pilot reports showed that pilots showing motion sickness symptoms also suffered from postural instability [103].

In 1996, Kennedy et al. [90] developed a protocol to measure postural instability of participants that suffered from motion sickness. These works tested several body kinematic variables, such as head movement and lateral movement. This measurement then motivated several studies to compare the posture of VR users before and after interacting with a VR scenario [35, 104, 140, 207, 208].

In particular, the study by Stoffregen et al. [208] reported how, right before their participants reported symptoms of motion sickness, postural instability started to appear. After interacting with a virtual scenario, participants answered an SSQ and made a balance test. Their results showed how participants with higher SSQ values also showed the most significant increases in postural instability. Most recently, and with the improvement of VR technologies, different studies have tried to study this theory [26, 27]. These studies found that the changes in CoG are different between people sick and non-sick people.

Interacting with mobile virtual scenarios increased the appearance of both VR sickness and postural instability in users. The works of Janeh et al. [83] attempted to measure the changes in participants' CoP and stepping distance in a virtual environment. Their results showed that those changes closely resemble those of someone struggling to maintain balance [179]. Moreover, contrary to previous studies, users did not show a significant increase in VR sickness symptoms. The authors theorized that physically walking on the scenario eliminated the cognitive conflict of static scenarios that produced VR sickness symptoms.

Further proving if there is a relationship between VR sickness and postural unbalance is out of this project's scope. Nevertheless, the close relationship between these two issues is the motivation to tackle them under the same research project. The real scope of this project is trying to detect them and propose solutions to those problems promptly.

CHAPTER 3

MATERIALS, METHODS AND EXPERIMENT DESIGN

This chapter will focus on explaining the two different experiment designs utilized for this research project. Each section will explain the experiment's materials, and the methodologies followed to collect and process data. This chapter will also link how each experimental design tries to address the different research objectives proposed in Chapter 1.

This research project will consist of two different experiment designs based on two types of VR setups. The first experiment design focuses on static VR setups, where the user is limited to movements from the waist up. The second VR experiment focuses on mobile VR setups, where the user will physically walk inside a constricted area.

3.1 Loss of Balance in VR from a Static Position

With the assumption that the onset of a fall was given, the conducted experiment evaluated two balance recovery techniques: *video-see-through* and *auditory warning*. These techniques will be tested at two timings: at fall onset and 500 ms before fall onset. The decision behind choosing these techniques is that they do not require additional pieces of apparatus and are computationally feasible in a wide range of VR systems, from high-end systems, such as HTC Vive Pro, to mobile-based solutions as Google Daydream. This experiment aims to understand how the components of a VR headset can aid in balance recovery.

The experiment induced forward loss of balance using a tether-release protocol

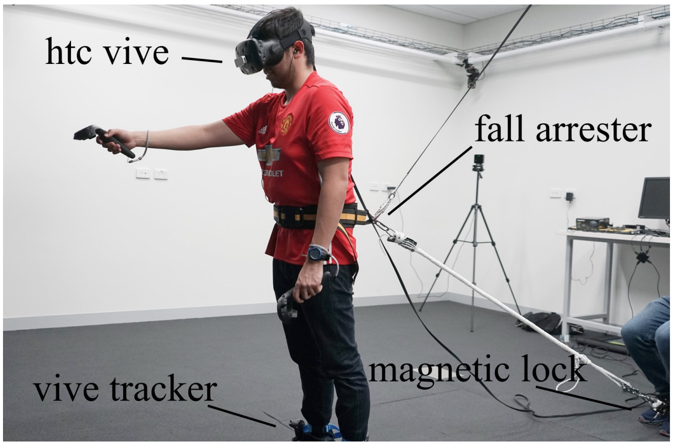

Figure 3.1: Lean and Release in VR experiment setup, which follows the tether-release protocol.

(Fig. 3.1), which is common in clinical fall prevention research [48, 76]. During the experiment, the subject was engaged in a secondary 3D object selection task using the Vive 3D controller. This experiment induced forward loss of balance by releasing a tether from a magnetic lock controlled by a solid-state relay. Following previous clinical trials using the tether-release protocol [20, 21], the three primary measurements generated were stepping strategies, step length, and step initiation. The Vive tracking system provided a reliable and robust methodology to access these measurements.

The experiment examined three main hypotheses:

LR-H1: Both video-see-through and auditory warning will increase the performance of balance recovery compared with the baseline condition of no intervention.

LR-H2: There will be a main effect of intervention timing.

LR-H3: The video-see-through technique will yield the best performance.

The main contributions of this experiment are the interdisciplinary effort to identify fall risks while wearing a head-mounted display, establishing an experimental protocol that evaluates balance recovery techniques, and evaluating two generic balance recovery techniques for two timings of intervention. The proposed experiment setup used only off-the-shelf components, and the evaluated recovery methods are feasible in most VR systems. Hopefully, the results from this experiment will help set the first stone towards developing useful recovery techniques for VR users suffering from falls.

The results of this experiment will focus on Research Objective 1. Hopefully, the mitigation techniques studied in this experiment can be further reproduced and improved by later studies to aid users to recover from potential falls suffered on VR.

3.1.1 Experiment

3.1.1.1 Participants

Twenty adults participated, whose ages ranged from 20 to 35 (mean = 25.38, variance = 10.23), of which three were female. All subjects received reimbursement of 20 Australian Dollars for their time. The key inclusion criteria for recruiting users were fluency in the English language and the absence of major cognitive impairments. This study received approval from the Institute's Human Research Ethics Committee. The data from 3 of the 20 recruited subjects (0 females) were discarded due to tracker malfunction, which produced incomplete or inaccurate data. Among the 20 subjects, data from 1 subject was removed due to inaccurate signal tracking. Data from 2 subjects were removed due to a light base movement during the experiment. Trials with a step length larger than 1.5 standard deviations were treated as outliers. Trials with distinct data defects, such as signal dropout or abnormal fluctuation, were also removed.

3.1.1.2 Balance Recovery Techniques

The experiment employed a 2-by-2 design with two independent variables: *techniques* (video-see-through and auditory warning) and *timing* (fall onset and 500 ms before fall onset). For the technique variable, this experiment utilised two different techniques: *video-see-through* and *auditory warning*.

The *auditory warning* has been extensively utilized in previous balance/postural control research [68, 135, 136]. For this experiment, the auditory warning consisted of a neutral sound played from the VR scenario. This sound was the only sound played during the experiment.

Due to the involvement of the visual input in human balance and posture [32, 87, 126, 152, 165, 215], this experiment implemented a *video-see-through* approach. This approach hopes to enable users to regain awareness of the surrounding physical environment to regain balance and avoid falling. This technique involves turning on the device's frontal camera to let the participant see the outside world.

Note that other balance recovery techniques, such as merging the 3D reconstructed real-world surroundings into the virtual world [19] or displaying the posture of users in the virtual world [215], are also plausible. However, these techniques require substantial computation and additional hardware components. Thus, the focus on the current techniques, which are generic and can be implemented in PC-based, phone-based, and stand-alone VR platforms.

For the timing variable, the *video-see-through* and *auditory warning* techniques appeared at two different times: 500 ms before fall onset and during fall offset. When deciding when to react, a number that provides ample time for the subject to process the visual and auditory information and react accordingly once a fall occurs was selected. The 500 ms time was chosen based on different relevant works discussing different reaction times.

Previous research by Lord et al. [121] indicated that a reactive behavior requires approximately 300 ms, while a decision-based behavior requires approximately 700 ms. Mochizuki et al. [136] found that cortical activities appear 950 ms before a self-initiated fall. Ng et al. [25] determined that the average finger response time to a visual stimulus is approximately 500 ms.

3.1.1.3 Experiment Protocol

The experiment employed a within-subjects design with five design combinations: *video-see-through at fall onset, auditory warning at fall onset, video-see-through at 500 ms pre-fall, auditory warning at 500 ms pre-fall* and a baseline condition with no intervention. Ten trials were performed for each condition, for a total of 50 trials to complete the experiment.

For all participants, the order of appearance of the intervention techniques was random. The average length of an experiment session was of approximately 30 minutes. The total number of trials collected for this experiment was 850 trials. But because of faulty data at some trials, 17 trials were removed.

In the introduction session, each participant experienced the experimental protocol explanation. The participant then proceeded to get weighted to register their weight in the system. After the participants wore the HTC Vive, Vive trackers, safety harness, and fall arrester, each subject performed 5 test trials to become acquainted with the virtual environment and experience each technique once.

During an experiment session, at the beginning of each trial, the subjects were instructed to stand in a fixed position and then lean forward. The rest of the body segments was aligned in a single plane [133]. When the load cell registered a tension force of 20% of their weight, a secondary dummy object selection task in VR (Fig. 3.2)

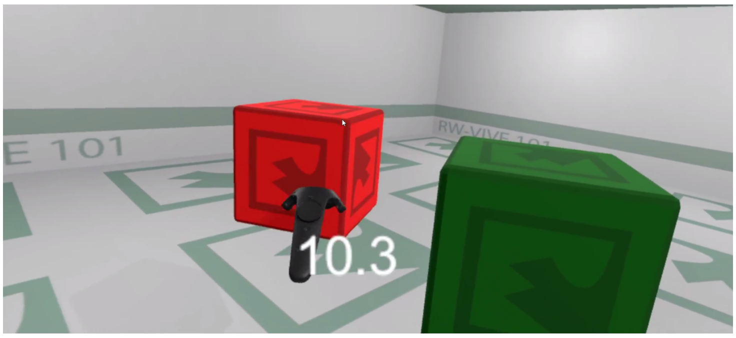

Figure 3.2: The secondary 3D object selection task. The red cubes are the cubes the participants had to touch with the controller and the ones that would trigger a fall.

started. Cubes changed color at random times, and subjects had to touch them with the controller as soon as this happened. The design of this secondary task intends to keep the subject engaged with the virtual environment.

After the secondary task started, the tether released at a random time between 5 and 10 seconds, and the subject's balance response was recorded, which ended the trial. At the end of the experiment, a questionnaire was given to the subjects, which enabled them to rate each technique on a Likert scale from 1 (the technique was not useful) to 5 (the technique was very useful). Later, the subjects answered an open-ended interview that enquired about how immersed the subject felt in the experiment, how disruptive the balance recovery methods were, and whether they preferred no intervention in favor of a seamless simulation.

Note that the threshold value of the tether tension affects the performance of the balance recovery [20]. The larger the leaning angle is, the more difficult it was for the subject to recover her balance. Previous studies [20, 99] suggested that a threshold value above 25% body weight caused all subjects would rely on the multiple-step strategy to recover their balance. Thus, this experiment adapted a 20% bodyweight threshold to cover the full spectrum of recovery strategies. The average leaning angle to achieve 20% body weight was approximately 15 degrees in this experiment, following previous observations by Barret et al. [10]. The angle was chosen because it is a reasonable leaning angle that neither induces a considerable fear of falling nor breaks the sense of immersion in VR.

As previously mentioned, a questionnaire was asked at the end of the experiment. This questionnaire will help understand the participants' feelings during the experiment and record their comments on the key features of the VR scenario. These questionnaire results can lead to a better understanding of why they behaved in a particular way

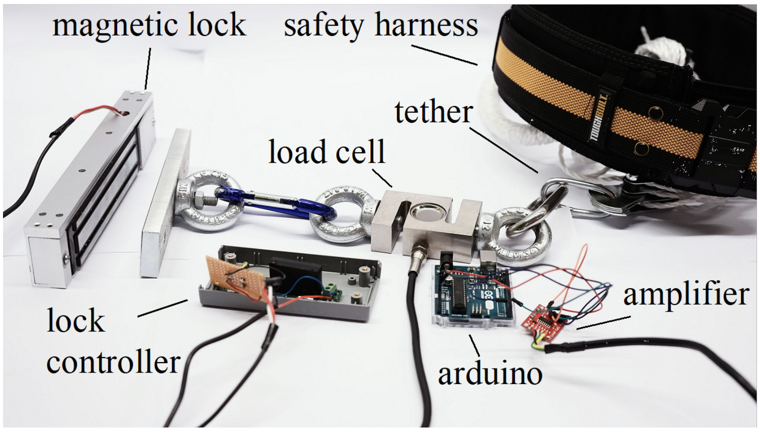

Figure 3.3: Components of the tether-release mechanism.

during the experiment.

3.1.2 Experiment Apparatus

3.1.2.1 Lean and Release Mechanism

The experiment simulated a forward loss of balance and followed the tether-release protocol [48]. The subject was initially held in a static forward-leaning position by a tether attached to a waist belt (Fig. 3.1). The subject was instructed to lean further until the load cell read a tension force of 20% of the subject's body weight. Forward falls were induced by releasing the tether.

Fig. 3.3 shows the components used to build the tether-release system. A Single Door 12 V Electric Magnetic Electromagnetic Lock of 280 kg, controlled by the Numato Labs Channel USB Solid State Relay Module, was connected by a serial port to the virtual scenario and served as the magnetic lock. A 0 — 300 kg S Type High-Precision Load Cell Scale Weighting Sensor served as the load cell. This load cell is positioned between the lock and the tether to record the tension force induced by forward-leaning. To obtain measurable data from the load cell, Sparkfun's Load Cell Amplifier HX711 was employed. An Arduino UNO R3 microcontroller was used to convert the data from the amplifier and send it to the virtual scenario via a USB serial port.

3.1.2.2 Other Apparatus

The VR HMD used for the experiment was the original HTC Vive. The headset has a resolution of 1080 by 1200 pixels per eye. The device also has a refresh rate of 90 Hz

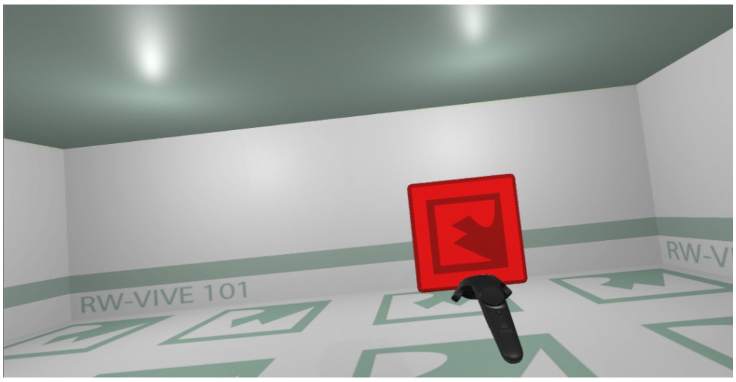

Figure 3.4: Empty room view from the perspective of the participant.

and a field of view of 110 degrees. A pair of Vive Trackers were attached to the subject's ankles (Fig. 3.1) to measure the different stepping responses of the user. The trackers reported their 3D position at a frequency of 1Hz. A ceiling-mounted fall arresting harness was utilized as a security measure (Figure 3.1). The purpose of the fall arrester was to prevent any possible accident from happening to the participants.

The Unity 3D game engine, version 5.1, was the engine of choice to build the virtual scenario. The scenario is a simplistic empty room with one generic texture applied to it. The room is shown in Figure 3.2 and Figure 3.4. Lab Streaming Layer (LSL) was the tool used to synchronize the system to prevent any delay of information from happening. This tool automatically synchronized the timestamp of the tracker data with the timestamps of the release mechanism.

3.1.3 Video-see-through and Auditory notification development details

The video-see-through technique was implemented using the front-facing camera on the HTC Vive. The camera's frame rate was set to 60 Hz, and the rendering mode was set to undistorted to correct the camera lens distortion. The camera continuously streamed the video content to avoid delaying the camera activation.

The stream was set as a video texture onto a 3D quad that was only visible when the video-see-through method was employed. The initial size of the quad was the default size set by the Steam VR library. Since the size was too small to help the subject in any way, the quad was doubled. The quad was meant to create an illusion of a "window to the outside world" to users.

After some informal pilot studies with subjects, this approach was determined as

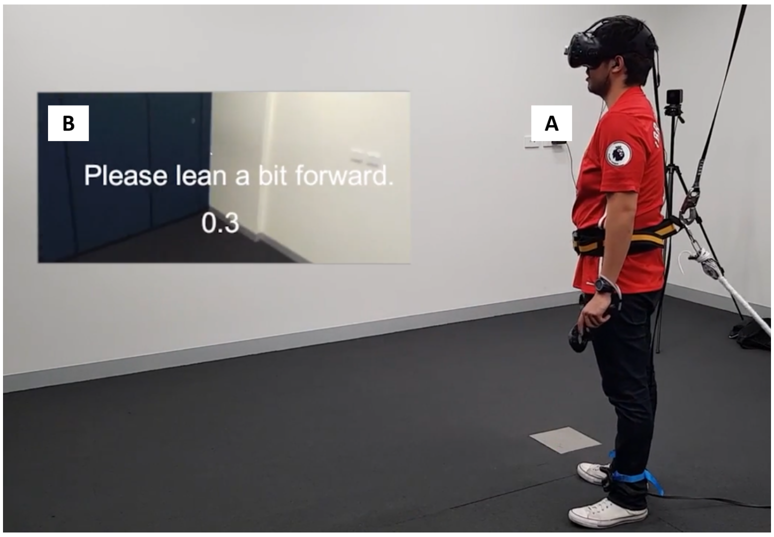

Figure 3.5: An example of the video-see-through technique. A: The user in the real world. B: Video-see-through from the perspective of the user.

not helpful. The next attempt at this approach was to make the quad sufficiently large to occupy the 110 FOV of the HTC Vive headset fully. Because a typical person has approximately 114 degrees of FOV, it was decided that attempting to achieve the 110 degrees of FOV of HTC Vive for the video-see-through will produce a similar experience of observing the real world. The quad was enlarged until it fully occupied a subject's vision. The quad followed the subject's view, which gave the subject the feeling that she was wearing glasses to view the outside world. Figure 3.5 shows a representation of this technique.

The auditory warning technique consisted of playing a one-second standard neutral notification sound to the participant. The participant wore a pair of headphones throughout the session. The neutral notification sound was the only sound effect in the experiment.

3.1.4 Measurements for the tether-release Protocol

The tether-release protocol has a set of well-defined measurements [20, 21], including stepping strategies, the margin of stability, sagittal plane angular position, and spatio-temporal variables such as stepping length and toe-off time. In this experiment, the Vive tracking system was used with the video stream from a web camera to record three major measurements: *stepping strategy, step length, and step initiation time.*

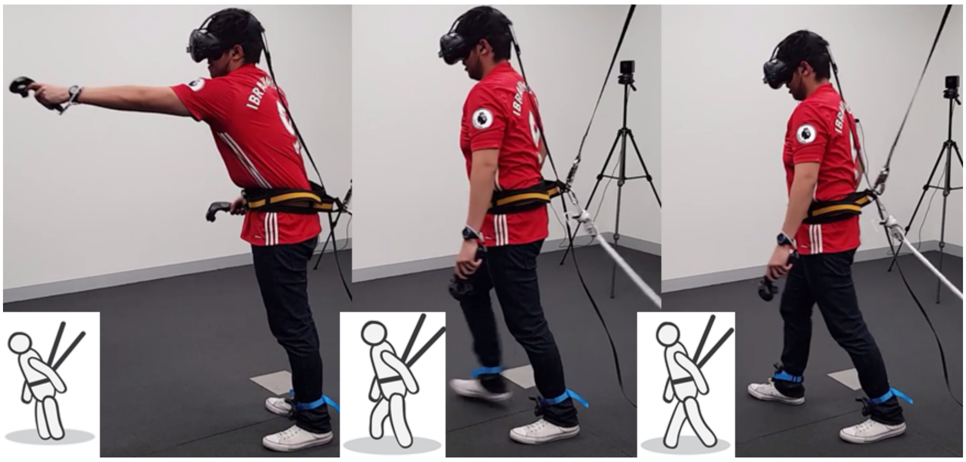

Figure 3.6: Representation of the body reaction when it executes the Single Step Strategy.

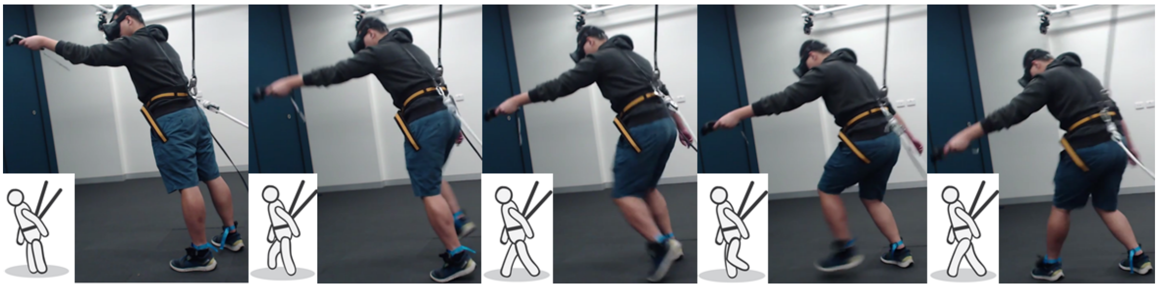

Figure 3.7: Representation of the body reaction when it executes the Multiple Step Strategy.

3.1.4.1 Stepping Strategies

Three stepping strategies were defined: *no-step, single-step, and multiple-steps* [20]. The *no-step* strategy is considered the best strategy because it exhibits the least body movement to recover balance. When adopting the *no-step* strategy, the subject recovers from a loss of balance by keeping her feet in place.

The most common strategy is the *single-step* strategy. In this strategy, the subject recovers balance by taking one step (Fig. 3.6). The *multiple-steps* strategy is the worse strategy. This technique often indicates a significant shift in the center of mass and instability of a subject and requiring more than one step to recover balance. Fig. 3.7 illustrates a typical multiple-stepping process in which the first step of the subject is inadequate for stabilizing the shift of the center of mass, and additional steps are required to regain balance.

