UNVEILING NEUROPHYSIOLOGICAL SIGNATURES OF INTERACTION IN IMMERSIVE WORLDS: A MULTIMODAL STUDY

by

Ankit Arvind Prasad

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Approved by:

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Dr. Vishnunarayan Girishan Prabhu

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Dr. Simon M. Hsiang

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Dr. Agnes Ozelkan

ABSTRACT

ANKIT ARVIND PRASAD. Unveiling Neurophysiological Signatures of Interaction in Immersive Worlds: A Multimodal Study.
(Under the direction of DR. VISHNUNARAYAN GIRISHAN PRABHU)

This thesis uses a controlled experimental design to assess the impact of different VR scenarios, this thesis explores the psychological, physiological and Neurophysiological effects of Virtual Reality (VR) on stress, anxiety, and brain activity. Participants were exposed to a nature-based environment with Respiration Rate(RR) biofeedback, a stress-inducing parkour video in a VR environment, and an anxiety-triggering experience, Richie's Plank. The study meticulously measured changes in stress and anxiety levels, cardiac and respiratory functions, and cerebral oxygenation patterns before and after VR exposure using biosensors and functional Near-Infrared Spectroscopy (fNIRS).

Findings indicate that VR can significantly alter psychological and physiological states. Stress and anxiety levels increased markedly during the parkour and Richie's Plank experiences, as evidenced by both self-reported measures and biosensor data. Conversely, the biofeedback-enhanced VR forest environment did not significantly change stress or anxiety levels, suggesting its potential as a therapeutic tool for relaxation and stress management. Neurophysiological data corroborated these findings, with significant increases in respiration rates (RR) and alterations in the heart rate variability (HRV) during stress-inducing scenarios compared to the biofeedback scenario. Additionally, brain activity data revealed distinct patterns of cerebral oxygenation that varied significantly across the different VR interventions, illustrating the profound impact of VR environments on brain function.

The comprehensive analysis of VR's impact on neurophysiology not only advances our understanding of its therapeutic potential but also highlights the importance of tailoring VR experiences to individual needs and conditions. This research underscores VR's capacity to significantly influence stress, anxiety, and neurophysiological responses, offering valuable insights for future applications in mental health and cognitive training.

DEDICATION

Dedicated to my parents and grandparents, whose unwavering support and belief in me have always pushed me to dream big.

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LIST OF ABBREVIATIONS

ANOVA	Analysis of Variance
AcqKnowledge	Software used with BIOPAC systems for data acquisition and analysis
ART	Attention Restoration Theory
BIOPAC	Brand of biometric data acquisition system
BNECG2	BIOPAC BioNomadix ECG Module 2
BPM	Breaths Per Minute
CI	Confidence Interval
CSV	Comma-Separated Values (file format)
DLPFC	Dorsolateral Prefrontal Cortex
ECG	Electrocardiogram
EEG	Electroencephalography
fMRI	Functional Magnetic Resonance Imaging
fNIRS	Functional Near-Infrared Spectroscopy
HbO	Oxyhemoglobin
HbR	Deoxyhemoglobin
HRV	Heart Rate Variability
IRB	Institutional Review Board
LF/HF Ratio	Low Frequency/High Frequency ratio, a metric used in HRV analysis
MEG	Magnetoencephalography
MPFC	Medial Prefrontal Cortex

MRT	Multiple Resource Theory
POV	Point of View
PTSD	Post-Traumatic Stress Disorder
RFB	Resonance Frequency Breathing
RMSSD	Root Mean Square of Successive Differences, a time-domain measure of HRV
RR	Respiration Rate
RSP	Respiratory Signal
STAI	State-Trait Anxiety Inventory
TCP	Transmission Control Protocol
Unity	Unity Engine (Software for creating and operating real-time 3D content)
VAS	Visual Analog Scale
VRET	Virtual Reality Exposure Therapy
VR	Virtual Reality

CHAPTER 1: INTRODUCTION

This thesis explores Virtual Reality (VR), a transformative technology that creates computer-generated environments simulating realistic experiences and its impact on neurophysiological dynamics—specifically, the brain activity and cardiac activity triggered by immersive VR experiences(Schumann et al. 2021a; Wiederhold et al. 2002). This study delves into comprehending the neurophysiological mechanisms by focusing on capturing the neural and cardiac responses, including changes in brain activity and cardiac patterns elicited by immersive VR experiences. Over the last several years, VR technology has revolutionized our digital interactions, offering new avenues for engagement, education, therapy, and more through immersive experiences that fully engage the user's senses(Schumann et al. 2021a; Wiederhold et al. 2002). This exponential growth and adoption in VR calls for improving our understanding of neurophysiological changes while interacting with VR.