3.1.4.2 Step Length

The step length is estimated using the 3D position of the Vive trackers that are bound to a subject's leg. For each trial, the 3D position of the tracker on the first stepping leg is utilized. For each trial, the time t is identified. The process to identify it involves identifying when the tracker has the largest displacement from its position at the onset of the trial. Those 3D positions were averaged in the range of $t-0.25s$ to $t+0.25s$. A smaller step length for the first reaction step is generally considered a better reaction toward an unexpected fall [21]. A smaller step may be taken if a person is not capable of taking larger steps. However, this outcome is less likely for the healthy and young participants in this experiment.

For the trials in which a subject adopts the multiple-steps strategy, the step length of the first reaction step was measured, as noted in previous studies [21, 76]. The accumulated step length of all steps was not calculated because the fall arrester (Fig. 3.1) usually disrupts a user's motion after the first step.

3.1.4.3 Step-Initiation Time

The step-initiation time means the amount of time required from when a subject initiates their response to the onset of a fall [76, 99]. A shorter step-initiation time indicates a better reaction performance toward an unexpected fall. Step-initiation is the measurement of how early or how late a foot starts moving after the onset of a fall. The earlier the foot starts moving, the better prepared the user is toward the fall.

3.1.5 Lean and Release Data Processing

The stepping strategies of the subjects were annotated for each trial by examining 20 hours of recorded videos of all experiment sessions. The trajectories of the foot movements were corroborated with the annotations. For the single-step strategy, plots in which only one of the feet moved arc-wise and the other foot remained stationary (Fig. 3.8 left) were selected. For the multiple-steps strategy, plots in which both feet moved arcwise (Fig. 3.8 right) were selected.

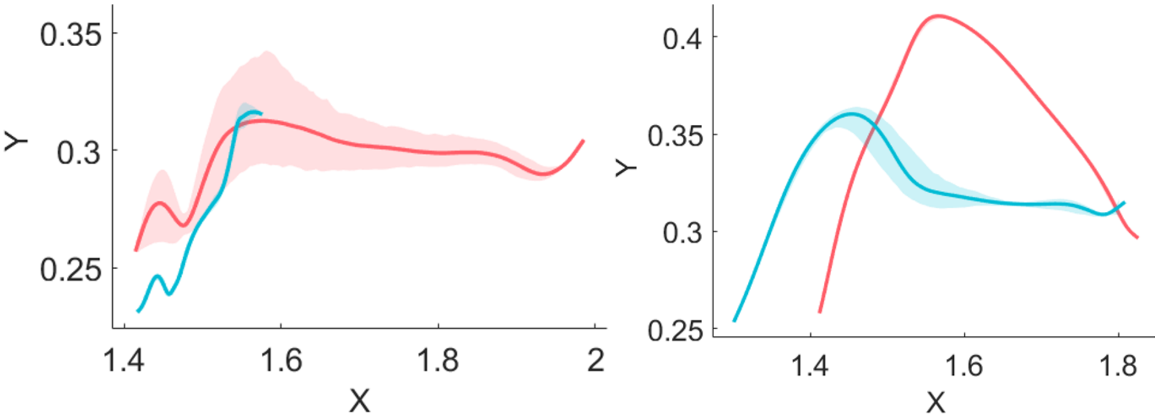

Figure 3.8: Left: plot representation of the movement in a single-step feet reaction. Right: plot representation of the movement in a multiple-step feet reaction. The blue line represents the trajectory of the right feet. The red line represents the trajectory of the left feet.

3.2 VR Sickness and Postural Instability on Mobile VR Setups

The main purpose of this experiment is to understand the appearance of both VR sickness and postural instability in mobile VR setups. Participants interacted with a non-isometric virtual walking experience, particularly at large and detectable translational gain (TG) levels. Figure 3.9 shows the experiment setup. The participant wore a VR head-mounted display (HMD) and a full-body motion capture suit, which enabled the recording of gait parameters (i.e., stepping distance and cadence) and center of mass (CoM) displacement.

The experiment consisted of two walking phases. In the first waking phase, the participant was instructed to walk toward a destination marked by a red arrow. The second phase consisted of walking back to the original position. The virtual scenario consisted of a virtual street in the city of Sydney. Six different levels of translational gain at an increasing order {1,2,4,6,8,10} (Figure 3.10) were applied to the scenario. This experiment will address Research Objective 2, by focusing on mobile VR setups.

3.2.1 Participants

Twenty-one healthy adults (17 males, four females) participated in the experiment. The mean age was 25.73, with a standard deviation of 3.594. All participants were paid for their participation and gave written informed consent. All participants had normal or corrected-to-normal vision. Participants were encouraged to wear contact lenses for a more comfortable VR experience.

Among all participants, 13 had prior experience with three-dimensional computer games, and 9 had previous experience in VR. 15 participants had experienced motion sickness of different severity previously in their life. All participants confirmed that they had no walking impairments before the experiment. There was no postural stability ability test practiced to any of the participants.

On average, the entire experiment took about 25 minutes per participant. Among the 21 participants, four were removed: 2 due to tracking malfunction and 2 to software malfunction during the experiment. Out of the 17 remaining participants, 3 participants terminated the experiment before TG $10x$ due to severe VR sickness symptoms at TG levels $4x$, $6x$, and $8x$, respectively.

3.2.2 Translational Gain

This experiment used the redirection technique that extends the physical space by amplifying the mapping between physical and virtual movement, called Translational Gain (TG). For example, with a TG of $10x$, one step in the real world would induce a displacement equals to the distance of 10-steps in the virtual environment. This technique is popular in VR [3, 79, 83, 172, 205] because of its simplicity and preservation of the natural walking and vestibular self-motion information. This technique also became popular because it has allowed users to explore considerably large environments within the confinement of small spaces [1, 18, 185].

Previous papers have examined the impact of the translational gain on gait parameters [3, 82, 83] and object selection performance [124, 229]. Proof exists that there is a detection threshold around 1.25x for translational amplification and 1.5x for rotational amplification [65, 205]. Once the changes become visible to the users, there have been reports of users suffering from VR sickness [229]. Previous works have reported an increase in VR sickness level due to an increase in TG in a Virtual Environment [79].

The experiment induced VR sickness and postural instability by gradually adjusting the translational gain(TG) value. Based on the sensory conflict theory [89, 109], the disparity between the actual motion in the real-world and the perceived motion in the virtual world would confuse the visual and the proprioception systems and induce VR sickness. The analysis of the data generated by this experiment has 2 phases. Phase 1 will focus on the appearance of VR sickness and its effects on Postural Instability. The second phase focuses on the cortical activity analysis of these issues.

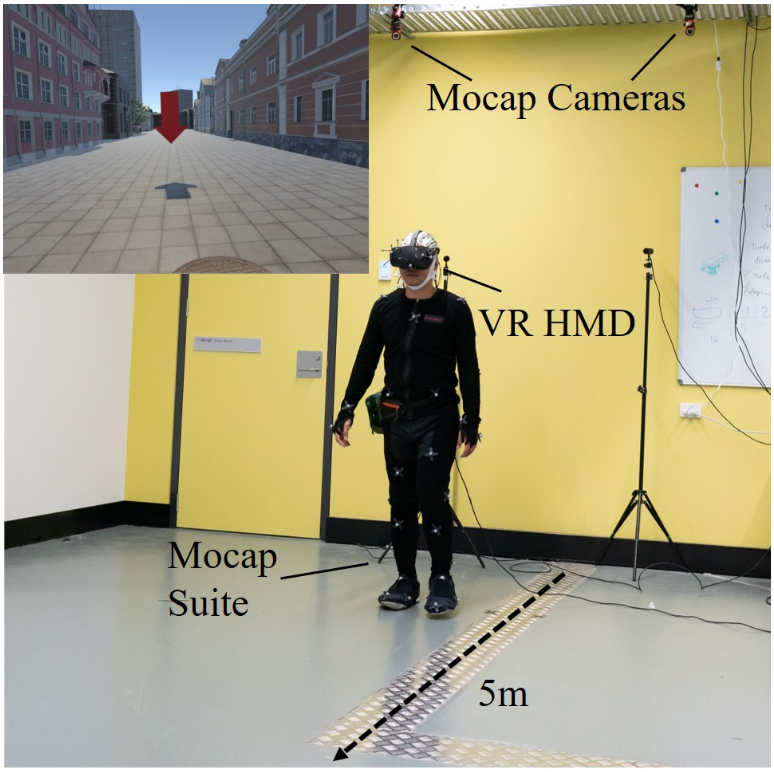

Figure 3.9: Experiment setup for non- virtual walking.

3.2.3 Phase 1: Influence of VR Sickness in Postural Instability

This analysis investigated the effects of VR sickness on postural instability and gait performance of users interacting with a mobile VR setup. Previous VR sickness and postural instability works talk about the appearance of a cognitive conflict between the vestibular and proprioceptive systems [91, 241]. Allowing the user to walk in a virtual environment eliminates this conflict [91, 164] but introduces a new conflict: between the visual and proprioceptive systems. Because it is still not well documented if this type of conflict will also generate VR sickness, Phase 1 will focus on measuring the appearance of VR sickness and studying if this issue creates postural instability on users.

Phase 1 analysis will study these hypotheses:

P1-H1 : The level of VR sickness will increase the level of postural instability.

P1-H2 : Users that suffered from VR sickness will show some effect on their CoM and gait parameters due to the influence of VR sickness.

P1-H1 focuses on VR sickness caused by the conflict between the visual and proprioceptive systems. This hypothesis states that constant exposure to the conflict and

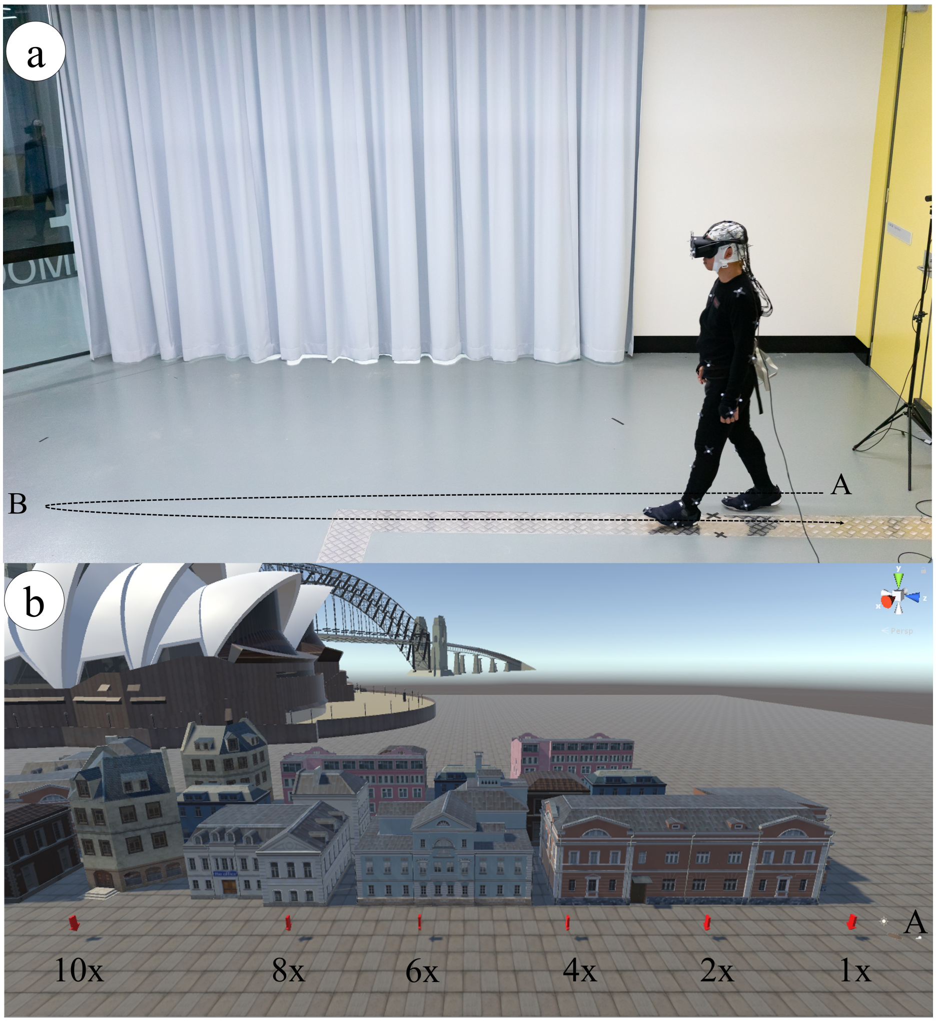

Figure 3.10: (a) Physical environment for the experiment, and (b) corresponding virtual environment with red arrows indicating the end point of the trials at different translational gains.

increasing the strength of the given conflict will intensify the participants' sickness symptoms.

P1-H2 focuses on the effects of VR sickness on postural instability of participants. This hypothesis theorizes that people who suffer from VR sickness will behave differently than those who did not. More specifically, the subgroup of users that suffered from VR sickness will see an increase in postural instability and a decrease in gait performance.

3.2.4 Phase 2: Cortical State of VR Sickness and Postural Instability on Mobile VR Setups

The second analysis investigated the cortical activity of VR sickness on a mobile VR setup. If phase 1 shows that a conflict between the visual and proprioceptive systems is capable of causing VR sickness. To a cortical level, how different is it from VR sickness caused by the vestibular-proprioceptive conflict? Can it be detected in the same way regular VR sickness is detected?

Other studies have previously studied the cortical state of postural instability caused by this type of conflict [164, 165]. However, even though these studies used a VR headset, they used a video-see-through camera to generate the conflict. Moreover, because the study implemented the headset's camera instead of a virtual scenario, no user suffered from VR sickness.

These studies also reported how decreases in the alpha frequency at the Parietal and Occipital brain regions result from postural perturbation. However, these results come from postural instability caused by manipulating the frontal camera of a VR headset. This research project intends to study if these same phenomena can be observed when postural instability happens due to the interaction with the virtual scenario.

This research project will study several brain regions and frequencies to measure VR sickness with EEG. Previous relevant works [28, 98, 131, 156] studied the delta frequency at the Frontal-Central and Occipital brain regions and Theta frequency at Occipital brain region. These works reported an increase in power in these frequency-brain regions, which means an increase in VR sickness. However, these studies implemented a sitting driving simulator setup. The participants were not wearing a VR headset and were not moving.

Previous relevant works have reported decreases in Gamma activity at the Frontal, Central, Parietal, and Occipital brain regions when a person struggles to maintain balance. [164, 195, 196]. These studies had people either struggle for balance without a VR headset or struggle for balance with a VR headset passing through the real world through their frontal camera. This research project intends to study if this phenomenon replicates when the users struggle with balance while looking at a virtual environment.

Phase 2 analysis will study the following hypotheses:

P2-H1: An increase of Delta frequency power will happen at the Frontal-Central and Occipital brain regions. Theta frequency will also increase in the Occipital brain region. These increases will correspond to the increase of VR sickness of the participants.

P2-H2: A decrease of Gamma frequency power will happen at the Frontal, Central, Parietal, and Occipital brain regions. These changes will happen due to the posture adjustment of participants inside the VR environment.

P2-H3: A power suppression of the EEG Alpha frequency at the Parietal and Occipital brain regions will happen due to body gait modification caused by posture perturbation. As the level of TG increases, this frequency will also increase.

P2-H1 focuses on the signals produced by *VR sickness*. This hypothesis intends to understand if the most significant VR sickness results on static setups can translate to a mobile VR setup, and if so, how different the results are from each other. The previously mentioned works report the cortical state of VR sickness produced by scenarios with a conflict of the visual and vestibular systems. Because this study involves a mobile scenario, the type of conflict users will experience is visual and proprioceptive systems. This hypothesis also tries to understand if the produced signals will differ under different types of conflict.

P2-H2 and *P2-H3* are focused on studying signals related to *postural instability*. Previous works have discussed a relationship between VR sickness and postural instability [35, 103, 104, 140, 175, 208] and between postural instability and the proprioceptive-visual conflict on VR [164]. Other reports showed how postural instability affects user behavior [27, 104, 140], and the human brain cortical state [54, 147, 165] when interacting with a virtual environment. For these reasons, this study will also report the cortical changes caused by postural instability since they are also a side effect of proprioceptive and visual conflict.

P2-H2 focuses on the Gamma frequency in most brain regions. Previous reports showed how Gamma frequency shows significant changes when posture gets challenged on static scenarios [195, 196] and mobile scenarios [164]. The study of *P2-H2* will focus on the changes produced by the participant adjusting her posture as a product of interacting with the large TG levels.

P2-H3 focuses on studying signals related to gait changes while walking on a virtual scenario. This hypothesis follows the work of [164] that showed how gait changes produce suppression of the Alpha frequency. Because the large TG levels are expected to change the user's gait, these changes should be visible in the Alpha frequency.

There are three main contributions that this analysis provides. The first contribution is to compare the VR sickness signals of regular static setups and those from mobile setups. This study's second contribution compares the sickness signals between visual-vestibular conflict and those from a visual-proprioceptive conflict. This study's final contribution is to have a full cortical state report on the changes induced by the visual and proprioceptive conflict.

3.2.5 Experiment

This experiment investigated the correlation between the translational gain of virtual walking and the severity of VR sickness. Complementing previous works that examined the usability of translational gain ranges below 3x [3, 79, 83, 172, 205, 229], this experiment examined a more extensive gain range from 1 to 10. It focused on how VR sickness affected the users' behavior performing virtual walking while wearing an HMD.

The proposed experiment used large detectable TG to induce VR sickness in the participants. Users will experience a cognitive conflict between the visual and the proprioceptive systems from walking under different TG levels. The conflict derives from the user visualizing a different translation than the one expected from their proprioceptive system. The expectation is that this type of conflict causes some degree of VR sickness in the participants. The experiment aimed to understand how VR sickness in a mobile setup influences the user's biomechanics and brain dynamics.

3.2.5.1 Experiment Design

The experiment used a within-subject design with translational gain as the sole independent variable, with six levels $\{1,2,4,6,8,10\}$. The baseline is a walking recording without wearing a VR headset. An informal internal pilot test led to the decision to set $10x$ gain as the experiment's upper bound. During the informal pilot, several highly experienced VR engineers, who have extended experience working with different redirected walking scenarios, all considered the virtual walking experience uncomfortable and unusable at gain levels of 10 and above.

The participants experienced five trials for each of the 6 TG levels, 30 trials in total, in an increasing order during the experiment. Previous experiments [144, 229] suggested that larger TG levels and larger motion flows would induce a higher level of sensory conflicts. The intention was to let participants gradually build up VR sickness symptoms during the experiment and collect corresponding biomechanics and EEG signals.

The order of the translational gain levels was not randomized. Previous works [98, 131, 156] were users were exposed to gradual increases in VR sickness to monitor the progressive change in signals acted as the inspiration for this experimental design. Other works that applied the TG levels at a random order [82, 83] risk the users experiencing high levels of TG at the very early stages of the experiment. This scenario could lead to a sudden significant increase in VR sickness from users that could persist for the rest of the session. This event would prevent the study of the EEG signals' changes while the user experiences a gradual increase in sickness.

At the beginning of each trial, the participant received the instruction to move to a virtual utility hole in the virtual street (point A in Figure 3.10). She then received the instruction to walk toward a destination indicated by a red arrow (Figure 3.9) in the virtual scene and then back to the virtual utility hole. As the translational gain increased, the red arrow's position moved farther away from the starting point (Figure 3.10b). In the real world, the participant walked between points A and B (Figure 3.10a). The virtual environment possessed a collision system that prevents the unlikely event of participants running into the virtual buildings.

3.2.5.2 Procedure

This section lists and describes each of the steps previous to the experiment and the experiment flow.

- *Pre-experiment Questionnaire.* Each participant had to answer this questionnaire before any setup started. The questionnaire recorded the participant's familiarity with 3D and VR technologies and their subjective assessment of how susceptible they are to either seasickness, motion sickness, cybersickness, or any sickness. The questionnaire session lasted no more than 5 minutes.

- *Motion Capture System Preparation.* In this step, participants wore the motion capture suit. The markers were then placed around their bodies accordingly to the selected marker convention. Participants then received the instruction to walk in the tracking area to confirm that the motion capture cameras could track the full-body motion inside the tracking volume. This step lasted between 8 and 10 minutes.

- *EEG Preparation.* This step involved applying gel to the user. The gelling process lasted between 30 minutes up to 45 minutes. After the gel application, the EEG signals were visually inspected to ensure the quality of the signal.

- *Baseline Walking Trials.* After setting up the EEG device, each participant performed five baseline trials without wearing the VR headset. Each participant had to walk between the two ends of the walking area (i.e., positions A and B in Figure 3.10a). The duration of this step was of around 8 minutes.
- *VR Headset Setup.* After each participant finished the baseline walking trials, they wore the VR headset. After wearing the VR headset, each participant spent some time getting used to the virtual environment. After a couple of minutes of adaptation, the users received the indications of the tasks they need to perform. This step lasted a maximum amount of 5 minutes.
- *Experiment Flow.* Each participant had to walk from the starting point towards the endpoint (i.e., a red arrow) and back to the starting point. Each walk between the start, end, and start points constituted a single trial. Each participant was notified of the end of the trial by a virtual message displayed when they arrived back at the start point. The message notified them that the researcher would start the between-trial questionnaire. The participant had to report her sickness level from 1 to 10, where ten meant the symptoms were so severe that the experiment should stop immediately.
- *Post-Experiment Questionnaires.* After the experiment finishes, the user will answer two questionnaires. One is the post-experiment simulator sickness questionnaire. The second questionnaire, like in the previous experiment, is an open-ended questionnaire. In this questionnaire, the user has to think aloud about her decisions and experiences while interacting with the scenario.

3.2.5.3 Physical Space and Virtual Environment

The physical space of the experimental environment was three by 5 meters. For each trial, the user received the instruction to walk from point A to point B. After reaching point B, the user had to walk back to point A (Figure 3.10a). The floor at the experiment area had a mark to represent both points A and B. The distance between A and B was 4.5 m, which can be covered within eight steps by a 175 cm male adult.

The corresponding virtual space to the lab environment was a virtual street scene. The size of the whole Sydney scene was 100 m by 100 m. The virtual walking took place on a straight street of 70 m long and 5 m wide. Figure 3.10b shows the side view of the street, and Figure 3.9 shows the participant's first-person view while performing the walking task.

3.2.5.4 Translational Gain Implementation

Similar to previous works [6], the development of the different translational gains consisted of manipulating the translation matrix of the virtual scene in the opposite direction of the user's movements. However, unlike works from [83, 144, 229], the motion magnification was applied onto all axis, instead of only the forward direction. The design decision intends to ensure participants were subject to a unified motion magnification in each TG level. Otherwise, a non-uniform motion magnification along a different axis could be a potential confound when investigating the relationship between brain dynamics, TG levels, and VR sickness.

3.2.6 Experiment Apparatus

- *Motion Capture System.* An OptiTrack motion capture system was used with 12 Flex 13 cameras for full-body tracking. The Flex 13 cameras captured information at a rate of 120 frames per second. The system also consists of a motion capture suit. Participants wore this motion capture suit over their clothing. The OptiTrack Unity Plugin synchronized the motion capture data and the coordinate systems in both the OptiTrack cameras and the Unity3D engine. In this experiment, the Baseline + Toe marker skeleton setup with 41 tracked markers in the Motive: Body software from OptiTrack was used. This setup enabled the calculation of biomechanical measurements, including CoM [34, 107], stepping distance, and cadence.

- *VR Headset.* An Oculus VR CV1 headset was used in this experiment. The Oculus was chosen because of its compatibility with the OptiTrack Flex 13 cameras. The tracking information from the OptiTrack system overrode the head position of the Oculus VR plug-in in Unity3D, which enabled a larger walking area. The headset contained a pair of OLED displays that provided a 110-degree field-of-view with a resolution of 1080 x 1200 pixels per eye.

- *Electroencephalography.* The EEG data were recorded using an Ag/AgCI slim active sensors from 64 electrode positions according to the extended 10-20 electrode placement system. A portable and wireless LiveAmp system (Brain Products GmBH, Munich, Germany) was used to minimize the natural walking interference in the virtual environment. The EEG data were acquired at a sampling rate of 500 Hz, and the channel locations were used based on BEM standard location, which is distributed by EEGLAB toolbox [42, 43]. The Electrode impedances were kept below $5k\Omega$ for the EEG recording.

- *Data Synchronization.* For every major event described in the Procedure section (section 3.2.5.2), the virtual scenario generated one flag event. These flag events indicate the change to a different phase inside the simulation. These events, among the motion capture data and the EEG data, were all synchronized with the help of the LSL tool.

3.2.7 Experiment Questionnaires

This experiment had two types of questionnaires. The first questionnaire is the **Between-Trial Questionnaire.** At the end of each trial, each participant was asked to express on a scale from 1 to 10 their feelings of dizziness, discomfort, nausea, fatigue, headache, and eyestrain. The symptoms were chosen following previous works [116, 181, 229], which also used a sub-set of symptoms in trials to avoid disrupting the immersion.

The second questionnaire is the **Post-Experiment Questionnaire.** Upon completing the VR session, each participant was asked to complete a full SSQ, followed by a semi-structured post hoc interview session where the researcher encouraged them to think out loud about their experience and responses to the questionnaire.

3.2.8 EEG Data

Overall, there are three types of information obtained from an EEG device: **spatial, spectral, and temporal**. **Spatial** information refers to the different parts of the brain where the information is localized. **Spectral** information focuses on the changes in power at specific frequency bands. **Temporal** information focuses on the variations of the signal over time. This experiment will focus on **spatial and spectral** information. These two types of information have been proven to work better for movement-based experiments and are easy to be later exported to closed-loop systems [122].

This research project required building a data-processing pipeline that transforms the EEG data to a state ready for analysis. The design of this pipeline consists of three steps, *pre-processing, epoching, and output interpretation*:

- The first process is the *pre-processing* of data. Because the experiment involves participants walking, this step involves removing all the noise produced by these movements. The output of this step is clean, raw data.

- The second process is called *epoching*. Because the recorded EEG data is continuous, it must be cut into different segments [36]. The criteria to cut the data into segments needs to be something significant to the experiment. For example, this experiment will segment the data into segments based on each trial's start and end. The output of this step is clean, raw data divided into different segments.

- The final process is the *data interpretation*. This step involves transforming raw data into a data set that can be analyzed by standard statistical methodologies.

All the EEG data analysis steps were performed in EEGLAB [42, 43] version 14.1.2 in Matlab (Mathworks Inc., Natick, Massachusetts, USA). Overall the combination of these two tools is the gold standard for EEG analysis [37]. The next sections will talk in detail about each step that makes up the data-analysis pipeline.

3.2.8.1 EEG Pre-processing

This section lists and describes all the steps that involve pre-processing the EEG data. These pre-processing steps follow previous works [49, 115] that process EEG data for mobile experiment setups.

- *Data downsample.* The EEG data was first down-sampled to 250 Hz. The data needs to be down-sampled to reduce the computation time of the data [36]. The value of 250 Hz allowed so that, despite reducing complexity, the data still keeps its quality.

- *Band-pass filter.* A band-pass filter (1-100 Hz) is then applied to the data. This filter removes any unexpected, uncontrolled noise that may contaminate the EEG data [37].

- *Data cleaning.*The filtered data was then cleaned at a notch frequency of 50 Hz and its harmonics, the p-value for detection of significant sinusoid was set at 0.01 by CleanLine plug-in (v1.03) [139]. This process helps clean the data from the noise produced by external sources such as AC power suppliers, fluorescent lights, among other sources [157].

- *Bad data removal*. The next step is to remove any potential bad data. Any potential flat segments were removed if their signal was consistently flat for more than 3 seconds. Next was the identification and removal of any bad channels. This step involved using a correlation threshold (threshold = 0.85) between its value with nearby channels and its distribution power (std = 4). Next, the removed bad channels were interpolated via a spherical method. These processes help remove noisy information produced by eye blinks, muscle activity, sensor motion. The parameters are the default parameters suggested by the EEGLAB plug-in [42, 43].

- *Independent Component Analysis.* Finally, all the channel data were processed by independent component analysis (ICA). This process is a widely used process used by the EEG research community [42] and helps remove some unnecessary noise and extract the maxima independent source activation. The adaptive mixture independent component analysis (AMICA) [153] was then used in this study with default parameters. This process further improved the removal of any artifacts in the datasets.

3.2.8.2 Data Epoching

As previously stated, the data was divided into significant segments for their interpretation. For these data sets, the data was epoched into seven segments. Each data segment represented a TG level, defined in the experiment design: $\{NoVR, 1, 2, 4, 6, 8, 10\}$.

The first three-quarters of a walking trial were used to calculate the epoch length. This period consists of the point after the participant turned to start walking towards the red arrow and right before they stopped to turn back. The decision to use this section was to avoid any noise derived from body turning.

Each participant produced an average trial time value. These time values were used to calculate the exact length of each segment. The final epoch length then consisted of the shortest averaged trial length, which was 12.45 seconds.

3.2.8.3 EEG processing

The previous phases produced an EEG data set that could be interpreted by standard EEG processing methodologies. The following steps discuss each of the steps that were followed. The EEG analysis was based on channel power.

- *Divide channel power into brain regions.*To process the data, firstly, the data was divided into five brain regions: Frontal (*Fz, F1, F2, F3, F4, F5, F6, F7, F8*), Central (*Cz, C1, C2, C3, C4, C5, C6*), Parietal (*Pz, P1, P2, P3, P4, P5, P7, P8*), Occipital (*Oz, O1, O2*) and Temporal (*T7, T8*).

- *Noisy trial removal*. Because some of the trials still contained some noise values, these trials were further processed. The method of identifying and removing bad trials was them having a raw value outside the $mean \pm 3std$. In this process, it was discovered how the first trial of TG $1x$ for all participants fell into this category because most participants interrupted the trial to ask questions, adjust the headset or other things that caused noise in the EEG signals. In this process, two entire subjects were removed.
- *Data Grouping*. The first grouping of data was by the level of TG. For each user, the trials were grouped into levels of TG. Afterward, the data of each of the channels that make up each brain region was averaged. At this point, the data was organized by TG, for each brain region, for each user.
- *Power Spectral Density Calculation.* The next step is to calculate the Power Spectral Density (PSD) of the signal of each channel. This methodology is a widely used methodology to make channel-based comparisons on EEG data [36, 37, 225]. The *spectopo.m* function from EEGLAB was used to generate the PSD data for each user. This process was repeated for all the TG levels, for all the brain regions, for all the users.
- *Data Organization*. Finally, the data was organized into different bands based on the data's frequency. These bands are delta (1Hz - 4Hz), theta (4Hz - 8Hz), alpha (8Hz - 13Hz), beta (13Hz - 30Hz), and gamma (30Hz - 80Hz).

3.2.9 Biomechanics Measurements

3.2.9.1 Center of Mass

The analysis of the changes in the CoM consisted of calculating the displacement between the CoM measured during the baseline walking trials without the VR headset and the CoM measured during virtual walking at different TG. The methodologies described by Lafond et al. [107] were used to calculate CoM. The length of all trials was aligned by MATLAB's Dynamic Time Warping function to facilitate average CoM displacement calculation.

3.2.9.2 Gait Parameters

The gait parameters calculated were step distance, cadence, and time to complete a trial. Step distance was calculated based on the motion of the markers on the participant's feet.

The work by Hreljac and Marshall [75] was followed to obtain the stepping information. Each step was segmented by detecting changes in acceleration direction during walking. More specifically, the function called *findpeaks.m* from MATLAB was used. The *MinPeakProminence* parameter was set to 0.01 to remove all the noise peaks, leaving only those peaks that represented a significant movement of the feet. This information was later used to calculate the number of steps a user used in each trial. Finally, to calculate cadence, the number of steps per minute given by each user was calculated.

CHAPTER 4

EVALUATION OF BALANCE RECOVERY TECHNIQUES OF STATIC VR-USERS

This chapter presents the results and discussion based on the experiment design explained on Chapter 3, Section 3.1. The results will be reported using the following abbreviations: *AW* for auditory warning, *VST* for video-see-through, *PFAW* for pre-fall audio warning, *PFVST* for pre-fall video-see-through, and *N* for the baseline condition with no intervention. For the stepping strategies, the abbreviations will be NS for No-Step, SS for Single-Step, and MS for Multiple-Steps. For brevity, we refer to trials in which subjects adapted the single-step strategy as SS trials; the same naming convention applies to the MS trials and N Trials.

4.1 Experiment Results

4.1.1 Stepping Strategies

The bar chart in Fig. 4.1 shows the percentage of the resulting stepping strategies for all five mitigation methods. The SS strategy was the most predominantly employed strategy across the conditions; the MS strategy was the second most prevalent strategy. *PFAW* and *PFVST* conditions induced some use of the NS strategy, while *VST* and *N* conditions did not induce any use of the NS strategy. The no-step and single-step recovery strategies yield more desirable reactions to an unexpected fall [64]. These results suggest that *PFVST* may enable a better recovery, while *VST* appears similar to the baseline

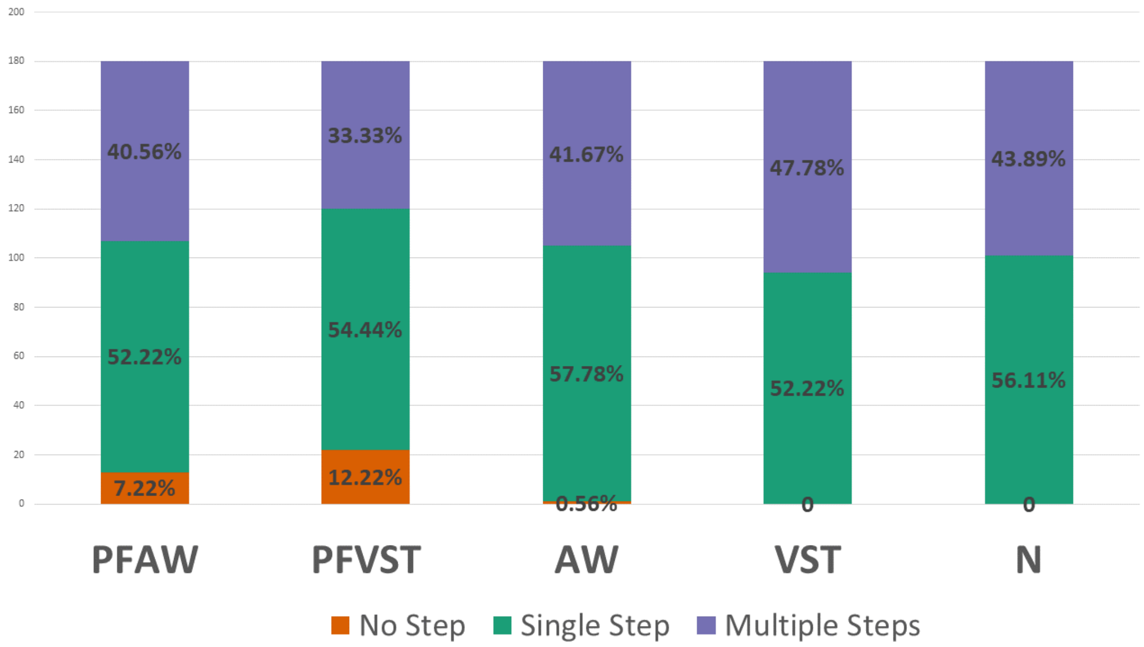

Figure 4.1: Bar charts that represent the distribution of the step reactions (no-step, single-step, and multiple-steps) for the 5 mitigation methods.

condition.

4.1.2 Overall Analysis

Fig. 4.2 shows the first step length for all five conditions. Fig. 4.3 shows a box plot of the step length for each condition. For the MS trials, only the first step length is presented. The step length for each condition are *PFAW* ($\mu = 0.4459, \sigma = 0.1916$),$PFVST(\mu = 0.3742, \sigma = 0.2026), AW(\mu = 0.4897, \sigma = 0.17504), VST(\mu = 0.5063, \sigma = 0.1769), andN(\mu = 0.50908, \sigma = 0.19108)$.

A multiple linear regression analysis showed that the *timing* variable had a significant effect on the step length ($Beta = -0.04375, p = 0.03252$), whereas the *technique* variable does not have a significant effect on the step length ($Beta = 0.01659, p = 0.41818$). A significant effect from the *timing* * *technique* interaction ($Beta = -0.08827, p = 0.00238$) was observed. The total model fit was R-squared = 0.06542.

A Kolmogorov-Smirnov (with Lilliefors Significance Correction) test and a Shapiro-Wilk test for normality were performed to test the data for normality. The analysis showed that the data do not follow a normal distribution ($p < 0.05$ for all 5 methodologies). A permutation test of independence was conducted to determine if any difference exists

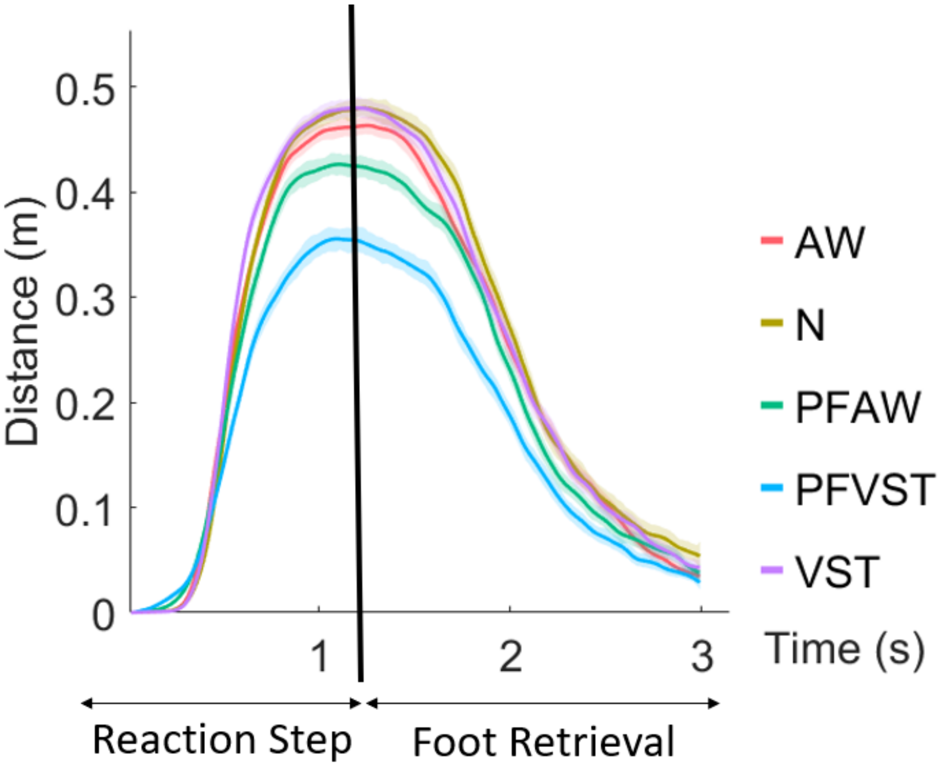

Figure 4.2: First reaction step movement vs. time for all trials.

among the methodologies. The test showed a difference in at least two of the methodologies ($maxT = 6.7289$, $p - value = 6.97e - 11$). A permutation test was performed to examine the differences among all methodologies. This analysis indicated that *PFVST* had a shorter step length than the other techniques and was significantly different compared with all techniques: between *PFVST* and *PFAW* ($\pm 0.0717m$, $p = 0.0011$), between *PFVST* and *VST* ($\pm 0.132m, p < 0.001$), between *PFVST* and *AW* ($\pm 0.1154m, p < 0.001$), between *PFVST* and *N* ($\pm 0.1348m, p < 0.001$). The second shortest step length was produced by *PFAW*, which produced a significantly different step length compared with *VST* ($\pm 0.06m, p = 0.003$), compared with *AW* ($\pm 0.09m, p = 0.03$) and compared with *N* ($\pm 0.063m, p = 0.003$).

Both the *PFAW* method and the *PFVST* method outperformed the baseline regarding the step length and the step initiation time. The *PFVST* method exhibits the best performance. Conversely, the measurements of *AW* and *VST* do not show a significant difference against the baseline condition.

Fig. 4.4 shows the step initiation timing for each condition. Auditory notification before the fall onset causes an earlier step initiation for the *PFVST* and *PFAW* conditions.

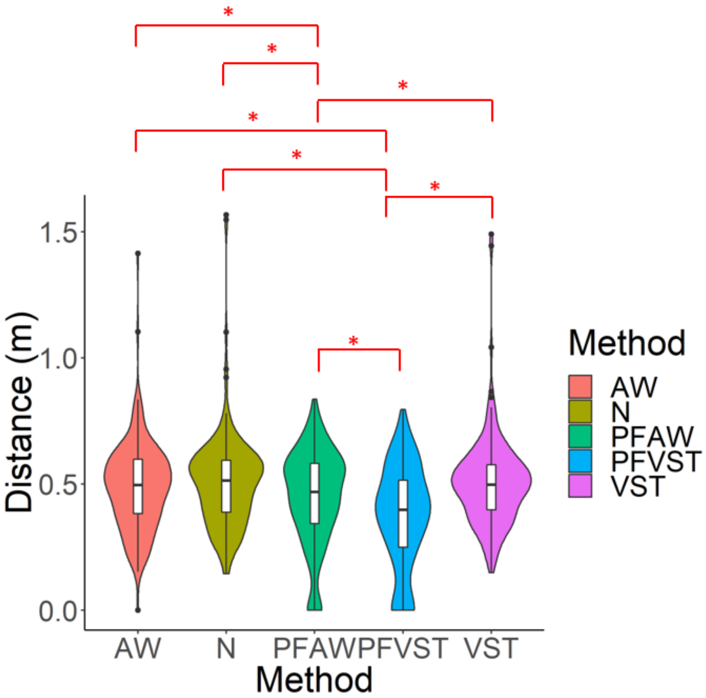

Figure 4.3: First step length (m) box plot for all trials. * means significant difference (p <0.05).

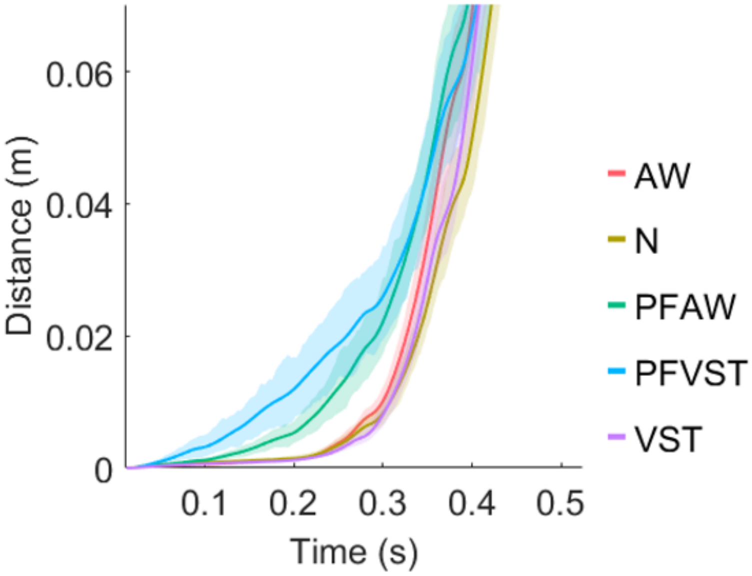

Figure 4.4: Step Initiation for all trials. The shorter the time, the better. In this case, *PFVST* and *PFAW* are the methods that present a faster step initiation.