1.1 Significance of Topic

Integrating VR into modern society represents a significant transformation in human-computer interaction, with wide-ranging implications for our comprehension of the human brain and neurophysiology within digital contexts. It is important to investigate VR's effects on brain activity, a subject of critical importance from academic, therapeutic, and technological aspects(Schumann et al. 2021b; de With, Thammasan, and Poel 2022a).

Academically, the urgency of understanding VR's effects on human physiology cannot be overstated, especially as we navigate a digital evolution using the metaverse. Understanding the VR-induced changes in neurophysiology is critical to advancing cognitive neuroscience and developing VR technologies that are mindful of their effect on human performance and perception. Therapeutically, the potential of VR as a treatment method is profound. Given the complex neurophysiological nature of mental health disorders, VR's capacity to offer customizable, immersive environments presents a novel avenue for therapy in the comfort of one's personal space. Grasping the neural adjustments prompted by VR paves the way for pioneering VR-based therapies, potentially transforming treatment methodologies for conditions such as anxiety, Post-Traumatic Stress Disorder (PTSD), phobias, and depression(Beidel et al. 2019; Deng et al. 2019; Donnelly et al. 2021).

From a technology standpoint, as VR's incorporation into educational, leisure, and professional environments grows, understanding its neurological ramifications is crucial. Similar to how smartphones trigger compulsive checking with social media notifications (Kim, Kim, and Kang 2016; Świątek et al. 2023), VR's immersive environments could lead to dependence, raising concerns about a new kind of digital addiction (Vishnunarayan Girishan Prabhu, Stanley, and Morgan 2020). The insights derived from this study aims to inform the variables that foster cognitive well-being, enhance educational outcomes, and mitigate adverse effects.

Overall, the focus of this thesis extends beyond disciplinary confines, contributing significantly to scientific knowledge, therapeutic innovation, and VR technology's evolution. This thesis addresses a notable void in the existing literature by identifying VR's neurophysiological signatures. Furthermore, this thesis aspires to establish a foundation for future VR design considerations informed by a comprehensive understanding of its effects on the human brain.

1.2 Review Of Existing Research

Prior research studies have extensively investigated the impacts of immersive environments on human cognition, emotion, and behavior. This includes exploring VR's utility in simulating environments for providing realistic virtual experiences and its use in interactive applications like Richie's Plank Experience, each contributing to a nuanced understanding of human behavior while interacting in virtual environments.

From a therapeutic aspect, researchers have investigated the efficacy of VR for exposure therapy, which is a form of treatment method that utilizes virtual reality technology to address psychological disorders such as phobias, anxiety disorders, and PTSD. It entails subjecting individuals to simulated environments or situations that deliberately provoke their symptoms in a controlled and therapeutic manner. Multiple studies have validated its potential and reported several advantages over traditional exposure therapy, including greater control over the exposure process, enhanced safety, and the ability to simulate environments that may be difficult or impossible to recreate in reality.

Similarly, environmental observation through VR refers to using virtual environments to simulate real-world settings, allowing users to explore and interact with these settings in a controlled manner. This approach has been pivotal in assessing VR's potential to replicate the therapeutic effects of nature exposure, such as stress alleviation and cognitive rejuvenation(Seabrook et al. 2020). Studies have documented VR's efficacy in emulating the positive impacts traditionally linked to direct interaction with physical nature by immersing individuals in virtual natural landscapes, evidenced by marked decreases in stress levels and improvements in mood and cognitive performance (Browning et al. 2023; Seabrook et al. 2020).

Richie's Plank Experience is an existing VR environment designed to induce high levels of emotional and physical response \where the participant walks on a plank off the edge of a high building in a virtual world. This application can be used to investigate VR's capability to provoke intense reactions, highlighting its ability to simulate scenarios that elicit fear or excitement with considerable authenticity. Such experiences underscore VR's effectiveness in generating strong physiological responses, including significant elevations in heart rate and electrodermal activity—a measure reflecting emotional or physiological arousal (Kalatzis et al. 2022; Kalatzis, Stanley, and Prabhu 2021).