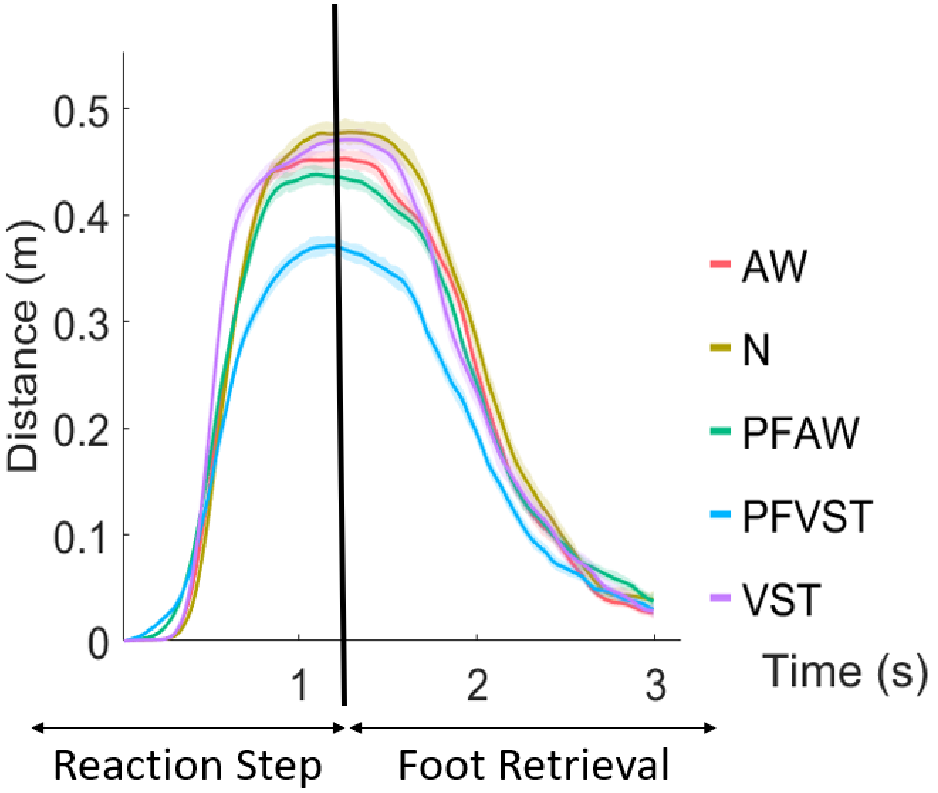

Figure 4.5: Movement of the reaction step in single-step trials.

As suggested in previous studies, [21, 76], an early step initiation is optimal for improved recovery from an unexpected fall, which corroborates the result of the step length.

4.1.3 Trials with Single Step Strategy

This subsection reports the measurements for SS trials. Fig. 4.5 shows the averaged foot movement distance after the fall onset for SS trials. Fig. 4.6 shows the box plot for the averaged step length for SS trials. The step length for each condition are $PFAW\ (\mu = 0.4767, \sigma = 0.1532), PFVST(\mu = 0.4222, \sigma = 0.1558), AW(\mu = 0.4879, \sigma = 0.1278), VST(\mu = 0.4966, \sigma = 0.1555), andN(\mu = 0.5059, \sigma = 0.1821)$.

A multiple linear regression analysis revealed that the *timing* variable has a significant effect on the step length ($Beta = -0.04266, p = 0.00775$). The *technique* variable does not have a significant effect on the step length ($Beta = -0.02231, p = 0.162212$). A significant effect from the *timing* * *technique* interaction ($Beta = -0.0631, p = 0.0473$) was observed. The total model fit was R-squared = 0.03754. A Kolmogorov-Smirnov (with Lilliefors Significance correction) test and a Shapiro-Wilk test for normality were

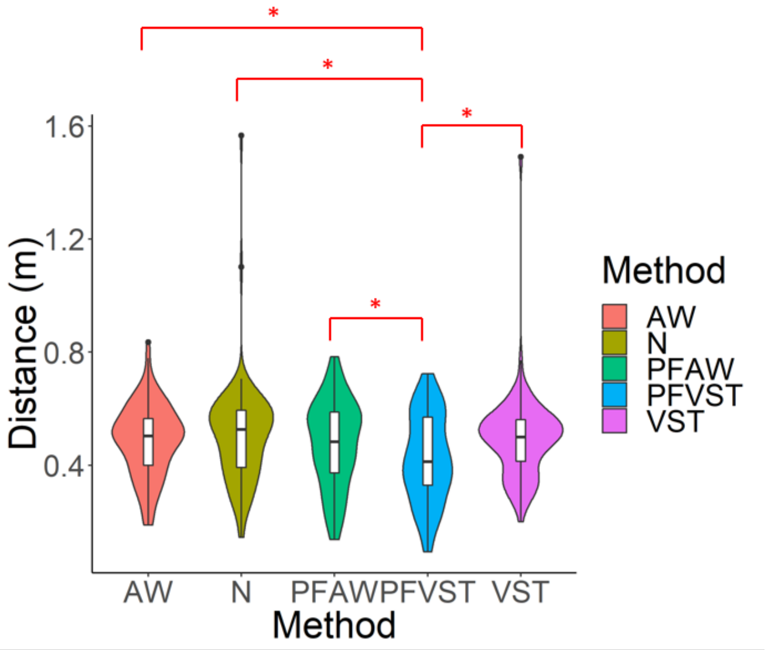

Figure 4.6: Step length (m) box plot for trials using the single-step strategy.

performed to test the data for normality. The analysis showed how only *PFVST* followed a normal distribution in the KS test, and how *AW*, *PFAW*, and *PFVST* follow a normal distribution in the SW test ($p > 0.05$). A permutation test of independence was conducted to determine if any differences exist among the methodologies. The test showed a difference among at least two of the methodologies ($maxT = 3.7218, p-value = 0.001024$). A pairwise permutation test was utilized as a post hoc test to identify any significant differences among the methods. The test showed a significant difference between *PFVST* and *PFAW* ($p = 0.02273$), between *PFVST* and *VST* ($p = 0.002137$), between *PFVST* and *AW* ($p = 0.00237$), and between *PFVST* and *N* ($p = 0.001317$).

For the SS trials, *PFVST* condition outperforms all other techniques, including the *PFAW* condition, due to the sudden interruption in the simulation to display the visual input to assist balance recovery compared with the auditory input.

Fig. 4.7 shows the step-initiation times for the SS trials. Similar to the results shown in Fig. 4.4, the *PFAW* and *PFVST* techniques exhibit an earlier step initiation.

4.1.4 Trials with Multiple-Steps Strategy

This subsection reports the measurements for the MS trials. Figure 4.8 shows the average foot movement distance of the first reaction step among multiple steps after

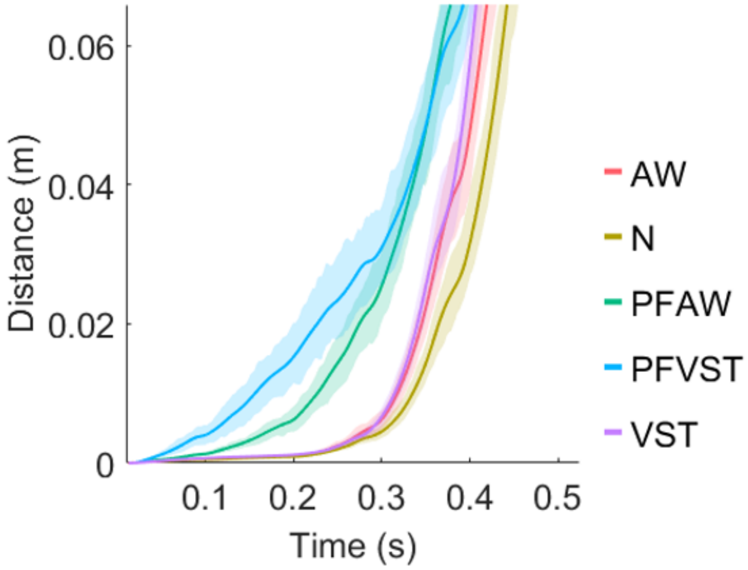

Figure 4.7: Step initiation for trials that used the single-step strategy. *PFVST* and *PFAW* present the better step initiation.

fall onset for the MS trials. Figure 4.9 shows a box plot for the step length of the first reaction step for each condition. The step length for each condition is *PFAW* ($\mu = 0.4909, \sigma = 0.1401$), *PFVST* ($\mu = 0.4382, \sigma = 0.1512$), *AW* ($\mu = 0.4985, \sigma = 0.2152$), *VST* ($\mu = 0.5163, \sigma = 0.1973$), and *N* ($\mu = 0.5129, \sigma = 0.228$).

A multiple linear regression analysis reported that the *timing* variables do not have a significant effect on the step length ($Beta = -0.00764, p = 0.799$) and the *technique* variable does not have a significant effect on the step length ($Beta = 0.0177, p = 0.544$). No significant effect from the *timing * technique* interaction ($Beta = -0.0704, p = 0.106$) is observed. The total model fit was R-squared = 0.02273. A Kolmogorov-Smirnov (with Lilliefors Significance correction)test and a Shapiro-Wilk test for normality were performed to test the data for normality. The analysis indicated that only *N* does not follow a normal distribution for the KS test and *PFAW*, and *PFVST* follow a normal distribution for the SW test ($p > 0.05$). A permutation test of independence was conducted to identify any differences among the methodologies. The test revealed no differences among at least two of the methodologies ($maxT = 2.4618, p-value = 0.6422$).

Figure 4.10 shows the step-initiation times for the MS trials. Unlike the plot for the SS trials (Fig. 4.7), the *PFAW* and *PFVST* conditions do not exhibit a distinct advantage over other conditions. Because subjects were less prepared for the fall, which evidenced using the multiple-step strategy, they could not take full advantage of pre-fall stimuli.

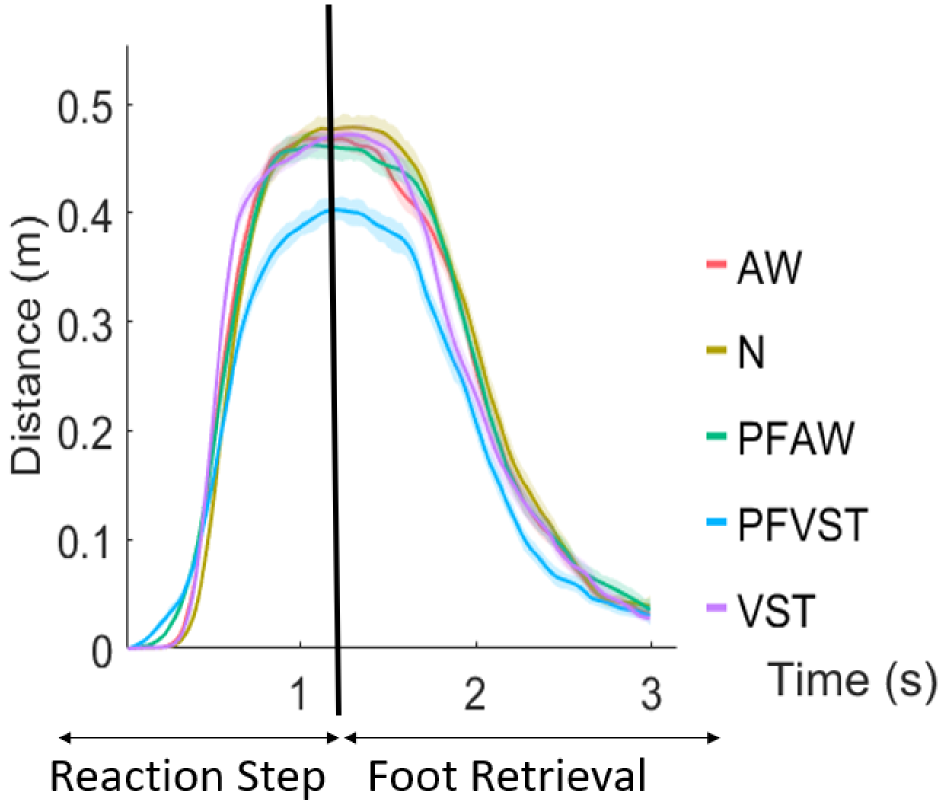

Figure 4.8: Movement of the first reaction step in trials where users implemented the multiple-steps recovery technique.

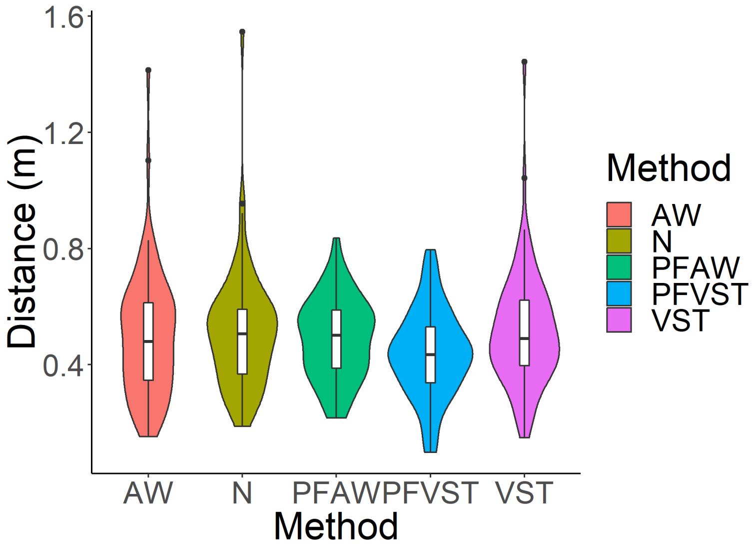

Figure 4.9: Step distance (m) box plots for the first reaction step of trials where multiple-steps strategy was used.

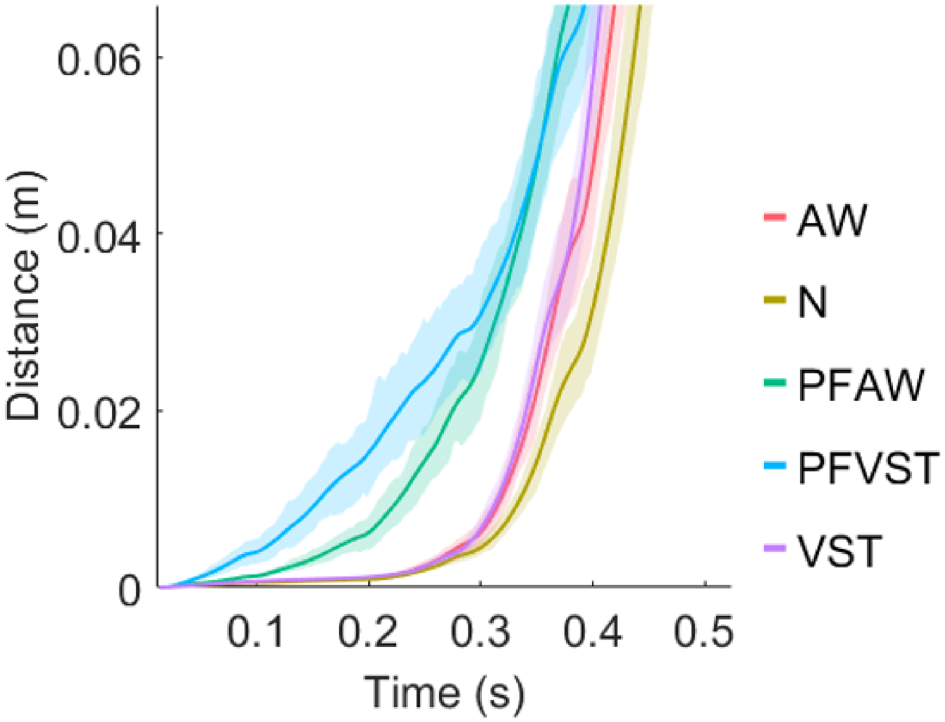

Figure 4.10: Step initiation for the first step in trials using multiple-steps strategy.

4.1.5 User Ratings

Figure 4.11 shows the questionnaire results about subjects' preferences for the assistive techniques for regaining balance after fall onset. The results suggest that subjects preferred pre-fall interventions, i.e., *PFVST* and *PFAW*, while baseline had the lowest rating. A permutation test was performed to identify any differences among any of the conditions. The results show how *AW* and *VST* are statistically equivalent, and how *PFAW* and *PFVST* are also statistically equivalent. The remaining combinations were significantly different.

4.2 Overall Results Discussion

The results showed that *LR-H2* was correct and that pre-fall interventions generally induce better performance. The *PFVST* and *PFAW* conditions more efficiently help users recover from a fall than the no intervention (baseline) condition. The *PFVST* condition produced the smallest step length, an earlier step initiation timing, and the largest number of no-stepping trials. The questionnaire also suggested that *PFVST* was most

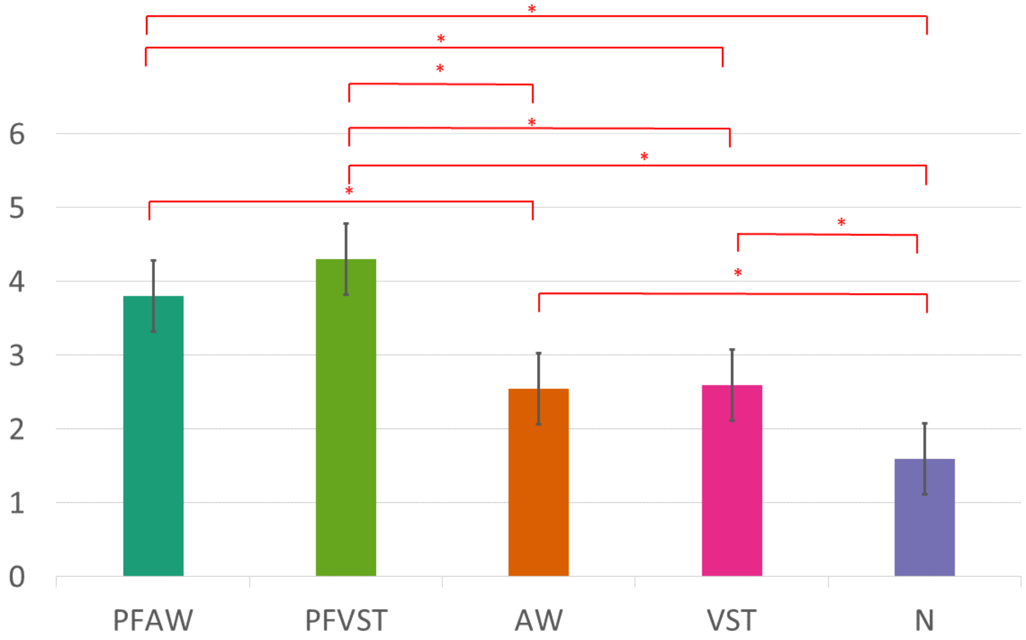

Figure 4.11: User ratings for the 5 different recovery techniques. A 1-5 Likert scale was used.

effective among all conditions. The results provide preliminary evidence that re-exposing a user to the real-world environment helps the balance recovery process, although at the cost of disrupting the virtual experience.

Both *LR-H1* and *LR-H3* were only partially correct. Contrary to expectations, the *AW* and *VST* conditions, which occur at fall onset, did not cause significant improvement compared with baseline. Only the pre-fall interventions increased the performance of fall recovery. The *VST* condition even induced a larger average stepping distance and a larger step initiation time. *LR-H3* was only partially correct because *PFVST* proved to be the best method among the pre-fall methodologies.

VST and *AW* provided additional sensory information and required multisensory integration at fall onset. The earlier may have disrupted the subjects' mental process of regaining balance. Achieving proper balance is a process that requires integrating sensory inputs, such as visual, proprioception, haptic, and the vestibular systems [126, 136]. When a sensory input is missing, the remaining of the sensory inputs take charge of balance. This experiment blocked the vision of a subject with the VR headset. In this situation, participants mainly relied on the proprioception and the vestibular system for balance control. The sudden introduction of visual (*VST*) or auditory (*AW*) input at fall onset forced an untimely sensory integration process and further disrupted the balance, at least for a short time. *PFVST* and *PFAW* conditions caused better performance because the sensory integration processes were completed before fall onset, improving the subjects preparedness for a fall.

Given the current results of the experiment were both *VST* and *AW* performed similarly, it would be challenging to find a proper differentiation of both techniques at fall onset. Both techniques' timing provides an additional cognitive load to the user when reacting to the fall, having a similar result between these techniques and no intervention. Adding more participants to this experiment will not provide any difference between these techniques. On the contrary, it will solidify how there isn't much difference between these two. Because both add an extra cognitive load (either visually or auditory), adding more participants will only lead these techniques to perform either too similar or worse than no intervention technique.

4.2.1 Disruption of Immersion

According to the post hoc interview, all subjects seem to be fully engaged in the secondary task of object selection in VR. There were no significant behavioral changes from 5 to 10 s when the tether was randomly released. Eight subjects commented that all intervention techniques disrupted their sense of presence in the virtual environment. One subject even favored the baseline of no intervention as the best method because she disliked being interrupted in the virtual environment, even when facing the fall hazard. Ten subjects preferred the auditory warning because it was less disruptive to the VR experience. However, five subjects commented that they completely disengaged from the object selection task and were started preparing for the upcoming fall upon hearing the auditory warning.

4.2.2 Effect of Video-See-Through

Although *PFVST* yielded the best performance, the results do not provide direct evidence on how participants utilized the visuals of the surrounding environment in the process of balance recovery. In the post hoc interview, two participants explicitly stated that the video stream enabled them to look down at their feet, giving them more confidence in their recovery from a fall. Five participants complained about the low resolution of the HTC Vive video. They stated that they believed a higher quality video stream would make the video-see-through method more preferable. These responses seem to suggest that some users are aware of the see-through video content during balance recovery. The

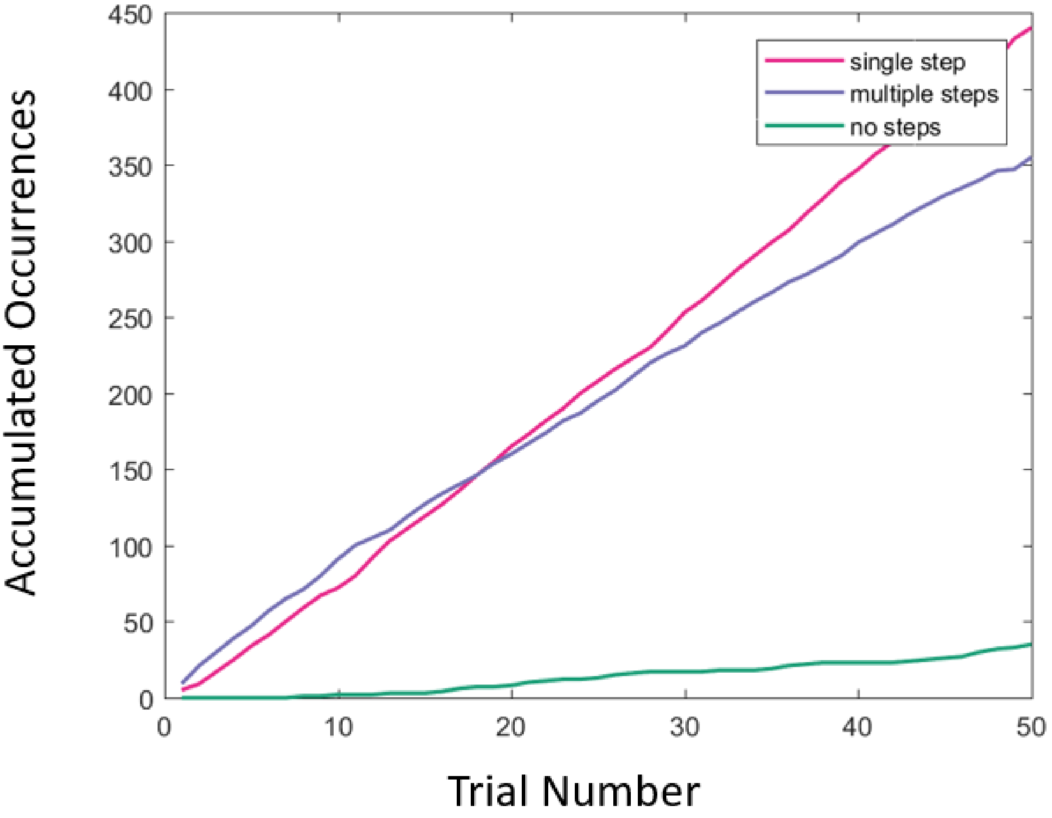

Figure 4.12: Accumulated trial numbers for each stepping strategy.

use of an HMD with an integrated eye-tracker is an exciting research topic to understand how the video feed affects user behavior during fall recovery.

4.2.3 Learning Effect

A learning effect appeared in multiple subjects who initially employed a multiple step strategy to regain balance and evolved into a single-step strategy or a no-step strategy. Fig. 4.12 shows an accumulated stepping strategy usage. There is a slight decrease in MS and an increase in NS toward the end of the experiment. As the experiment progressed, the results suggested that subjects gradually became more efficient in regaining their balance when experiencing an unexpected fall. This experiment protocol addressed this issue by counterbalancing the occurrence of the conditions for each subject.

Another possible interpretation of this result is that the subjects gradually shifted their attention toward the tether's release during the object selection task. However, the data did not show a significant change in the reaction time of the object selection task, and the current design of using a random release timing from 5 to 10 s is plausible.

4.2.4 More Naturalistic Setting

This experiment chose the tether-release protocol for this experiment because its setup has the precise control of fall onset and has a set of well-established measurements. However, it has two significant limitations: 1) it is constrained to forward falling (tripping), and 2) leaning forward is usually not a naturalistic posture for VR users. While forward falling is a common way to lose balance on VR, leaning forward is not a naturalistic posture for VR users to interact with VR scenarios. There are many different experimental paradigms to induce a fall, e.g., a sliding tile on the floor [161], an unexpected obstacle [167], or a sudden force at the waist [162]. Because of the nature of other falls, the findings described in this experiment should be applicable in other paradigms. However, they are bound to finding an effective method to detect the fall on time since the timing required for balance recovery might be quite different.

4.2.5 Detection on Fall Onset

The detection of the onset of a fall has been a significant research problem. The marginal stability method [73] provides reliable prediction but requires the center of mass and the base of support information. Previous research has achieved fall detection using accelerometers on the waist [241], and in a phone [88]. Tong et al. [216] proposed a fall prediction model based on a triaxial accelerometer. As previously mentioned, several research projects achieved detection of postural unbalance combining motion capture systems and EEG devices [92, 194]. An experiment that induces postural unbalance, detects it, and then utilizes the methods proposed by this experiment will shed more light on the timing of these techniques and which one will be better suited to interact with a closed-loop scenario.

4.2.6 Intervention Time

Having a methodology for detecting the fall onset can provide more light on the proper time to intervene and help the user. By using a brain-computer interface, fall prediction can happen within a range of 950 ms [136] to 200 ms [196] before the user starts a reactionary movement to the unbalance her body is suffering. Furthering this experiment with those timings might shed some light on whether an earlier or later intervention will be more helpful for the user and its impact on immersion.

4.2.7 Other Potential Techniques for Balance Recovery

In addition to the video-see-through and auditory warning techniques proposed in this paper, numerous techniques remain to be explored. For example, displaying the user's full-body posture to enhance the user's awareness, or using electrical muscle stimulation to navigate a user [119, 166], or even rendering inertia to counter a fall [66]. However, for this experiment, techniques that work on most of the VR devices available were used. This project intends to propose a hardware-independent technique to provide some help to the highest number of users possible.

4.2.8 Key Takeaway Points

- *L1-H1* was partially correct. Both methods performed well, but only on the pre-fall stage. Video-see-through performed similarly or even worse to no intervention.
- *L1-H2* was correct. The timing of the intervention affected the type of response.
- *L1-H3* was partially correct. Video-see-through performed better than the auditory warning only in the pre-fall mode. On fall onset, auditory warning performed worse.
- On the post-hoc interview, some participants mentioned preferring the auditory warning method over the video-see-through. This group of participants disliked the idea of interrupting their VR session. Other participants explained how pre-fall video-see-through was the best method because it allowed them to look at their feet to prepare for a fall. Other participants preferred to suffer a fall rather than interrupt the scenario.

The results of this experiment can address Research Objective 1. Activating the VR headset's frontal camera or using an auditory notification as soon as a postural instability issue is detected can help users mitigate the issue. Similar to Oculus' Guardian System, that activates the camera when the user walks out of their security boundary. This system can activate the camera once the user is suffering from an uncomfortable posture.

CHAPTER 5

ANALYSIS OF VR SICKNESS AND POSTURAL INSTABILITY ON MOBILE VR SETUPS

This chapter will present the results from the experiment design on Chapter 3, Section 3.2, Analysis 1 (refer to subsection 3.2.3). Later parts of this chapter will discuss those results.

5.1 Experimental Results

5.1.1 Questionnaire Responses

Table 5.1 shows the results of the post-experiment questionnaire. Kennedy et al. [89, 203] suggested a threshold around 18 as an indicator of a problematic sickness level. Eight out of 17 participants had a total severity (TS) score around or higher than 18, including three who quit the experiment prematurely (marked with an * in Table 5.1).

To further investigate the relationship between VR sickness and gait parameter changes, those 8 participants with high TS scores fell into the motion sickness group (MS) and the remaining 9 participants into the no-motion sickness group (No-MS). The analysis followed these divisions. First, the overall group was analyzed. Later, the data was divided into the MS group and the No-MS group for further individual analysis. The descriptive statistics of the questionnaire responses are in Table 5.2.

Table 5.1: Post-experiment SSQ results. Rows with * sign are participants who quit the experiment prematurely. SSQ-N is the nausea score, SSQ-O is the oculomotor score, SSQ-D is the disorientation score, and TS is the total score. Rows with red background color are participants in the MS group, and rows with green background color are participants in the No-MS group.

	SSQ-N	SSQ-O	SSQ-D	TS
S1	19.08	7.58	55.68	17.96
S2*	57.24	75.8	83.52	38.44
S3	9.54	0	13.92	4.74
S4	57.24	45.48	111.36	41.92
S5	0	0	0	0
S6	19.08	30.32	0	6
S7	28.62	22.74	27.84	13.48
S8	9.54	0	13.92	4.74
S9	38.16	22.74	125.28	40.66
S10	19.08	22.74	0	5
S11	0	0	0	0
S12	66.78	75.8	180.96	65.62
S13	28.62	7.58	55.68	18.96
S14*	38.16	7.58	97.44	31.18
S15	0	0	0	0
S16*	76.32	90.96	153.12	61.14
S17	28.62	0	41.76	14.22

Table 5.2: Descriptive statistics for the post-experiment questionnaire responses.

Group	**Mean**	**Variance**	**Standard Deviation**
Overall	24.42	137.993	21.33
MS Group	39.485	264.24	17.38
No-MS Group	5.35	25.77	5.38

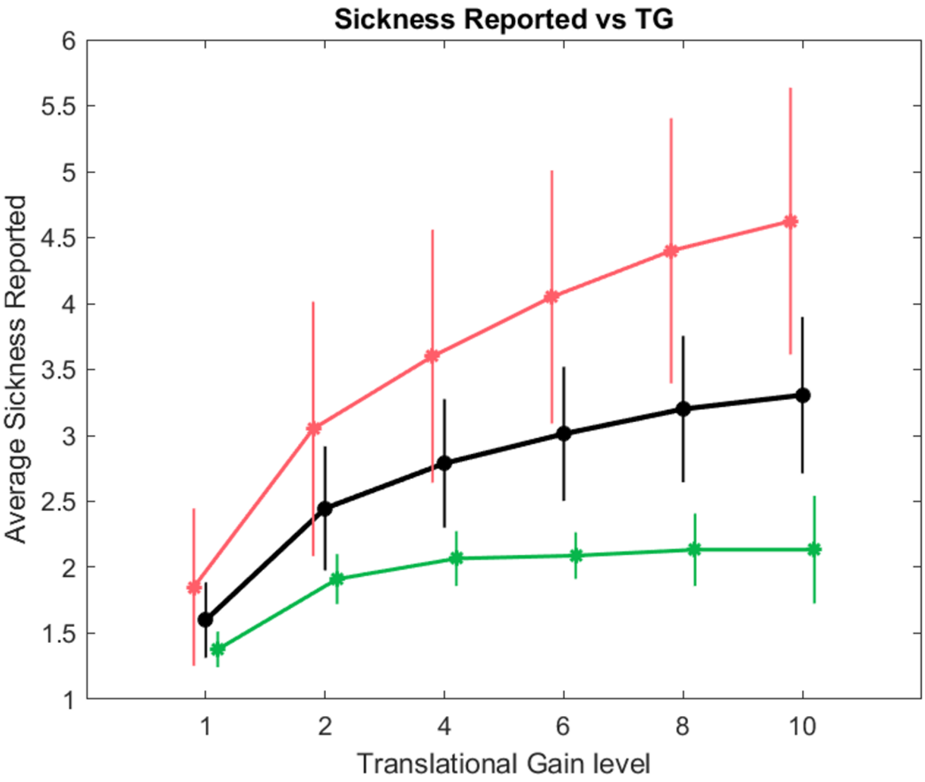

Figure 5.1: Average per-participant response to each TG level. Black Line: Reported sickness levels for all the participants. Red Line: Reported sickness levels for MS participants. Green Line: Reported sickness levels for No-MS participants.

5.1.2 Trial Questionnaire Results

Out of the symptoms recorded, every participant recorded some levels of dizziness, discomfort, and nausea. Only 2 participants reported changes in eyestrain. Four participants reported an increase in fatigue (which they later confirmed was due to wearing the equipment and not because of the interaction with the scenario). Only 3 participants reported headache (2 of which, again, reported it was due to finding the VR headset uncomfortable and not interacting with the scenario).

The responses were averaged from all symptoms at each trial to visualize the between-trial questionnaire results. Those responses were then grouped per TG level for each participant and then averaged with the rest of the participants. Figure 5.1 shows the resulting values for the overall group and the MS and No-MS groups.

A Friedman test was used to test for the main effect of TG on the user questionnaire responses. A Wilcoxon Signed-rank test was used as a post hoc test if there was any effect. For the overall data, the results showed a significant effect of TG on the reported between-trial sickness scores. Results and post hoc tests appear in Table 5.3, the last row.

Table 5.3: Statistical results for the different measurements. The first 4 rows represent different behavior measurements. The last row represents the sickness level reported by each participant. Inside each row, the first horizontal group represents the results of the effect tests. If there was a significant difference, the results of those differences are represented in the in the lower horizontal group.

Behaviour	Overall	MS Group	No-MS Group
Cadence	$\chi^2(5) = 33.59$ $p < 0.001$	$\chi^2(5) = 15.97$ $p = 0.007$	$\chi^2(5) = 21.31$ $p < 0.001$
	$g\{2,4,6,8,10\} - 1$ $g\{4,6\} - 10$	$g\{2,6,8,10\} - 1$ $g\{6,8\} - 4$ $g\{8\} - 2$	$g\{2,4,6\} - 1$ $g\{4,6\} - 10$
Center of Mass Displacement	$\chi^2(5) = 22.98$ $p < 0.001$	$F(1.82, 7.31) = 6.74$ $p = 0.023$	$F(2.46, 19.69) = 5.72$ $p = 0.008$
	$g\{4,6,8,10\} - 1$ $g\{2,10\} - 8$	$g\{4,6,8,10\} - 1$ $g\{10\} - 8$	$g\{4,6,8,10\} - 1$ $g\{4,6,8\} - 2$
Step Distance	$F(2.77, 36.07) = 6.07$ $p = 0.002$	$\chi^2(5) = 18.03$ $p = 0.003$	$F(2.44, 19.55) = 2.52$ $p = 0.097$
	$g\{4,6,8,10\} - 1$ $g\{6,8\} - 2$	$g\{6,8,10\} - 1$ $g\{4,6,8,10\} - 2$	-
Trial Completion Time	$\chi^2(5) = 22.57$ $p < 0.001$	$F(1.26, 5.06) = 2.96$ $p = 0.145$	$\chi^2(5) = 14.65$ $p = 0.012$
	$g\{2,4,6,8,10\} - 1$	-	$g\{2,4,6\} - 1$ $g\{10\} - 6$
Reported Sickness Level	$\chi^2(5) = 41.27$ $p < 0.001$	$\chi^2(5) = 37.49$ $p < 0.001$	$\chi^2(5) = 12.52$ $p = 0.028$
	$g\{2,4,6,8,10\}$ - $\{1,2,4\}$ $g\{8\} - 6$	$g\{1,2,4,6,8,10\} -$ $g\{2,4,6,8,10\}$	$g\{2,4,6,8\} - 1$

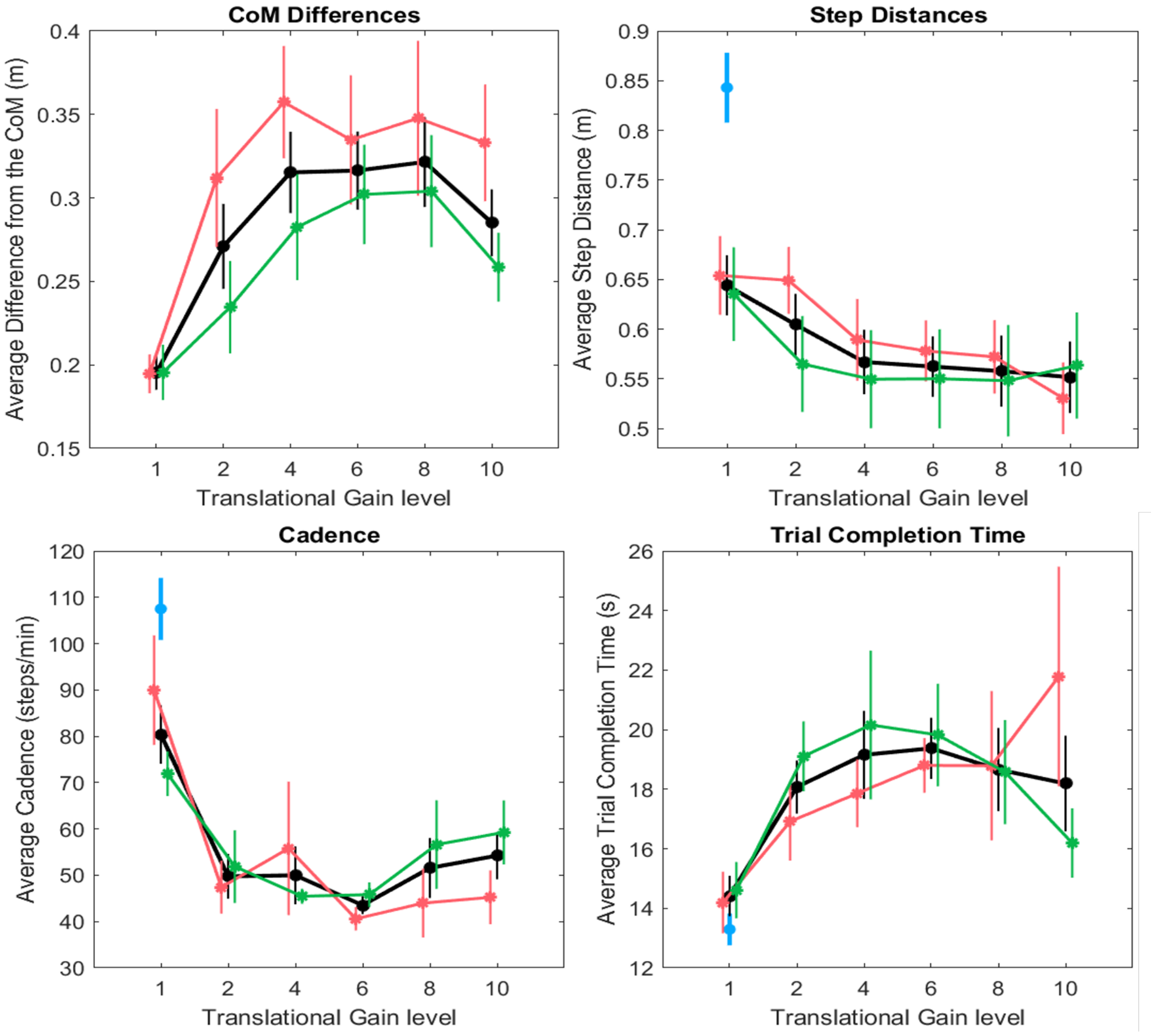

Figure 5.2: Results of different behavior measurements vs. different levels of TG. Black Line: Average. Red Line: Results from participants belonging to the MS group. Green Line: Results from participants in the No-MS group. Blue Line: Average baseline recording without VR. Position dodge function was used to avoid the overlapping of standard error bars.

5.1.3 Behavior and Gait Analysis

The four analyzed measurements were CoM displacement, stepping distance, cadence, and trial completion time. Figure 5.2 shows the changes in each of the measurements at the different levels of TG for all data, MS group, and No-MS group, respectively. Note that for the participants that did not finish the experiment, only the data of the trials they were able to finish was used, producing an unbalanced analysis for the MS group.

The first set of tests compared baseline normal walking without HMD against an isometric virtual walking with $1x$ TG. Normality was tested in the three pairings (cadence, step distance, and trial time completion) using a Shapiro-Wilk test for normality. Cadence and trial completion time failed to follow a normal distribution while step distance followed a normal distribution. For data sets that did not follow a normal distribution, a Friedman test was used to see if there was an effect from walking with the VR headset. For data sets that followed a normal distribution, a repeated measure ANOVA with Greenhouse-Geisser correction was used. For cadence, an effect existed ($\chi^2(1) = 10.28, p = 0.001$). The test on stepping distance revealed that an effect existed ($F(1,21) = 61.54, p = 0.000005$). For trial completion time, there was an effect ($\chi^2(1) = 4.571, p = 0.033$). This analysis was skipped for the CoM data since it already measures a difference between the TG levels and no-VR walking.

The next set of tests compared measurements between different levels of TG. In the case that the data sets followed a normal distribution. A repeated-measures ANOVA with a Greenhouse-Geisser correction to test for effects was used. A paired sample t-test was used as a post hoc. For data that does not follow a normal distribution, A Friedman test was used as a repeated measure test, and a Wilcoxon Signed-rank test was used as a post hoc. Table 5.3 summarizes the results.

For each row, the first set of results shown in Table 5.3 are the results of the effect tests. In case that a difference existed between some levels of TG, these differences appear in the second set of results. For the differences between TG levels, the numbers to the left of the hyphen are the levels of TG that are statistically different from TG levels to the right of the hyphen. For example, $g\{2,4,6,8,10\}$ - $\{1,2,4\}$ means that TG levels 2, 4, 6, 8 and 10 are all statistically different to TG levels 1, 2 and 4.

Finally, a Spearman's rank-order correlation was run to determine the relationship between the different behavior and gait measurements, and the between-trial questionnaires and their different symptoms. Only two statistically significant correlations were found. The first one was a negative correlation between Cadence and the Discomfort symptom of the between-trial questionnaire ($R = -0.36, p = 0.01$). The second was a negative correlation between Step Distance and the Dizzy symptom ($R = -0.33, p = 0.02$).

5.1.3.1 Cadence

The data from the three groups were treated as not following a normal distribution, and the repeated measure tests were used to see if there was any effect of TG levels on the cadence. The results showed that for all the groups, there was an effect of TG on cadence. Row 1 in Table 5.3 shows the results of the post hoc tests.

5.1.3.2 Center of Mass Displacement

After doing a normality test on the three different groups of the center of mass difference, the overall group was treated as not following a normal distribution. In contrast, the MS and No-MS groups followed a normal distribution. For the overall group, the repeated measure test showed an effect of TG levels on the difference in CoM. Row 2 in Table 5.3 shows the results of the post hoc tests.