It is important to note that some observational studies within VR have also examined neurophysiological measures alongside psychological assessments. These measures, such as brain wave activity, provide insights into the deeper brain functions and responses triggered by VR interactions(Vishnunarayan Girishan Prabhu, Stanley, and Morgan 2020; de With, Thammasan, and Poel 2022a). The exploration of VR for environmental observation has thus been instrumental in understanding its psychological impacts and gauging its physiological effects. This multifaceted approach highlights VR's ability to closely mimic real-world experiences, offering a comprehensive view of its potential for stress reduction and cognitive enhancement. Furthermore, while discussing the "psychological outcomes of passive VR engagement," it is crucial to acknowledge that several studies have also incorporated physiological outcomes. These investigations have expanded our understanding of VR's effects, illustrating how passive interactions with VR environments can influence not just psychological states (Beidel et al. 2019; Deng et al. 2019; Donnelly et al. 2021) but also physiological and neural responses (Cull et al. 2019; Vishnunarayan Girishan Prabhu, Stanley, and Morgan 2020; de With, Thammasan, and Poel 2022a). By integrating these diverse outcomes, research in this domain offers a more holistic view of the myriad ways in which VR can affect the human condition.

1.3 Identification Of Research Limitation

Significant advancements in Virtual Reality (VR) research are shadowed by notable limitations, particularly in exploring neurophysiological changes, especially in capturing brain activity(Landowska et al. 2018a; de With, Thammasan, and Poel 2022a). The existing literature demonstrates a considerable gap in deep neural insights crucial for understanding how VR impacts brain functions. This shortfall restricts the comprehensive understanding of VR's effects and its potential applications in therapeutic, educational, and cognitive enhancement domains.

A prominent issue in current VR studies is their focus on behavioral and psychological outcomes, often at the expense of exploring neurophysiological processes. This oversight neglects the brain's complex mechanisms that underlie these responses, leaving a gap in our knowledge of how VR environments influence neural functions. Moreover, the limited use of advanced neuroimaging techniques, such as Magnetoencephalography (MEG), functional Magnetic Resonance Imaging (fMRI) and Electroencephalography (EEG), and hampers the depth of neurophysiological insights(Landowska et al. 2018a; de With, Thammasan, and Poel 2022a). These methods are vital for uncovering the neural correlates of VR-induced experiences, providing a level of detail unattainable through behavioral analysis alone.

Additionally, the field is characterized by a predominance of short-term studies, which do not adequately capture the long-term neural adaptations resulting from prolonged or repeated VR exposure(Palmisano and Constable 2022). Such understanding is critical for applications in neurorehabilitation, cognitive training, and mental health interventions, where long-term neural changes are paramount(Landowska et al. 2018a; Palmisano and Constable 2022; Vishnunarayan Girishan Prabhu, Stanley, and Morgan 2020; Seabrook et al. 2020).

Another critical limitation is the scant research on neural changes across different VR scenarios, including Resonance Frequency Breathing (RFB), stress-inducing situations in VR, and stress comparisons between VR and video-based scenarios. Exploring these diverse contexts is essential for a holistic view of VR's neurological impact, offering insights into how different types of VR content affect brain function and stress responses.

This thesis aims to address these shortcomings by incorporating advanced neurophysiological measurement techniques in VR research, focusing on a wide array of VR scenarios. This work seeks to provide a nuanced understanding of virtual environments' influence on brain function by uncovering the brain activity signatures associated with diverse VR interactions. Such a comprehensive approach aims to enhance the application of VR in various fields, including clinical psychology and cognitive neuroscience, by offering a detailed perspective on VR's potential to modulate neural activity across different contexts.

1.4 Contribution and Scope of the Thesis

This thesis explores the neurophysiological dimensions of VR interactions at the nexus of neuroscience, psychology, and immersive technology. To achieve this goal, we utilize a multimodal methodological framework—an approach that combines psychological assessments and neurophysiological monitoring to uncover the neural mechanisms underlying VR's impact on human cognition, emotion, and behavior. Specifically, we use biosignals, including Functional Near-Infrared Spectroscopy (fNIRS) for monitoring cerebral hemodynamics, respiratory signals (RSP) for respiration rate, electrocardiogram (ECG) for cardiac activity, and heart rate variability (HRV) analysis, and validated questionnaires for perceived stress and anxiety.