5.1.3.3 Step Distance

After running a normality test on the different step distance groups, the results showed that the overall group and the No-MS group followed a normal distribution and that the MS group did not follow a normal distribution. For the overall group, the repeated measures test showed an effect from TG on step distance. Row 3 in Table 5.3 shows the results of the post hoc tests.

5.1.3.4 Trial Completion Time

The overall group and the No- MS group did not follow a normal distribution for the trial completion time. The MS group followed a normal distribution. For the overall and No-MS group, the level of TG affected trial completion time. Row 4 in Table 5.3 shows the results of the post hoc tests.

5.1.4 Interview Responses

All participants except one (S2) reported that the symptoms significantly decreased after removing the headset at the end of the experiment. Out of the 17 participants, 8 participants reported that their level of sickness was partially due to the prolonged use of VR; 3 participants (S3, S9, S10) thought their sickness symptoms were mainly due to TG's sudden changes across trials. Three participants reported having no symptoms after the experiment finished.

Three participants (S2, S14, S16) reported high susceptibility to motion sickness from the pre-experiment interviews. S2 and S16 stated that they started to feel uncomfortable as soon as they wore the VR headset. S2 had to stop the experiment at trial 27 (at the gain level of 8x). S2 was also the only participant whose sickness symptoms did not diminish after removing the headset. S5, S11, and S15 did not report any symptoms after the experiment. S5 stated that she is so used to playing first-person shooting video games online that her experience with constant frame drops prevented her from suffering any symptoms. S11 mentioned that she suffers from motion sickness on the bus regularly. However, to her surprise, her VR sickness symptoms subsided once she removed the VR headset. S6 also expressed how each change in translational gain caused her surprise and how this surprise caused her to experience vertigo. S16 expressed her difficulty traveling on an airplane because looking at the movement outside the window causes her motion sickness. During the experiment, the participant expressed that after reaching level 2x, she started feeling the same symptoms. This participant dropped out of the experiment the earliest, quitting once the gain level changed from 2x to 4x.

Out of the 17 participants, 5 participants (S6, S7, S10, S11, S13) reported that after reaching 15 to 16 trials, they could confidently prepare themselves for the next translational gain change, which helped decrease the level of dizziness. Contrary to these statements, 2 participants (S12, S14) expressed that five trials were not enough to get used to the translational gain and that the constant change in translational gain caused their symptoms. It is also worth noting that 2 out of the 17 participants (S13, S14) started to feel dizziness and nausea 20 minutes after the experiment ended, although they reported no symptoms at post-experiment SSQ.

5.2 VR Sickness and Postural Instability on Mobile VR Discussion

The result showed that as the TG level increased, the reported sickness levels in the between-trial questionnaire also increased (Figure 5.1). However, for the No-MS group, whose participants reported low severity scores in the post-experiment SSQ questionnaires, the between-trials VR sickness scores stayed low even after $2x$ TG. They showed no significant difference among the larger TGs $\{4x, 6x, 8x, 10x\}$. This result suggests that non-isometric virtual walking with a large TG could be an effective and practical navigation method for at least a sub-group of users in a scenario where precise destination selection is not required.

Note, one participant reported lower VR sickness at the end of the experiment, possibly because she was better able to adapt to the non-isometric virtual walking or because she was just more resilient to VR sickness in general. Given that none of the participants had ever experienced non-isometric virtual walking before, it would be safe to assume the latter to be correct.

All participants suffered some degree of the symptoms, as reported by their between-trial questionnaire. Half of the participants even suffered from these symptoms to a degree where they were considered significantly sick. During the interviews, participants expressed how TG's changes generated a "surprise," causing the intensity of their symptoms to increase. This response suggests that one of the reasons participants suffered from these symptoms is the visual-proprioceptive conflict happening due to the increasing TG levels. One could argue that their predisposition to motion sickness, seasickness, or other sickness types might be why these users suffered from VR sickness in this experiment. As previously reported, one user mentioned her sensibility to motion sickness during her regular bus travel. To her surprise, she did not suffer from significant symptoms during the experiment.

5.2.1 Gait Performance

This study found that gait performance was significantly different between VR walking and the baseline non-VR walking, which concurred with the findings of Janeh et al. [83]. Among the VR walking trials, the most significant differences in gait performance and CoM displacement were between the $1x$ and other TG levels. The difference was particularly prominent when the study participants first experienced an amplified TG at $2x$, as shown in Figure 5.2. At $2x$ TG, a sudden increase in CoM displacement happened, indicating a decrease in posture stability. Also, the corresponding gait patterns, namely a significantly smaller stepping distance and slower cadence, were signs of participants spending more than usual attentional resources trying to control their gait [232, 234]. These changes also led to a significantly longer trial completion time, even though each trial's physical walking distance is the same.

At larger TG levels, namely $\{4x, 6x, 8x, 10x\}$, there were few pair-wise significant differences between the measurements. Surprisingly, the participants, even on average, performed slightly better at large TG $\{8x, 10x\}$ in some measurements, such as demonstrating smaller CoM displacements and a shorter task completion time. The participants in the No-MS group, i.e., those who did not report severe MS symptoms after the experiment, seemed to adapt to the increase of TG particularly well and even started increasing their step distances and thus reducing the task completion time after $4x$ TG. In contrast, participants in the MS group, i.e., those who had reported severe MS symptoms, struggled to perform the virtual walking task on higher TG levels. With the latter group, all their performance measurements steadily decreased, even though at this stage, the participants had more experience with non-isometric virtual walking. The discomfort from their MS and other MS symptoms seemed to impede their ability to learn and adapt to virtual walking at larger TG levels.

Previous results show how VR sickness affected users' performance and increased the postural instability of the MS group. The sub-group of users who did not suffer from VR sickness was able to perform to the increase of TG better and better adapt at the end of the scenario. Even though the sub-group of MS users was able to adapt at the end, showed by the improvement of performance at the last trials of the experiment, it is still clear how VR sickness affected users' performance.

5.2.2 Difference between Non-VR and VR

Figure 5.2 shows how the difference in CoM increased as the levels of TG increased. It is well known how differences in CoM are a sign of postural instability [130], and we can see how the differences start to appear even on level TG $1x$. Previous reports suggest that instability while wearing a VR headset is similar to standing with eyes closed [74], so it is natural to see these changes happen compared to No-VR. Stepping distance also saw a decrease in the different VR conditions compared to the No-VR condition. Previous reports show how changes in step distance reflect the struggle for balance [21], an how just wearing a VR headset and not having the ability to see one's feet influence the step distance [83].

5.2.3 Hypotheses discussion

P1-H1 This hypothesis is partially correct. There was an increase in VR sickness that increased with the difference in CoM. However, the behavior at the end of the experiment changed based on the participants' group. Participants that did not suffer from VR sickness showed an improvement in their displacement in CoM by the end of the experiment. This improvement happened despite their symptoms, not lowering during the last instances of the experiment. The contrary happened to participants that suffered from VR sickness, which failed to adapt to later stages.

P1-H2 focuses on the effects of VR sickness on postural instability of participants. This hypothesis is also correct. The participants from the MS group suffered from a more significant displacement on their CoM, which is a sign of postural instability [92]. Note how in the No-MS subgroup, users decreased their stepping distance while the MS group did not. Later in the experiment, MS users started to decrease their stepping distance, causing a decrease in their CoM displacement. It would be interesting to study whether participants who suffered from high VR sickness levels were unable to adapt to the scenario like their No-MS counterparts due to them dealing with the severity of their symptoms.

5.2.4 Limitations

The presented experiment design used a single independent variable of translational gain. It would be interesting to investigate whether the results could be generalized for other types of redirected walking techniques, such as rotational and curvature gain. Previous works [65, 205] found that users are more sensitive to translational gain than rotational gain. So it would be interesting to test this statement at larger gain values and people with different susceptibility to VR sickness.

Another limitation of this study is the number of participants. This number was greatly reduced when dividing them into the MS and No-MS groups. It would be interesting to see if these results can be replicated when collecting the information from a larger group of participants. Having a larger number of participants in the MS-Group can also help understand more about the MS population that could not finish the experiment.

Previous works reported that visualization of a virtual avatar would affect the level of a user's presence and induce different responses toward visual stimuli in the virtual environment [9, 188, 191]. However, this experiment opted not to show the virtual avatars because of the challenges involved in visualizing the locomotion animation correctly with the increase in the translational gain. At larger TG, an accelerated animation would create an illusion of sliding on the floor. To avoid the risk of this confounding our participants, we decided to hide the avatar. Nevertheless, it is an interesting research question, and future studies should investigate how to visualize the walking animation correctly when using an amplified translational gain.

5.2.5 Key Takeaway Points

For the group of users that did not suffer from VR sickness:

- Changes in gait performance and displacement of the center of mass were most prominent at level TG $2x$ because it was the first time participants experienced a TG change.
- Gait performance seemed to stabilize and remain stable after TG $2x$.
- This group of participants showed signs of adapting to the large levels of TG. They even started to show improved performance at the end of the experiment.

For the group of users that suffered from VR sickness:

- Out of the eight people in this subgroup, only five people could reach level TG $10x$ of the experiment. The symptoms were so intense for these participants that they had to quit early.
- Unlike the No-MS group, this group could not adapt to the changes in TG. If there was some adaptation, it happened at the end of the experiment.

Regarding the stated hypotheses:

- *P1-H1* is partially correct. While there was an increase in VR sickness that increased with CoM displacement, at the end of the experiment, the group that did not suffer from VR sickness adapted and improved their CoM displacement performance.
- *P1-H2* is correct. There was a big difference in behavior between the two subgroups of users. The difference in behavior between both groups makes it even more relevant to find a detection and solution method for VR sickness and postural instability issues.

These results contribute to the Research Objective 2. Understanding how postural instability is affected by VR sickness contributes to understanding more about their relationship and how necessary it is to detect and mitigate VR sickness. Using the differences in the center of mass to measure postural instability in mobile VR contributes to different ways of measuring postural instability of users in mobile scenarios, and not just using the gait changes.

CHAPTER 6

CORTICAL ANALYSIS OF WALKING IN VIRTUAL REALITY

Following the experiment used in Chapter 5, this chapter presents the cortical results of users interacting with the experiment design proposed at Chapter 3, Section 3.2 (reference subsubsection 3.2.4). Unlike the results of Chapter 5, this chapter's behavioral results are all grouped. Out of the 15 participants described in Chapter 5, two more participants were removed due to the EEG measurement problems.

6.1 Experimental Results

Like the previous chapter (Chapter 5), the results of CoM displacement, stepping distance, cadence, and trial completion time are presented after removing the two participants with faulty EEG signals. Figure 6.1 shows the changes in each of the measurements at the different TG levels for all data. The procedure to analyze our datasets is as follows. The first test applied was a normality test using a Shapiro-Wilk test for normality. If the data followed a normal distribution, a repeated-measures ANOVA with a Greenhouse-Geisser correction was used to test for effects with a paired sample t-test as a post hoc. For data that did not follow a normal distribution, the data were tested using a Friedman test as a repeated measure test and a Wilcoxon Signed-rank test as a post hoc. The statistic results appear on Table 6.1.

Table 6.1: Statistical results for the different biomechanical measurements. The first four rows represent different behavior measurements. The last row represents the sickness level reported by each participant.

Behaviour	**Effects and Statistical Differences**
Cadence	$\chi^2(6) = 45.429$ $p < 0.001$ $g\{2,4,6,8,10\} - \{NoVR,1\}$ $g\{4,6\} - 10$
Center of Mass Displacement	$\chi^2(5) = 18.429$ $p = 0.002$ $g\{2,4,6,8,10\} - 1$ $g\{6,8\} - 10$
Step Distance	$F(2.19, 24.085) = 17.892$ $p < 0.001$ $g\{1,2,4,6,8,10\} - NoVR$
Trial Completion Time	$\chi^2(6) = 28.429$ $p < 0.0001$ $g\{1,2,4,6,8,10\} - NoVR$ $g\{2,4,6\} - 1$
Reported Sickness Level	$\chi^2(5) = 36.067$ $p < 0.001$ $g\{2,4,6,8,10\}$ - $\{1,2\}$

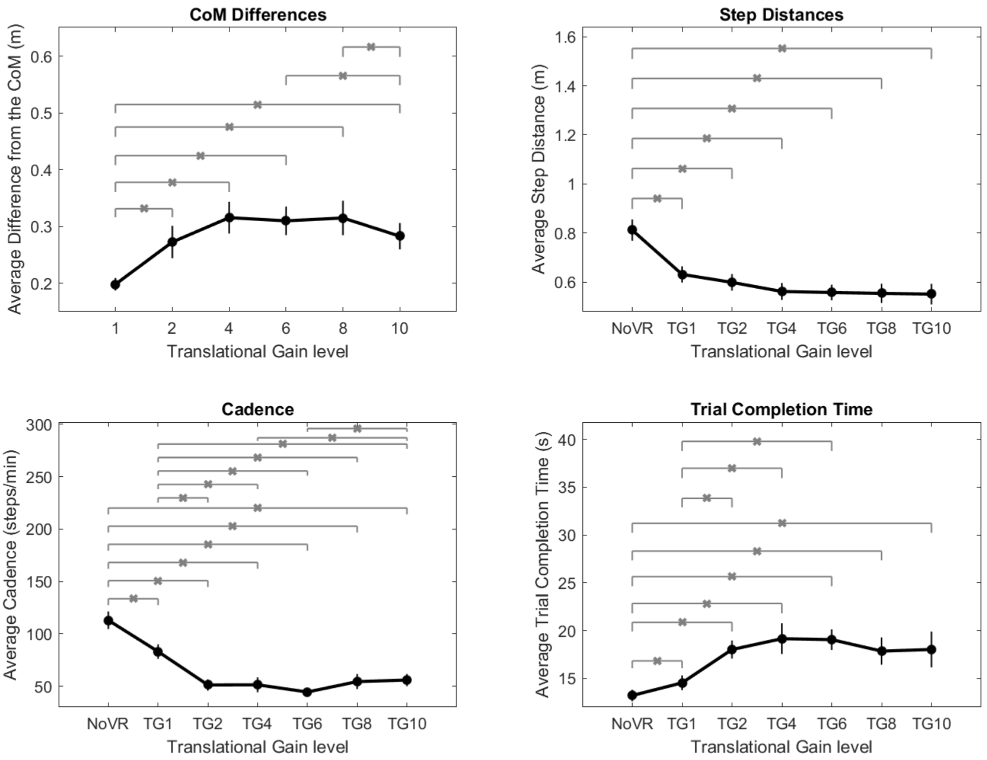

Figure 6.1: Results of the different behavior measurements vs. TG levels. (*) indicates for statistic difference ($p<0.05$).

6.1.1 Analysis Procedures

Figures 6.2 - 6.6 show the power change on each TG level for each brain region for each frequency. For all the plots, the x-axis shows the different levels of TG. The y-axis represents the average power at that specific level. Each of the lines represents each of the different brain regions. In this analysis, the selected brain regions and frequencies were those related to two main categories: VR sickness and gait, balance, and posture.

On each data set, the procedure was the same as the behavior data. The first step was to test for the normality of the data. None of the datasets followed a normal distribution. The second step was to use a Friedman test to find a statistical difference between TG levels. The third step was to apply a Wilcoxon Signed-rank test as a post hoc if the Friedman test detected a statistical difference. The last analysis performed on the data was a Spearman correlation test. This test allowed us to see if there was a relationship between EEG power and the different behavior results. The comparisons were made against CoM difference, step distance, cadence, completion time, the added up

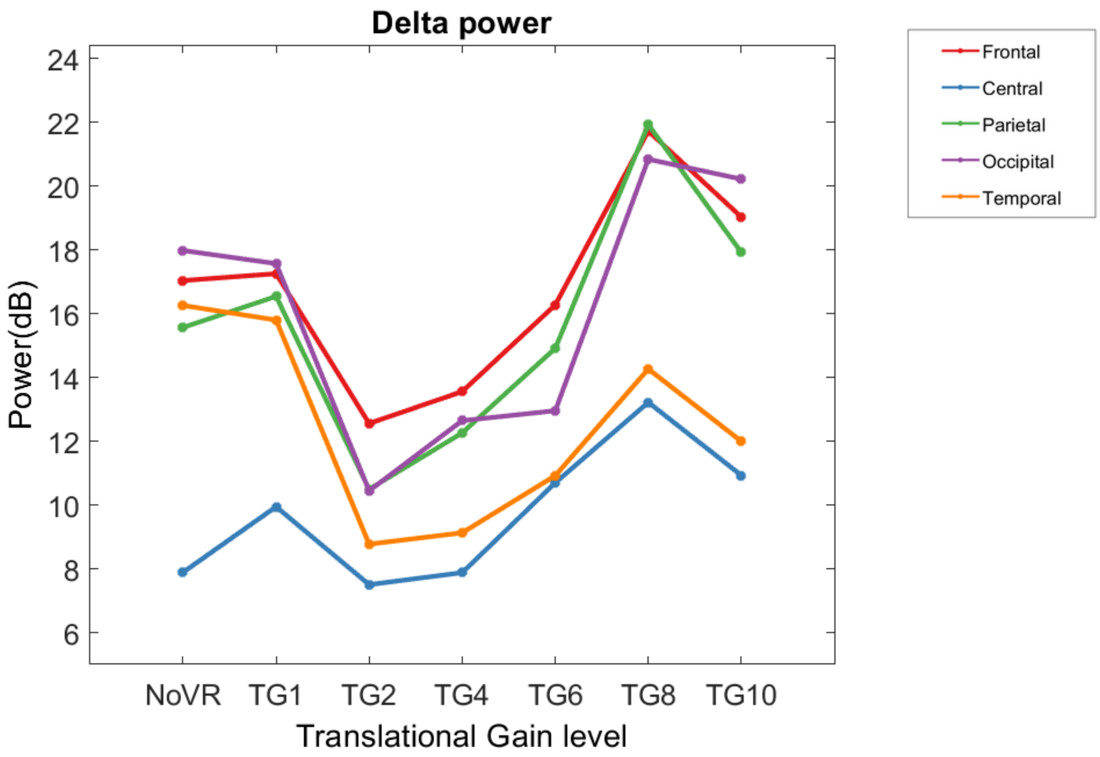

Figure 6.2: The power of the Delta frequency in dB for each TG level at each brain region.

results of the between-trial SSQ, and the set of sub-symptoms used for the between-trial questionnaire.

6.1.2 VR Sickness Results

Based on previous works on VR sickness [28, 29, 98, 131, 156], several brain regions and frequencies of interest were selected for the analysis. The Delta frequency was selected for all the brain regions and Theta frequency for Central and Parietal regions.

6.1.2.1 Delta Frequency for VR Sickness

Figure 6.2 shows the Delta frequency results in the different brain regions. Table 6.2 shows the statistical results from this frequency. Figure 6.2 shows how most brain regions follow a similar pattern. There is an increase in power at TG level $1x$, compared to the baseline No-VR condition. Then all the signals suffer a significant decrease at TG level $2x$. The overall power then continues to increase over all TG levels before reaching

Brain Region	Effects and Statistical Differences	Correlations
Frontal	$\chi^2(6) = 8.107$, $p = 0.23$	SSQ ($R = 0.3$, $p = 0.004$) Discomfort($R = 0.23$, $p = 0.02$) Dizziness ($R = 0.26$, $p = 0.008$) Fatigue ($R = 0.45$, $p < 0.001$) Headache ($R = 0.44$, $p < 0.001$) Nausea ($R = 0.36$, $p < 0.001$)
Central	$\chi^2(6) = 3.429$, $p = 0.753$	SSQ ($R = 0.28$, $p = 0.004$) Discomfort ($R = 0.22$, $p = 0.02$) Dizziness ($R = 0.28$, $p = 0.004$) Eyestrain ($R = 0.21$, $p = 0.03$) Fatigue ($R = 0.34$, $p < 0.001$) Headache ($R = 0.28$, $p = 0.005$) Nausea ($R = 0.3$, $p = 0.002$)
Parietal	$\chi^2(6) = 13.036$, $p = 0.042$ $g\{8\} - 1$ $g\{4,8\} - 2$	SSQ ($R = 0.22$, $p = 0.02$) Dizziness ($R = 0.22$, $p = 0.02$) Fatigue ($R = 0.43$, $p < 0.001$) Headache ($R = 0.33$, $p < 0.001$) Nausea ($R = 0.26$, $p = 0.009$)
Occipital	$\chi^2(6) = 18.107$, $p = 0.006$ $g\{NoVR, 1, 4, 8\} - 2$ $g\{4,6\} - 8$	SSQ ($R = 0.21$, $p = 0.04$) Dizziness ($R = 0.2$, $p = 0.04$) Fatigue ($R = 0.44$, $p < 0.001$) Headache ($R = 0.37$, $p < 0.001$) Nausea ($R = 0.26$, $p = 0.009$)
Temporal	$\chi^2(6) = 15.143$, $p = 0.019$ $g\{NoVR, 1, 4, 6, 8\} - 2$ $g\{4\} - 1$	SSQ ($R = 0.23$, $p = 0.02$) Dizziness ($R = 0.26$, $p = 0.01$) Fatigue ($R = 0.38$, $p < 0.001$) Headache ($R = 0.3$, $p = 0.003$) Nausea ($R = 0.3$, $p = 0.002$)

Table 6.2: Delta Frequency results

TG level $10x$, where the signal decreases. Table 6.2 shows only a statistical difference at Parietal, Occipital, and Temporal brain regions.

The last column of Table 6.2 shows the correlation analysis results. While there was no correlation between the Delta frequency and any kinematic behavior, correlations between the different between-trial questionnaires and the frequency were found. The results show how the Delta frequency at all brain regions correlated with the between-trial SSQ questionnaire values. Correlations with the individual symptoms of Dizziness, Fatigue, Headache, and Nausea were also found.