The study's core objective is to elucidate the neurophysiological responses to VR, with implications extending beyond academia to educational paradigms and therapeutic interventions, exploring how virtual environments can be tailored for treatments addressing mental health issues like anxiety and stress(Vishnunarayan Girishan Prabhu, Stanley, and Morgan 2020; Seabrook et al. 2020). By identifying distinct brain activity patterns, the research seeks to inform the development of VR applications to support mental health and learning outcomes, exploring VR's utility in simulating environments for observational purposes and interactive applications.

This thesis is guided by four primary objectives:

1. Enhancing Neurophysiological Insight: It aims to deliver a detailed analysis of brain response patterns to VR, delving into how various VR scenarios influence cognitive functions, emotional states, and physiological responses.

2. Evaluating Therapeutic Applications: Leveraging neurophysiological findings, the study assesses VR's therapeutic potential, particularly in managing anxiety, stress, and cognitive rehabilitation, to support the creation of VR-based therapeutic interventions backed by scientific evidence.

3. Advancing Methodological Innovation: This research introduces a multimodal approach to neurophysiological measurement in VR, enhancing data collection accuracy and establishing a new benchmark for future VR research.

4. Creating an Open-Source Dataset: A significant contribution is the development of an open-source dataset of brain activity responses during VR interactions, facilitating broader research collaboration and innovation in the field.

Structured across several chapters, the thesis comprehensively examines various facets of the VR experience—from sensory perception to spatial navigation, integrating meticulous data analysis to distill findings into practical insights for both academic and applied realms.

CHAPTER 2: LITERATURE REVIEW

This section of the thesis discusses observations from prior research studies utilizing VR to induce specific emotions and the efficacy of VR in eliciting those targeted emotions. Specifically, we discuss the theoretical underpinnings that support the efficacy of VR in distracting the user and immersing them in the virtual world. Additionally, we discuss how studies have integrated VR with biofeedback to enhance the user experience and activate the autonomous nervous system, which motivates this thesis. Further, we discuss the findings from prior studies investigating the neurophysiological responses during specific emotions while experiencing VR and not experiencing VR. Finally, we highlight the existing research gaps and the unique contribution of this study in addressing those gaps.

2.1 Theoretical Framework

Virtual Reality (VR) is an innovative technology designed to completely engage an individual by simulating various senses through a virtual experience. Specifically, it aims to distract the user from the real world to an imaginary world by capturing the user's attention by providing stimulating experiences that engage multiple sensory systems, including audio, visual, olfactory, and other sensory inputs. Along with VR, various distraction techniques, such as music, videos, games, and paced breathing, have proven to effectively reduce negative emotions such as stress and anxiety (Good et al. 2002; Hoffman, Patterson, and Carrougher 2000; Vishnunarayan G. Prabhu et al. 2019; Vishnunarayan Girishan Prabhu, Stanley, and Morgan 2020).These strategies are especially advantageous during medical procedures such as venipuncture, burn wound care, blood transfusions, surgery, mammography, and chemotherapy. Studies have also utilized these distraction techniques to manage data-to-day anxiety.

The underlying concept of these techniques lies in their capacity to captivate the user’s attention, diverting it from the negative stimuli. Previous research indicates that the perception of negative emotions necessitates the individual's deliberate and concentrated attention on the respective sensation. Therefore, redirecting this attention can significantly reduce the brain's perception of negative emotions such as pain, anxiety, stress, and other related feelings(Blum, Rockstroh, and Göritz 2019; Melzack and Wall 1965). Moreover, considering that individuals possess a limited cognitive capacity for information processing, employing distraction techniques that involve multiple senses, such as VR, is likely to be more efficacious compared to singular sensory methods, like music or videos, in engaging an individual's attention and, consequently, reducing their perception of negative emotions(Eccleston and Crombez 1999). The theoretical framework supporting the efficacy of VR as more efficacious than other distraction methods is the multiple resource theory (MRT) proposed by Wickens. MRT posits that the human cognitive capacity, specifically attention, is finite and that various sensory modalities, such as the visual and auditory systems, vie for these limited cognitive resources(Bendell, Vasquez, and Jentsch 2019). Compared to a 2-D video or music, the ability of VR to engage multiple senses simultaneously enables it to effectively monopolize these resources. This monopolization diminishes the brain's ability to process other stimuli, such as pain, anxiety, or negative emotions.

Although VR environments are efficacious in engaging and distracting users, prior studies have identified that specific VR environments are more efficacious than others in capturing user’s attention and distracting them from negative emotions. Specifically, researchers have investigated the efficacy of nature-based environments in mitigating negative emotions such as pain, anxiety, depression, and other distressing feelings in a variety of settings (Girishan Prabhu et al. 2023; Vishnunarayan G. Prabhu et al. 2024; Vishnunarayan Girishan Prabhu et al. 2022). The fundamental theories supporting the efficacy of nature-based VR environments in mitigating negative emotions are the (i) Attention Restoration Theory (ART) and (ii) biophilia hypothesis. The Attention Restoration Theory (ART) posits that engaging in activities in natural environments can aid in the recovery of attention and reduce mental exhaustion. Nature-based environments provide a peaceful ambiance that enables individuals to interact with rejuvenating elements such as trees, plants, and picturesque landscapes. This alteration in the environment has the potential to diminish adverse emotions, such as anxiety, stress, and irritability(Grinde 1996, 2005; Kaplan and Kaplan 1989; Von Lindern, Lymeus, and Hartig 2016; Ulrich et al. 1991).

Similarly, the biophilia hypothesis posits that humans possess an inherent propensity towards nature due to our evolutionary past(Barbiero and Berto 2021). This correlation suggests that being exposed to natural environments can have a beneficial impact on our overall well-being. Plants and vegetation are commonly regarded as enjoyable, but their absence can result in stress(Bringslimark, Hartig, and Patil 2009; Hartig 1993). Hence, exposure to nature through direct interaction or visual observation can foster positive emotions and alleviate stress and anxiety (Vishnunarayan G. Prabhu et al. 2020). Research has shown that interacting with the natural environment can result in elevated moods, decreased stress levels, and heightened overall well-being. The visual representation of natural elements, such as plants and green landscapes, can elicit aesthetic reactions that encourage relaxation and happiness. In addition, the biophilia characteristic, which can be shaped by individual learning, proposes that individuals who may not outwardly demonstrate a strong affinity for nature might nevertheless derive advantages by engaging with natural environments.(Grinde 1996, 2005; Kaplan and Kaplan 1989; Von Lindern, Lymeus, and Hartig 2016; (PDF) Effects of gardens on health outcomes: theory and research n.d.; Ulrich et al. 1991)

Beyond identifying and developing VR environments to mitigate negative emotions, prior studies have also integrated HRV biofeedback with VR to reduce anxiety, stress, and other distressing feelings. HRV biofeedback is a technique that assesses the heart rate and respiration rate (RR) to coach the user to breathe at a particular rate to engage their parasympathetic nervous system(Arns et al. 2020; Sokhadze, Cannon, and Trudeau 2008; Tan et al. 2009). The theory underpinning the efficacy of biofeedback to improve neurophysiological regulation is the Biofeedback Theory, which presents a systematic way to acquire mastery of bodily functions by delivering prompt feedback on one's physiological state(Frank et al. 2010). Real-time training involves providing users with physiological measurements as feedback, allowing them to learn how to adjust their performance accordingly(Hallman et al. 2011; Prato and Yucha 2013a; Rockstroh, Blum, and Göritz 2019). This practice allows individuals to consciously modify their physiological reactions, customizing interventions to address specific therapeutic requirements. Different biofeedback approaches are employed, each focusing on distinct physiological signals. This thesis is pertinent to RR (Respiration Rate) biofeedback, a technique that assesses the respiration rate, which has been discovered to be effective in promoting relaxation and managing pain and anxiety.(Hallman et al. 2011; Henriques et al. 2011; Prato and Yucha 2013a; Rockstroh, Blum, and Göritz 2019)

2.2 Neurophysiological Response To VR

2.2.1 Respiratory Response

Prior studies have extensively investigated the changes in respiratory responses in various VR environments, including stress-inducing environments, relaxing environments, and interactive games. Findings suggest that VR environments, particularly those created for relaxing purposes, can cause a reduction in respiration rates when individuals are fully immersed in the virtual environment. Additionally, to further induce relaxation, studies have integrated VR environments with HRV biofeedback to coach and train users to modify their breathing patterns. Immediate feedback on respiratory parameters facilitates the development of regulated and calm breathing, which is advantageous for overall wellness(Lin, Tai, and Fan 2014).