6.1.2.2 Theta Frequency for VR Sickness

Figure 6.3 shows the different power values at the different TG levels at the Theta frequency. Table 6.3 shows the results of the relevant brain regions related to VR sickness. The Central and Parietal brain regions are represented by the blue and the green lines, respectively. There is a decrease of power in the Central brain region that starts at the baseline No-VR level and continues at TG level $1x$ and finishes at TG level $2x$. Then the signal proceeds to increase until TG level $8x$. After that, the power decreases again at level $10x$.

The Parietal brain region follows a similar trend to that of the Central brain region. However, the decrease in TG level $2x$ is more accentuated than that in the Central brain region. Statistical results at table 6.3 reflect the differences between the two brain regions. The Central brain region shows no statistical difference between any of the levels of TG. In contrast, the Parietal brain region shows a difference between the No-VR baseline level and levels $2x, 6x$, and $10x$. There is also a significant difference between TG levels $2x$ and $4x$.

The correlation results are found on Table 6.3, third column. Both brain regions correlated with Fatigue, Headache, and Nausea symptoms from the between-trial questionnaire.

6.1.3 EEG Postural Unbalance Results

Based on several previous works that study VR sickness [147, 165, 194–196], this study selected several brain regions and frequencies that are known to activate when a user is struggling to maintain balance. Previous reports suggest that Gamma frequency changes in the Frontal brain region represent changes in posture [194, 196]. Similar reports suggested using the Central brain regions in the Alpha, Beta, and Gamma frequencies

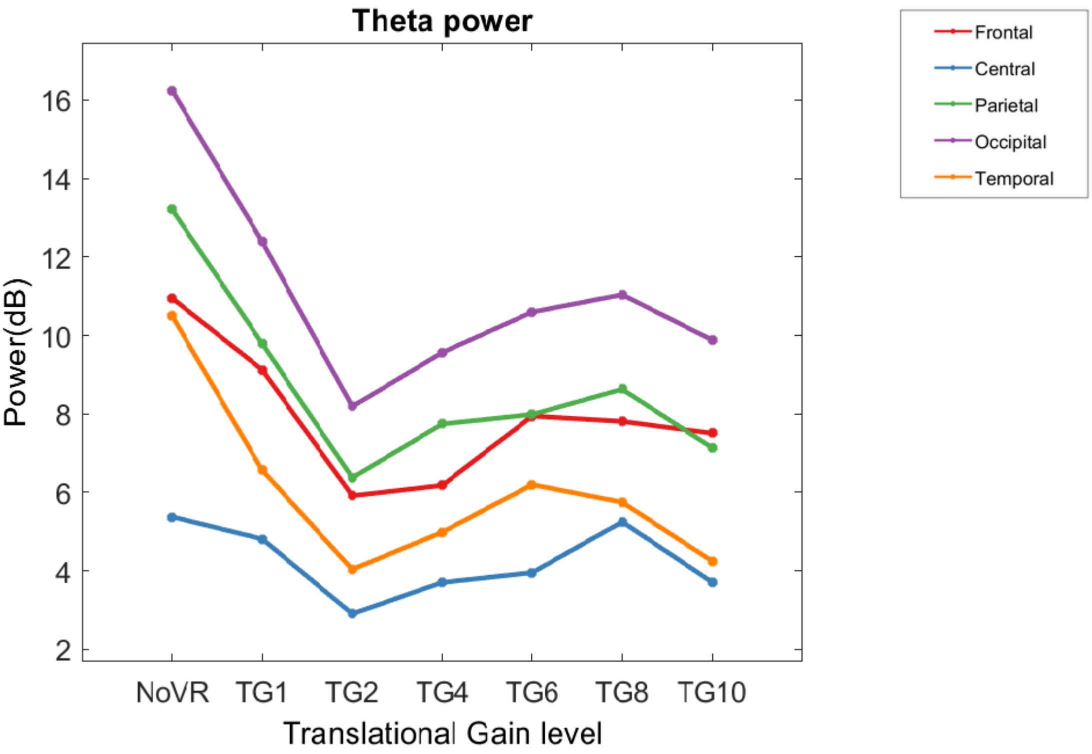

Figure 6.3: The power of the Theta frequency in dB for each TG level at each brain region.

[195]. Theta and Alpha frequencies at the Parietal and Occipital brain regions also contribute to postural control [194], so these frequencies/brain regions were also selected for this study. For postural disturbances in VR setups, the work of Peterson et al. [165] was followed and selected the Alpha frequency at the Frontal, Central, Parietal, and Occipital regions.

For the modification of gait, the analysis was based on previous works [182, 190, 224] to select brain regions and frequencies that get activated while modifying gait. Beta and Gamma frequencies in the Central region and the Beta frequency in the Parietal region were analyzed. For statistical analysis, the same procedures, as previously described, were followed. Results can be seen on Tables 6.3 - 6.6.

Brain Region	Effects and Statistical Differences	Correlations
Central	$\chi^2(6) = 8.646$, $p = 0.206$	Fatigue ($R = 0.29$, $p = 0.003$) Headache ($R = 0.32$, $p = 0.001$) Nausea ($R = 0.26$, $p = 0.008$)
Parietal	$\chi^2(6) = 14.607$, $p = 0.024$ $g\{2,6,10\} - NoVR$ $g\{4\} - 2$	Fatigue ($R = 0.39$, $p < 0.001$) Headache ($R = 0.37$, $p < 0.001$) Nausea ($R = 0.23$, $p = 0.03$) Cadence ($R = 0.33$, $p = 0.001$) CoM ($R = -0.36$, $p = 0.001$) SD ($R = -0.27$, $p = 0.008$)
Occipital	$\chi^2(6) = 20.143$, $p = 0.003$ $g\{2,4,10\} - NoVR$ $g\{10\} - 1$	Cadence ($R = 0.26$, $p = 0.01$) CoM ($R = -0.39$, $p < 0.001$)

Table 6.3: Theta Frequency Results. SD means Step Distance.

6.1.3.1 Theta Frequency for Postural Control

The Theta frequency was also used to study the postural control of VR users. The Parietal and Occipital brain regions (represented as green and purple, respectively, in Figure 6.3) were the main frequencies used to study this phenomenon. Figure 6.3 show that both frequencies follow a very similar pattern. They both show decreased power that starts at the No-VR baseline condition and decreases towards TG level $2x$. After this TG level, the power at these brain regions starts to increase at each TG level until it reaches TG level $8x$, where it starts to decrease again at TG level $10x$.

Table 6.3 shows how Parietal had significant statistical differences between baseline No-VR and TG levels $2x$, $6x$ and $10x$ and between levels $2x$ AND $4x$. The Occipital brain region had significant differences between the No-VR baseline level and TG levels $2x$, $4x$, and $10x$. This brain region also had a significant difference between TG levels $1x$ and $10x$.

The correlation results show how both brain regions had a positive correlation with Cadence, while they negatively correlated with the difference in CoM. The only difference is that the Parietal brain region had a negative correlation with the Step Distance value.

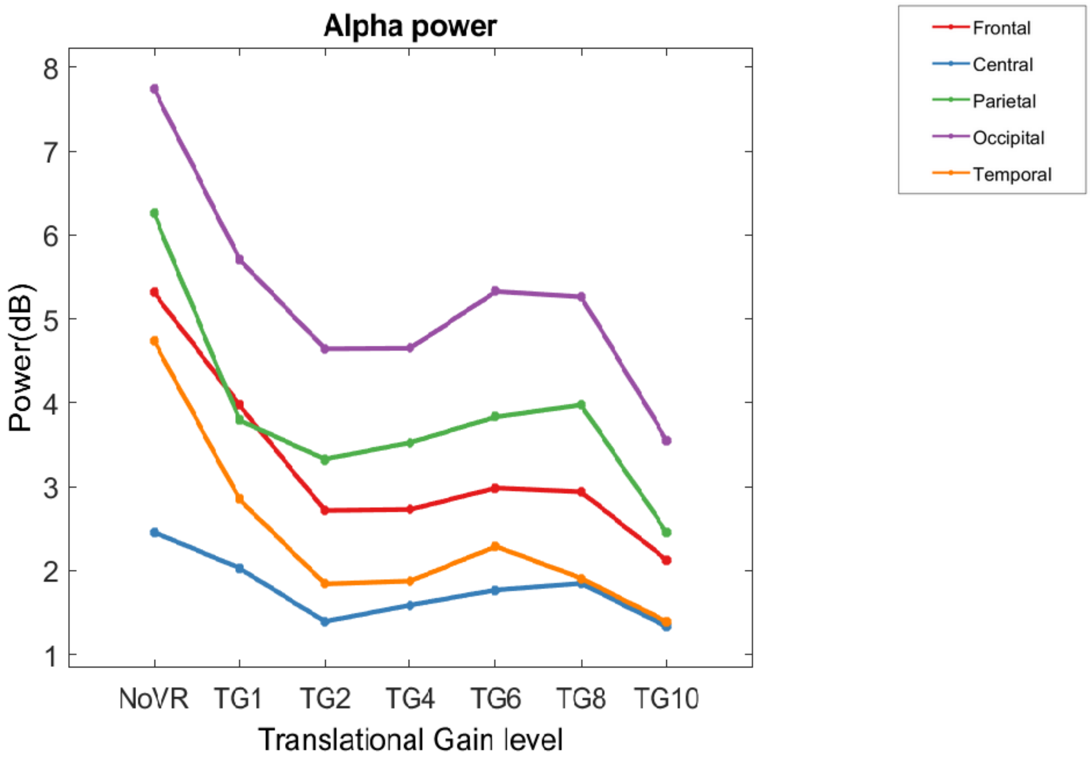

Figure 6.4: The power of the Alpha frequency in dB for each TG level at each brain region.

6.1.3.2 Alpha Frequency for Postural Control

The Alpha frequency at the Frontal, Central, Parietal, and Occipital brain regions was studied for postural control. Figure 6.4 shows the changes in this frequency through the different TG levels. Overall, most of the brain regions follow a similar pattern except the Occipital brain region. All regions start with a decrease from the No-VR baseline level that finishes at TG level $2x$. From here, all but the Occipital brain region increase again up to level $8x$. The Occipital brain region stays at a similarly low level at TG levels $2x$ and $4x$. Then it follows the other brain regions on increasing towards TG level $8x$ to later decrease at TG level $10x$.

Table 6.4 shows the statistical results for the different brain regions. The No-VR baseline condition is statistically different to all the other brain regions on the Frontal brain region but TG level $1x$. The Central brain region has a statistical difference between the No-VR baseline level and TG levels $2x$ and $4x$. On the Parietal brain region,

Brain Region	Effects and Statistical Differences	Correlations
Frontal	$\chi^2(6) = 21.429$, $p = 0.002$ $g\{2,4,6,8,10\} - NoVR$	Cadence ($R = 0.222$, $p = 0.03$) CoM ($R = -0.25$, $p = 0.02$)
Central	$\chi^2(6) = 13.357$, $p = 0.038$ $g\{2,4\} - NoVR$ $g\{2\} - 1$	CoM ($R = -0.25$, $p = 0.02$)
Parietal	$\chi^2(6) = 17.571$, $p = 0.007$ $g\{1,2,4,6,8,10\} - NoVR$	Cadence ($R = 0.34$, $p = 0.001$) CoM ($R = -0.27$, $p = 0.01$)
Occipital	$\chi^2(6) = 15.179$, $p = 0.019$ $g\{4,6,10\} - NoVR$	Cadence ($R = 0.26$, $p = 0.01$) CoM ($R = -0.26$, $p = 0.01$) TCT ($R = -0.24$, $p = 0.01$)

Table 6.4: Alpha Frequency Results. TCT Means Trial Completion Time.

the No-VR baseline condition is statistically different from all TG levels. On the Occipital brain region, the No-VR is statistically different to levels $4x$, $6x$, and $10x$.

For the correlation analysis, all the brain regions showed negative correlations with the difference in the Center of Mass. The Frontal, Parietal, and Occipital brain regions also showed a correlation with the Cadence measurement. Finally, the Occipital brain region had a negative correlation with the Trial Completion Time.

6.1.3.3 Beta Frequency for Postural Control and Gait Modification

For the Beta frequency, the Central and Parietal brain regions will be explored. Figure 6.5 shows the changes they suffer for the different levels of TG. Both frequencies follow a similar pattern where there is a decrease from the No-VR baseline level to TG level $2x$. The difference is that the drop in the Parietal region is more significant than in the Central region. After this, an increase in power stops at level TG $8X$ and decreases towards TG level $10x$.

Table 6.5, second column, shows the results for the significant differences. There was a significant difference between the No-VR baseline level on the Central brain region, and TG level $4x$ and TG level $1x$ and $8x$. For the Parietal brain region, there is a significant difference between the No-VR baseline level and TG levels $1x$ through $8x$.

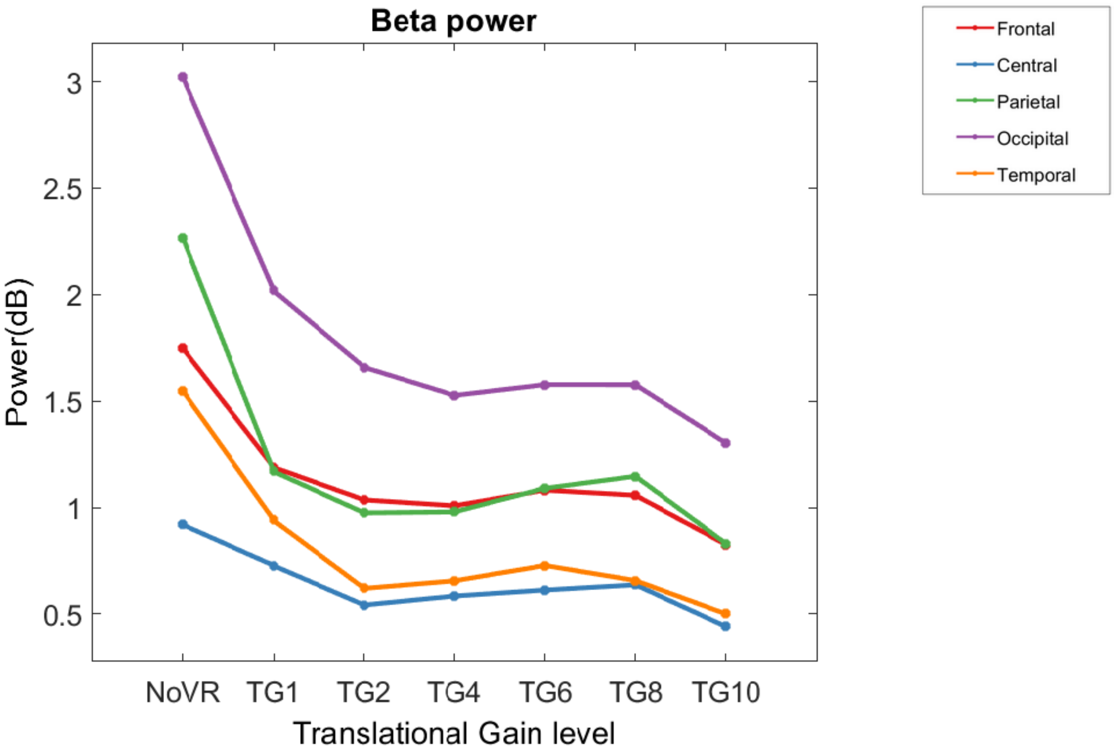

Figure 6.5: The power of the Beta frequency in dB for each TG level at each brain region.

Brain Region	Effects and Statistical Differences	Correlations
Central	$\chi^2(6) = 14.714,\ p = 0.023$ $g\{4\} - NoVR$ $g\{8\} - 1$	CoM ($R = -0.24,\ p = 0.03$) TCT ($R = -0.23,\ p = 0.02$)
Parietal	$\chi^2(6) = 17.571,\ p = 0.007$ $g\{1,2,4,6,8\} - NoVR$	Cadence ($R = 0.4,\ p < 0.001$) CoM ($R = -0.31,\ p = 0.006$)

Table 6.5: Beta Frequency Results. TCT Means Trial Completion Time.

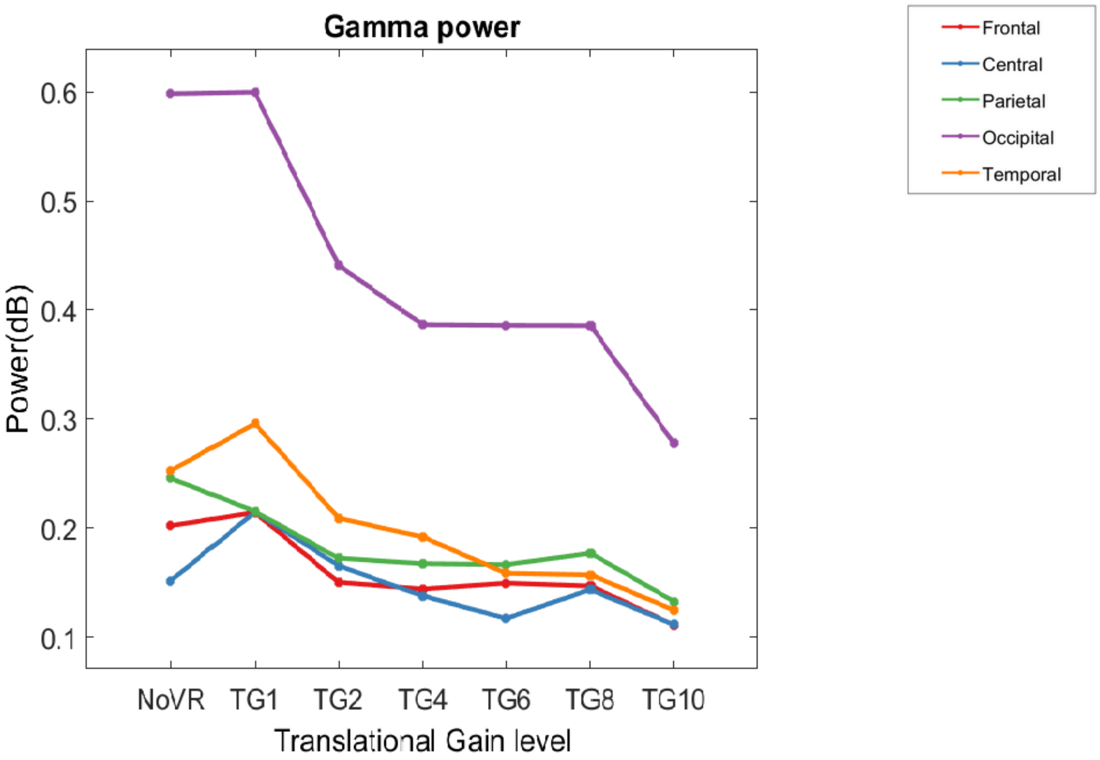

Figure 6.6: The power of the Gamma frequency in dB for each TG level at each brain region.

The third column of Table 6.5 shows the results from the correlations. Both brain regions had a negative correlation with the difference in CoM. The Central brain region had a negative correlation with the Trial Completion Time. The Parietal brain region, on the other hand, had a positive correlation with Cadence.

6.1.3.4 Gamma Frequency for Postural Control and Gait Modification

Figure 6.6 shows the changes in power at the different TG levels at the Gamma frequency. This study will focus on the Frontal, Central, Parietal, and Occipital brain regions. For this frequency, all the brain regions follow different patterns. The Frontal brain region starts with a slight increase from the No-VR baseline condition towards the TG level $1x$. Then there is a decrease in power towards TG level $2x$, and the power remains relatively similar until a decrease at TG level $10x$.

There is an increase of power from the No-VR baseline condition in the Central brain

Brain Region	Effects and Statistical Differences	Correlations
Frontal	$\chi^2(6) = 11.357$, $p = 0.078$	Cadence ($R = 0.3$, $p = 0.005$) CoM ($R = -0.47$, $p < 0.001$) TCT ($R = -0.23$, $p = 0.02$)
Central	$\chi^2(6) = 18.357$, $p = 0.005$ $g\{4,6\} - 1$ $g\{2\} - 6$	CoM ($R = -0.44$, $p < 0.001$)
Parietal	$\chi^2(6) = 18.143$, $p = 0.006$ $g\{4\} - NoVR$ $g\{4,6,8\} - 1$	Cadence ($R = 0.35$, $p < 0.001$) CoM ($R = -0.49$, $p < 0.001$) TCT ($R = -0.25$, $p = 0.02$)
Occipital	$\chi^2(6) = 15.786$, $p = 0.015$ $g\{2,8\} - \{NoVR, 1\}$	Cadence ($R = 0.2$, $p = 0.04$) CoM ($R = -0.41$, $p < 0.001$) TCT $R = -0.23$, $p = 0.02$)

Table 6.6: Gamma Frequencies Result. TCT Means Trial Completion Time.

region towards TG level 1x. This change is followed by a decrease in power towards TG level 6x. There is another increase in power for TG level 8x, to later decrease again towards TG level 10x.

The Parietal brain region follows a different pattern. A decrease in power starts at the No-VR baseline condition that stops at TG level 2x. The power then stays relatively at the same level until TG level 8x, where there is a slight increase. Finally, there is a decrease in TG level of 10x.

The Occipital brain region follows an entirely different behavior compared to the previous brain regions. There is relatively no change between the No-VR baseline condition and TG level 1x. Then, there is a considerable decrease that stops at the TG level of 4x. The power then stays relatively the same until the TG level 8x. Finally, the power drops towards TG level 10x.

Table 6.6, second column, shows the results for the statistical differences. The Frontal brain region had no statistical difference among any level of TG. At the Central brain region, there was a difference between TG level 1x and TG levels 4x and 6x. There is also a statistical difference between the TG level of 2x and 6x. There is a statistical difference between the No-VR baseline level in the Parietal brain region and TG level 4x. There is also a statistical difference between TG level $1x$ and TG levels $4x$, $6x$, $8x$. At the Occipital brain region, there is a statistical difference from both the No-VR baseline condition and the TG level $1x$ and TG levels $2x$ and $8x$.

The correlations for the Gamma frequencies are shown in the last column of Table 6.6. All brain regions had a negative correlation with the difference of Center of Mass. The Frontal, Parietal, and Occipital brain regions also positively correlated with cadence and a negative correlation with the Trial Completion Time.

6.2 Cortical State of Mobile VR Discussion

After acknowledging that VR sickness harms users' performance, this next part of the study aims to measure the users' levels of VR sickness. Unlike previous works where participants remained in stationary positions, this experiment induced VR sickness while actively navigating the virtual environment with natural walking. This part of the analysis focused on studying the EEG characteristics of VR sickness of users. In other words, the manipulation of the mapping between virtual and physical worlds via TG also induces a unique type of sensory conflict among visual and the proprioceptive systems, which is different from the sensory conflict between visual and vestibular systems in stationary VR setups. This analysis wants to study the differences in the cortical state caused by that conflict.

6.2.1 Changes in the Cortical State after introducing VR

After the introduction of the VR headset, most Theta frequencies show a considerable decrease in power. Previous works [11, 100] associated decreases in the lower bands to users experiencing memory retention tasks or spatial understanding tasks. It is to believe that the drop from No-VR to TG level $1x$ is due to the change from the room setup to the virtual scenario. User responses in the post-experiment interview further support this event since some of them reported being surprised by the virtual scenario's size.

6.2.2 The cognitive challenge of TG

Previous works [232, 234] related the changes in completion time and cadence as a response to the cognitive challenge of a changing virtual scenario. More traces of this cognitive challenge are noticeable in the drop in power in Delta and Theta frequencies from TG $1x$ to TG level $2x$. The decrease in these frequencies is similar to previous reports [194, 200] that found how unexpected visual changes in VR created an increase in cognitive processing from users, leading to decreases in the lower frequencies.

Intense cognitive challenges during walking tasks usually produce decreases in overall Alpha power. Several previous works [165, 170, 235] have pointed out how Alpha decreases significantly on walking while doing a cognitive task than merely walking. This cognitive challenge would explain the decreases that Alpha suffers from the No-VR level to TG levels $4x$ and $6x$.

This study implemented the cognitive challenge between the visual and proprioceptive systems to induce sickness in the participants. The Beta frequency at the Parietal brain region shows a significant decrease from the No-VR state to TG levels $1x$ and $2x$. Engel et al. [55] previously reported that decreases in Beta power are due to users visualizing a change in their perceived status quo and how a visual-proprioceptive conflict causes this [164]. These results confirm how the user experienced this type of conflict during the first part of the experiment.

6.2.3 Adaptation to TG

Note in Figure 6.1 how users reach peak behavior on levels TG $4x$ or $6x$ to start later decreasing (in the case of CoM and completion time) or increase (step distance and cadence). During the user interviews, most of them described how they learned to adapt to the TG changes in the middle of the experiment. For this reason, we can see how behavior stabilizes or, in some cases, improves by the end of the experiment.

There is a similar behavior in the Alpha frequency, which decreases TG levels $4x$ and $6x$ to start later increasing. Decreases in this frequency show higher cognitive processing [165, 170, 235], so this could mean users reached a level of adaptation to TG at levels $6x$ and $8x$. Later in the experiment, Alpha frequencies start to decrease again in level TG $10x$. Based on users' responses after the experiment, level TG $10x$ was the most challenging to navigate in the scenario. One of these users quitted during TG level $10x$ due to the significant discomfort it produced. The results suggest how the drop in Alpha power reflects the difficulty of navigating level TG $10x$.

Another sign of adaptation is showed by the increase of the Parietal-Beta frequency after TG level $2x$. Based on previous works [55, 164], these results suggest how this decrease in power was due to the conflict the users suffered during the first TG levels of the experiment. After the users had managed to adapt to the constant changes in TG, the Beta frequency increased in the rest of the TG levels.

6.2.4 Posture Instability as TG Increases

Frontal and Central Gamma activity showed a negative correlation with the differences in CoM. Changes of power on these bands are usually related to body sway changes to adjust to visually induced postural unbalance [196, 200]. In this case, the changes in Frontal and Gamma activity may be due to the postural adjustment the user suffered after each TG level. Parietal and Occipital Gamma decreases also appear at posture adjustment [165, 194]. These changes have a negative correlation with the difference in CoM. The more significant the difference in CoM, the lower the decrease in these bands. Note how these correlations happen with all users, no matter the subgroup. These results suggest that even the subgroup that did not suffer from VR sickness still suffered some level of postural instability.

P2-H3 spoke about the relationship between postural adjustment and the Alpha band. The results show how the Alpha band at most regions had correlations with changes in CoM and other gait parameters. These results align with previous results studying the Alpha band, and its relationship with postural instability [164, 165]. Slobounov et al. [195] suggested that suppression in Alpha frequency at the Central brain region happens when a user is voluntarily adjusting her posture. This result would explain the negative correlation with the changes in CoM.

Changes in gait are also a sign of struggling to maintain balance [21, 41]. Previous works show how suppression of Parietal Beta frequency is due to modulation and control of gait [182]. These results show how there is a suppression of this band at TG levels $4x$ and $8x$. Never the less, there was not any significant correlation with cadence or stepping distance. On the other hand, the Parietal-Beta frequency correlated with the number of steps per minute. Previous works use Parietal-Beta suppression as an indicator of change in gait speed [224]. These results show a correlation with cadence, suggesting the suppression in this band was due to the participants changing their steps per minute under the different levels of TG. For future references, the Beta frequency can also be an indicator of postural instability.

After level TG $2x$, the Theta frequency shows an increase in each level of TG. Besides the changes produced by the sickness symptoms, other works [54, 165] describe alternative reasons for these changes. Edwards et al. [54], and other works [78, 190] previously reported an increase in the Theta frequency as a result of struggling to maintain an upright posture. Peterson et al. [164, 165], and Slobounov et al. [200] have reported how unexpected perturbations to balance generated an increase of Theta activity, especially in the Frontal brain region. These results relate to some of the participants' responses, who reported that every change in TG surprised them.

6.2.5 Competition of Attention Resource

After level TG $2x$, the data follows previous results [98, 131, 156], where they explained how these frequencies gradually increase as the reported level of MS increases. Chen et al. [28] reported something similar, reporting an increase of 2db in Delta and Theta power every time the user reported an increase in sickness. Tables 6.3, 6.4, 6.6, third column, show the correlations between the changes in power and the reported sickness values in the in-between questionnaire. A positive correlation appears between power and the reported symptoms despite the decrease these bands suffered in TG levels $1x$ and $2x$.

After finishing TG level $2x$, the results suggest that the users got accustomed to VR and TG. User adaptation would explain the later increases of power in these frequencies. After the user managed to adapt, users unconsciously shifted their cognitive resources to the next issue at hand: the increase in sickness symptoms. This behavior follows the reports by Harada et al. [69] and Kline et al. [100], where they reported a "takeover" of more critical signals. Usually, these signals are related to the cognitive load of adjusting gait.

Another example of this "takeover" in signals are the changes in Alpha and Beta frequencies, which are also related to VR sickness. Previous works [28, 131] reported how both frequencies tend to increase in power as the reported level of sickness increases. Nevertheless, as Figure 6.4 and Figure 6.5 show, the results display a decrease in power instead of an increase. Different from the scenarios used in the previously mentioned studies, this scenario asked participants to be actively walking. The results suggest that this type of interaction leads users to involuntarily shift their cognitive resources toward reacting and adapting to TG levels. Thus, and because these signals are related to other cortical processes, they did not appear in the sickness-related hypotheses.

The Theta frequency has been a topic of discussion regarding its involvement in several areas related to VR. These areas include postural control [165, 200, 231], cognitive processing [100], sense of presence [12], and motion sickness [131] . Given the involvement of the Theta frequency in various cortical processes and how this signal tends to be overridden by different cognitive processes [69, 100], the part of *P2-H1* regarding Theta band was rejected. Results suggest that the Delta frequency can be a more reliable source for VR sickness detection. The Alpha frequency can be a more reliable source for postural unbalance detection on non-stationary VR setups.

6.2.6 Limitations

This experiment design had relatively short experiment times compared to other redirected walking, EEG experiments. Depending on the user's ability to navigate the virtual scenario, sessions as short as 12 minutes were frequent, with the most extended session being almost 30 minutes. Other redirected walking experiments [83, 205] and VR sickness experiments [28] lasted from 30 minutes up to one hour and a half. The benefits of a more prolonged experiment are the generation of more EEG data points to strengthen the analysis and results. It is also unsure if it would be possible to have longer experiment sessions with this experimental design. Because several subjects quitted early on the experiment, it would not have been easy to have users stay in the scenario for such a long time.

Another limitation of this study is the number of participants. This section of the study also attempted to divide participants into MS and No-MS groups for the analysis. This analysis suffered from the loss of two more datasets due to the EEG device's malfunction during the data recording. When analyzing both groups separately, there was no significant difference between the MS and the No-MS groups. That was the reason why, for this study, participants stayed in a single group. An increased number of participants could provide more data points to draw any EEG differences between the MS and the No-MS groups.

This experiment introduced the levels of TG in increasing order. Having applied these levels in a decreasing order instead would have had several complications to the experiment. Previous informal pilot studies with our VR engineers showed how for those who have extensive experience using high TG levels, the level of TG $10x$ is challenging. Given this, not only having such a strong TG level at the start would have created a significant decrease in the lower frequencies, but it is also unsure if this decrease would have allowed studying the signals of VR sickness properly.

6.2.7 Key Takeaway Points

- The mere introduction of the VR headset to the user caused a considerable change in their cortical state. This behavior appears in the decreases that most frequencies suffered between levels No-VR and TG $1x$.

- Decreases in the Delta, Theta, Alpha, and Beta frequencies happened due to the cognitive challenge of adjusting to TG.

- Alpha signals were able to show some adaptation of particular users. The signal decreased in power after the first levels of TG. Then, it proceeded to increase in later levels of TG following some of the users' adaptation in gait performance.
- Postural instability suffered by users produced changes in the Alpha, Beta, and Gamma frequencies.
- There was a competition of attentional resources shown by the different changes in different frequencies. Different processes overtook the Theta band during the user interaction. The Alpha and Beta frequencies followed more their previous reported behavior on postural challenges (decrease) than their motion sickness reported behavior (increase).

These results contribute to Research Objective 2. Having a set of neurological signals that contribute to the kinematic results found in the first part of this analysis strengthens the possibility of promptly detecting these issues. Combining these signals with the kinematic data can also strengthen the system proposed for Research Objective 3 and decrease the likelihood of false positives.

CHAPTER 7

CONCLUSIONS AND FUTURE WORK

7.1 Closed-Loop Systems

Our bodies are usually generating all types of physiological data, from the electrical signals on our brains, to the changes in body temperature, to the different kinematic measurements that our body produces. A closed-loop system can accumulate physiological responses from the user's body interacting with a computer. Without the user knowing, the system can "understand" the user state and automatically modify the computer's content, sometimes without the user being aware of it [238].

In the context of Brain-Computer Interfaces, a neuroadaptive system is a closed-loop system that leverages a BCI to aid in performing specific tasks [238]. These closed-loop BCI systems usually help people suffering from different impairments to perform specific daily tasks such as speaking [189], eating [33], or even a combination of various daily-life tasks [112]. Because of its portability, BCI systems can easily jump to VR systems to improve the user experience [186]. A BCI system to detect certain types of cognitive conflicts is an excellent example of using BCI closed-loop systems to solve issues with VR users [186].

As presented in Chapter 1, Research Objective 3 talks about proposing the design of a system that is capable of monitoring a VR user, detecting if any of the common problems with VR are in danger of appearing, and promptly reacting to given problems. Previous sections have discussed several different projects that successfully identify postural instability [73, 88, 194, 216, 241]. Similarly, for VR sickness, projects that successfully detect the appearance of VR sickness [28] on static VR setups already exist. For mobile systems, this project proposed methodologies that reinforce previous findings on detecting mobile postural instability [164, 165]. Furthermore, this project also proposed a technique for the measurement of VR sickness in mobile setups. This section will now discuss the design of the closed-loop system and how to integrate its parts.

7.1.1 Input Systems for Monitoring VR Users

As previously mentioned, Brain-Computer Interfaces create a connection between computer systems and the human brain, allowing the computer to take the brain signals as input, process those signals, and generate an output. Because current EEG devices require tedious setups, they are usually not considered for biofeedback systems. The introduction of dry sensor EEG devices counters this [114, 239], allowing the integration with a VR headset easier.

Thanks to projects like OpenBCI, Brain-Computer Interfaces are becoming consumer-available at low cost for users. As previous sections already discussed, EEG can measure postural instability and VR sickness in users. Some works are already using this technology to build postural unbalance detection systems, [7, 86]. A dry-sensor BCI monitoring the cortical activity for VR sickness and postural instability will be the first step towards building a detection system for these issues.

Kinematic information for a users' body is also essential in predicting postural instability [92, 93, 194]. However, full-body motion capture systems are too expensive for the average consumer to install with their home VR setups. Fortunately, some projects have tested devices like the Wii balance board [32] or Microsoft's Kinect [59] to provide cheaper methods for balance measurement. Like this one, other projects have even attempted to record body kinematics with HTC Vive trackers [22]. HTC Vive trackers, among similar technologies, can provide a cheaper, affordable system that can be combined with other balance input methods and the BCI inputs to measure the user's state.

Besides the physiological signal inputs, other inputs will improve the detection accuracy of this closed-loop signal. For starters, the type of VR interaction the user is experiencing. There will be different types of static, or even sitting, interactions where there will be little to no movements expected from the user. This setup should alert the system when violent displacements of the CoM are detected. Contrary to this scenario, there will be other types of VR interactions were extreme movements will be required from users like the action game SuperHot or the horror game Resident Evil VII. The first requires the user to move their body a bit more than what the user's regular position should be, while the latter has some "jump-scares" that will make the user suddenly move her center of mass. The system should tolerate these out of the ordinary movements based on the interaction the user is enjoying.

Another critical input for the closed-loop system is personal user preferences for the system's intervention. As mentioned in the first experiment results, some users expressed that they prefer to suffer an accident rather than break their VR immersion. The users of this closed-loop system should input their intervention preferences from the system for a very "protective" setting that intervenes as soon as an issue is detected, as frequently as possible. To something very relaxing that only intervenes in hazardous situations or that does not intervene at all.

7.1.2 A Machine Learning Model for VR users

One of the keys to a closed-loop BCI system is the algorithm beneath. This algorithm produces a usable output from the input generated by BCI. One useful tool to help build these systems is the use of different Machine Learning algorithms. Machine Learning is a technology that has had a significant impact on our daily lives. Many different projects are currently using different machine learning algorithms to predict different states of the human being. A great example is Weech et al. [227], which used a regression model to predict VR sickness using postural instability data. Like this, many projects have attempted to predict the outcome of a VR sickness state based on EEG and BCI data [7, 85, 96, 101, 111, 116, 236].

A machine-learning algorithm capable of receiving the user's EEG data and their kinematic data would be the "heart" of a closed-loop system for VR safety. Previous works trained Machine Learning algorithms such as Support Vector Machine to detect loss of balance of people based on data from gyroscopes [241]. Deep Learning has also been used in combination with EEG biosignals to categorize different states of VR sickness and find a link to the type of content that produces it [85].

This closed-loop system will favor the user of Support Vector Machines (SVM) or Deep Learning as the algorithm's heart. An SVM can use the EEG signals and the results of the between-trial questionnaire to categorize users in sick and not sick scenarios. For postural instability, the model can be trained with the EEG data, using the changes of CoM to classify the users based on their level of instability. Another option is the use of Deep Learning. The EEG data and the tracker location can act as the input of a Deep

Learning Algorithm. The output can tell us when the user is in a state of danger based on their physiological signals.

7.1.3 Closing the Loop with Mitigation methods

Once the problem's onset is known, there are already many innovative solutions for the VR sickness problem [2, 17, 163, 211]. Unfortunately, there is not much for postural instability but the techniques that this research project proposed, which will hopefully spark new research projects trying to improve over these works.

Once a machine learning algorithm runs at the heart of the closed-loop system, it can be tuned to the user's preferences on the correct timing to intervene, the degree of the intervention, or any necessary intervention. For postural unbalance, the user can decide whether she wants an auditory warning or a video-see-through option to aid her when postural instability is detected. For VR sickness, the user can decide she prefers to modify the rendering of the simulation [2, 56, 158] or if she prefers external techniques [24, 57, 163] to help mitigate the effects of VR sickness.

There are already some projects that utilize BCI-based closed-loop systems that aid people in their daily life activities [33, 189] or that even look at improving the user experience in VR [72, 186, 187]. These works show how BCI-based closed-loop systems are a fact and not a theoretical thing anymore and that they can be a reliable solution to improve the safety of VR users.

7.1.4 Final Conclusions on closed-loop systems

This research project presented a closed-loop system design to aid VR users suffering from postural instability and VR sickness. Using a support vector machine as the machine learning algorithm that classifies the user status is the primary proposed technique to use as the closed-loop system's heart. Using a system like this opens a window of opportunities to understand better VR sickness, postural instability, and overall user interaction with VR.

An interesting approach would be studying the level of adaptation to TG by users with the help of the closed-loop system. Having a closed-loop system monitoring the state of the users can help delay the change in TG in the scenario based on their level of VR sickness. This delay can help understand more about how long it takes for a user to adapt to different levels of TG.

Another interesting approach would be testing different machine learning algorithms and seeing which of them provide better accuracy in predicting these issues. Deep Learning looks like a promising tool to detect these issues more accurately than other techniques like support vector machines. Perhaps even a combination of both algorithms, each tackling a different issue, could be tested to achieve the highest accuracy possible.

7.2 Static Setup Conclusions and Future Work

The design space of enhancing user safety when wearing an HMD is underexplored. This project identified the risk of loss of balance while users are wearing VR HMDs and proposed a modified tether-release protocol to evaluate different balance recovery methods. Following the proposed protocol, this project presented an experiment that evaluated two balance recovery methods at two intervention timings. Both balance recovery methods, i.e., video-see-through and auditory warning, at 500 ms before fall onset improved balance recovery performance. However, the results also suggested that intervention at fall onset may distract a user's attention and harm the performance of fall recovery. Future developments of balance recovery methods in VR should carefully consider the intervention timing variable to avoid confusion.

Recently, HTC introduced to the market its new device: the HTC Vive Pro Eye. This device has the capabilities of eye-tracking and comes with a new pair of front-facing cameras. These improvements over previous iterations of the device can be useful in furthering this line of research. Testing the regular HTC Vive camera vs. the new camera system can shed some light on how users use the *VST* techniques to their advantage. As mentioned by some users, they leveraged the *VST* to locate their feet when preparing for a fall. Another interesting approach to study this phenomenon would be to study the users' looking at while the *VST* is active with the help of the devices' eye-tracking device. The new HTC Vive also posses 3D audio capabilities. It would be interesting to test if the location of the audio source and its distance will affect the user's performance in any way.

Finding optimal combinations of intervention timing and stimuli that increase the chance of a successful recovery from a fall while minimizing immersion disruption is an important and challenging research topic. As described in Section 3.1.1.2, this experiment investigates only the intervention timing of 500 ms. An ideal system should consider a user's physical capability and personal preference to VR experience and adaptively assist the user at different phases of a fall, i.e., before onset, during the onset, and after onset, with different techniques.

7.3 Conclusions on Mobile Setups

This part of the research project presented the findings from an experiment investigating VR sickness and gait parameters during non-isometric virtual walking with large and perceivable translational gain. This technique allowed the scenario to produce a visual-proprioceptive conflict when interacting with the scene. Most participants could accomplish the non-isometric virtual walking, even with large gains and without any prior training. However, overall, as the TG increased, participants reported higher VR sickness scores during the experiment. Changes in gait performance and CoM displacement were most prominent when the participants first experienced amplified virtual walking at $2x$ TG. However, the gait performance seemed to stabilize and remain relatively stable after $2X$ TG, and there were few significant differences detected among higher TGs $\{4x, 6x, 8x, 10x\}$. Surprisingly, participants with lower post-experiment SSQ scores adopted to the virtual walking with large TGs very well and even started showing gait performance improvement, even at large translational gain levels.

The cortical side of the experiment tried to understand the EEG signals behind VR sickness and postural instability on mobile VR scenarios. The results show how the increase in delta frequency in most brain regions is a reliable measurement for the level of VR sickness felt by the users. The results also found how decreases in gamma and alpha frequencies appear when the user struggles to maintain balance during a VR scenario. Finally, results also suggested that theta frequency, at least on mobile setups, would not be a reliable source to measure VR sickness since it tends to be "overridden" by signals involved in other gait activities.

7.4 General Conclusion

Previous to this research project, there was not enough attention to the different types of accidents that a VR user can suffer. The number of previous research projects trying to understand VR sickness and postural instability, and loss of balance of VR users shows that the issue still requires more attention to one day be able to eliminate it. Hopefully, this project starts a new trend to look at this issue further, in the hopes of providing a safer VR interaction.

This project showed how, based on previous work, detecting and mitigating VR sickness when the user interacts with a static VR setup is possible. However, there is not yet some technique developed to help users suffering from postural instability or falls. This project presented two simple techniques that can assist people suffering from postural instability. The tested techniques are simple enough that any VR headset can use them to help their users. Hopefully, these techniques can motivate different projects to improve them to provide the safest interaction possible.

It was still unclear if the detection methods for VR sickness and postural instability apply on mobile VR setups. This research project tried to test different methodologies to identify these issues in mobile VR setups. The hope is that future works can build upon this project to study different types of mobile scenarios further to define a complete and refined detection method for both these issues.

This project also proposed a closed-loop system's theoretical foundations to detect and prevent VR sickness and postural instability. Hopefully, this research sparks the curiosity to develop and test these systems to aid different VR setups. This project aims to move research towards making Virtual Reality a safer and enjoyable experience. This project provides a foundation of a system that provides a safer interaction for Virtual Reality Users. Hopefully, this research project moves Virtual Reality one step closer towards being a technology that everyone can safely enjoy.

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