VR therapies that include HRV biofeedback cues are becoming more prevalent for their capacity to direct users towards an ideal breathing rate, commonly established at 5.5 breaths per minute, in order to promote relaxation. These solutions utilize real-time feedback on breathing patterns, employing visual signals such as sine waves to assist individuals in achieving and sustaining the desired pace. In addition, VR environments are specifically created to be adaptive to provide cues to users, meaning certain aspects of the VR environment, such as visual and audio, that responds to the user's breathing patterns, enhancing sensory engagement. These cues aim to provide direction and real-time feedback to motivate users to achieve the goal. Further, text cues, such as directions to "Inhale" and "Exhale," were also used to help users synchronize their breathing with visual signs, encouraging a consistent and regular breathing pattern. Adapting biofeedback according to individual physiological reactions provides a personalized experience and actively involves users by creating a highly engaging experience that instills a feeling of control over one's physical state.

2.3 Cardiovascular Activity

Similar to respiratory responses, several studies have also investigated the changes in cardiovascular activity while interacting with VR. Specifically, researchers have investigated the alterations in HRV, which reflect the equilibrium of sympathetic and parasympathetic nervous systems, which indicate changes in the activity of the autonomic nervous system. VR interventions, particularly those integrating HRV biofeedback, have shown effectiveness in modifying HRV patterns to enhance parasympathetic (the "rest and digest" system) activity while decreasing sympathetic (the "fight or flight" system) activity(Prato and Yucha 2013b).

These interventions promote relaxation, reduce stress, and increase HRV coherence, indicating better regulation of the autonomic nervous system and physiological balance. By engaging in immersive experiences, VR has the ability to stimulate the parasympathetic nervous system, resulting in increased HRV and a state of relaxation. Additionally, VR interventions that aim to reduce stress have been observed to have a favorable impact on HRV measurements, indicating a shift towards a more balanced autonomic function. Studies investigating the efficacy of HRV-integrated VR compared to control groups have reported significant improvements in RR-Interval and RMSSD in participants in the intervention group compared to those in the control group. Similarly, the intervention group also showed a noticeable decrease in the LF/HF ratio, indicating an elevation in parasympathetic nervous system activity in these individuals. These findings indicate that HRV-integrated VR positively impacts HRV and cardiovascular functions, indicating a decrease in anxiety, stress, and pain. Overall, research suggests that immersing in VR environments that promote mindfulness and relaxation can enhance HRV, activate the parasympathetic nervous system to decrease the experience of negative emotions. Moreover, by incorporating biofeedback techniques into VR, users can acquire self-regulation skills to control their neurophysiological responses.

2.4 Brain Activity

There are several validated methods to collect brain activity; however, researchers primarily rely on two methods: (i) EEG (Electroencephalography) and fNIRS (functional Near-Infrared Spectroscopy), as these are portable and non-invasive approaches. The former measures the brain's electrical activity through electrodes placed on the scalp, providing information on the brain's electrical impulses, including frequency, amplitude, and synchrony. On the other hand, fNIRS uses light to measure changes in cerebral blood oxygenation, which correlates with neural activity. While both methods are helpful, prior studies have reported fNIRS to be more spatially specific, allowing for better localization of brain function, whereas EEG signals can be more diffuse. Additionally, fNIRS is less susceptible to electrical interference and movement artifacts, making it more robust for use in real-world settings. Finally, fNIRS also measures changes in cerebral blood oxygenation, which is more closely related to neural activity than the electrical signals measured by EEG.

Multiple studies have used fNIRS during VR interventions to examine human brain activity. As mentioned earlier, fNIRS uses a technique that measures alterations in cerebral oxygenation by detecting variations in the absorption of light by oxygenated and deoxygenated hemoglobin in the brain. Oxygenation (Oxy HbO) represents the amount of oxygen bound to hemoglobin in red blood cells, and Deoxygenation (Deoxy HbR) represents the amount of hemoglobin not bound to oxygen(de With, Thammasan, and Poel 2022b). In a study conducted among participants with high acrophobia and health subjects, the analysis of within-group fNIRS signals revealed that Oxy HbO values were notably higher during exposure to heights compared to baseline conditions. This elevation in Oxy HbO levels was significant across thirteen channels, predominantly located in the frontal region of the prefrontal cortex (PFC). These findings align closely with previous research, consistently showing significant increases in Oxy HbO during fear-induced conditions versus non-fear states. Such patterns are supported by extensive prior studies(Glotzbach et al. 2011; Köchel, Schöngassner, and Schienle 2013; Ma, Huang, and Wang 2013; Roos et al. 2011; Rosenbaum et al. 2020; Zhang et al. 2016). Another recent study(Landowska et al. 2018b) exposed participants to two anxiety-inducing VR environments:

(i) a training room and (ii) a pit room, where they walked on a virtual plank for 120 seconds, with a 20-second rest period between conditions reported significant change in the hemodynamic responses. Specifically, the researchers reported a significant increase in Oxy HbO levels in the bilateral dorsolateral prefrontal cortex (DLPFC) and the bilateral medial prefrontal cortex (MPFC), indicating increased brain activity in response to the virtual heights. Conversely, Deoxy HbR levels showed a significant decrease in the right DLPFC, suggesting reduced oxygen utilization in this region during exposure to the virtual heights.

Further, another experiment targeting participants with arachnophobia utilized virtual reality exposure therapy (VRET), a cognitive-behavioral technique that gradually introduces individuals to spiders and their specific fear stimulus within a controlled environment(Andersson et al. 2024; Rosenbaum et al. 2020). Functional near-infrared spectroscopy (fNIRS) was employed to monitor cortical oxygenation levels throughout the therapy sessions. The study observed a distinct pattern of increased Oxy HbO levels during initial exposure that later stabilized, suggesting a reduction in arachnophobia as the participant progressed through VRET. The findings indicate that the fear response to phobias can be effectively reduced through controlled exposure, enhancing our understanding of the neurophysiological mechanisms of fear and phobia. The overall findings indicate a significant increase in Oxy HbO levels and a decrease in Deoxy HbR while experiencing negative emotions.

Our detailed systematic literature review observed that prior studies have developed and evaluated the efficacy of nature-based VR environments integrated with HRV biofeedback for mitigating anxiety and pain. Further researchers have also investigated the changes in brain activity when exposed to negative emotions. However, none of the studies have explored the changes in brain activity while performing RR biofeedback in VR and compared it to changes in brain activity while exposed to stress-inducing VR environments. This thesis aims to fill this void by conducting a comprehensive analysis of brain activity physiological and psychological responses across three distinct VR scenarios: a nature-based VR environment with RR biofeedback, a stress-inducing video inside a VR Video Player, and a highly immersive challenge using Richie's Plank VR experience. This study will utilize functional Near-Infrared Spectroscopy (fNIRS) to measure cerebral blood flow and oxygenation patterns in the prefrontal cortex—a crucial area associated with cognitive functions and emotional regulation. By examining variations in oxygenated and deoxygenated hemoglobin levels, this thesis will provide detailed insights into how different VR contexts influence the autonomic nervous system and cognitive load.

The methodology will consist of participants engaging in four virtual reality (VR) scenarios. The first scenario will serve as a control, with no activity, to establish a baseline. The second scenario will involve participants receiving HRV biofeedback while immersed in a calming, nature-based environment. The third scenario will expose participants to a stressful point of view (POV) parkour video compilation, played within an immersive VR environment using a custom VR Video Player. Lastly, the fourth scenario will feature Richie's Plank VR experience, designed to induce a fear of heights. This study aims to assess and contrast the neurophysiological reactions, with a specific emphasis on the activation patterns of the frontal lobe that are essential for emotional processing and stress response.

In addition, this thesis will investigate how variations in stress reactivity and baseline anxiety levels impact the effectiveness of VR interventions in order to provide a more comprehensive analysis. The assessment will involve pre- and post-intervention measurements, which will include self-reported anxiety scales as well as physiological measures like heart rate variability and respiratory rate.

The objective of this research is to fill the existing gaps in knowledge regarding the influence of different virtual reality (VR) environments on brain activity. By incorporating multiple VR scenarios, the study will specifically investigate the interactive effects of different VR environments on brain activity, with a focus on stress-inducing versus relaxation contexts. The results are anticipated to not only establish a basis for creating more efficient virtual reality (VR) therapeutic treatments but also enhance and tailor these treatments to more effectively address anxiety, stress, and pain in both clinical and non-clinical groups.

CHAPTER 3: METHODOLOGY

3.1 Interventions

Designing the Adaptive Forest Environment

From our literature review, it is evident that nature-based virtual environments are efficacious in reducing stress, anxiety, and other negative emotions. Based on extensive research conducted among different populations, we decided to utilize the forest environment in our research. Further, to make the environment adaptive and induce further relaxation, we integrated RR biofeedback into the virtual environment using Unity (San Francisco, CA, USA). To provide participants with RR biofeedback, we used BIOPAC BioNomadix Device BNECG2 and the RSP Transducer, which collects and sends data to Biopac Smart Centre, which is then fed to the virtual environment.

Next, we present the operational procedure of the integrated system, which includes collecting data from participants using various biosensors live streaming that data Unity, which in turn manipulates the virtual forest environment presented to the participant in the VR headset. Participants are first outfitted with multiple biosensors, which include electrodes and chest strap that are connected to the BIOPAC system's ECG module and an RSP Module. Upon outfitting the participants with the biosensors, the AcqKnowledge software was initiated, and the data transmission was checked to start live streaming. This configuration enables uninterrupted monitoring of the participant's respiratory patterns. Along with the above, participants are fitted with the fNIRS system, which collects brain data. After the baseline collection, the participants are fitted with the customized VR headset. At this stage, the participant is presented with the VR forest environment.

The technical data flow encompasses multiple essential stages to guarantee seamless functionality and instantaneous response within the virtual reality system. At first, the AcqKnowledge software, operating on a computer with networking capabilities enabled, begins by loading a graph template that is set up for variable sampling rates. This configuration is essential as it manages the collection of numerous data channels, encompassing both analog and digital signals, enabling thorough monitoring and examination of physiological indicators.

After loading the graph template and setting the data connection to "single" mode, AcqKnowledge starts transmitting data for all currently active channels. The data is transmitted via a solitary TCP connection to uphold efficiency and minimize latency. For the VR system to adapt to the environment according to the participant's breathing rate, it is essential to transmit this physiological data in real-time. If the breathing rate falls outside the optimal range of 5.5 to 6.5 breaths per minute, visual cues, such as increasing fog density, are activated to help the participant return to the desired breathing pace. An AcqNdtDataServer object is instantiated to manage incoming data streams on the software side. This server is responsible for data processing, which involves tasks such as calculating averages or identifying trends. They then perform actions based on these calculations, such as updating the virtual reality environment or adjusting feedback mechanisms. Finally, the AcqKnowledge system transmits the processed data to the Unity server through a client socket connection. This configuration guarantees that the virtual reality (VR) system receives the processed data promptly, enabling immediate updates to the VR environment according to the participant's physiological reactions.

This advanced fusion of biofeedback technology and virtual reality creates a dynamic and adaptable system that not only enhances the realism of the virtual reality experience but also enables accurate monitoring and adjustment based on real-time physiological data. This approach has the potential to greatly influence the administration of relaxation techniques, potentially resulting in more effective methods for reducing stress.

The Biofeedback Forest VR Environment is used as a controlled setting to examine the effects of VR on relaxation, employing a distinctive combination of visual and auditory stimuli. Within this simulated forest, individuals are immersed in a visually serene environment, where trees sway autonomously, unaffected by the rhythm of the participant's respiration. The main auditory signal is a beep similar to that of a submarine, occurring every five seconds, with the purpose of directing the participant to achieve a breathing rate of around 6 breaths per minute. Crucially, there are no visual modifications, such as changing leaves or patterns of light, that specifically indicate when to breathe in and breathe out. Alternatively, the VR system utilizes a Bio Feedback mechanism by employing the Biopac Nomadix Device BNECG2 and RSP Transducer to observe and track the participant's respiratory rate. When the breathing rate falls outside the desired range of 5.5 to 6.5 breaths per minute, the visual clarity of the environment changes. This change is characterized by an increase in fog density, which serves as a signal to indicate the need for adjustment of breathing rhythm to achieve the 6 BPM goal.

Figure 1: Fog in the forest when the participant's breathing falls below 6 BPM, with the slider on the status bar indicating 'Breathe Rapidly'.

Figure 2: Fog in the forest when the participant's breathing goes above 6 BPM, with the slider on the status bar indicating 'Breathe Slowly'.

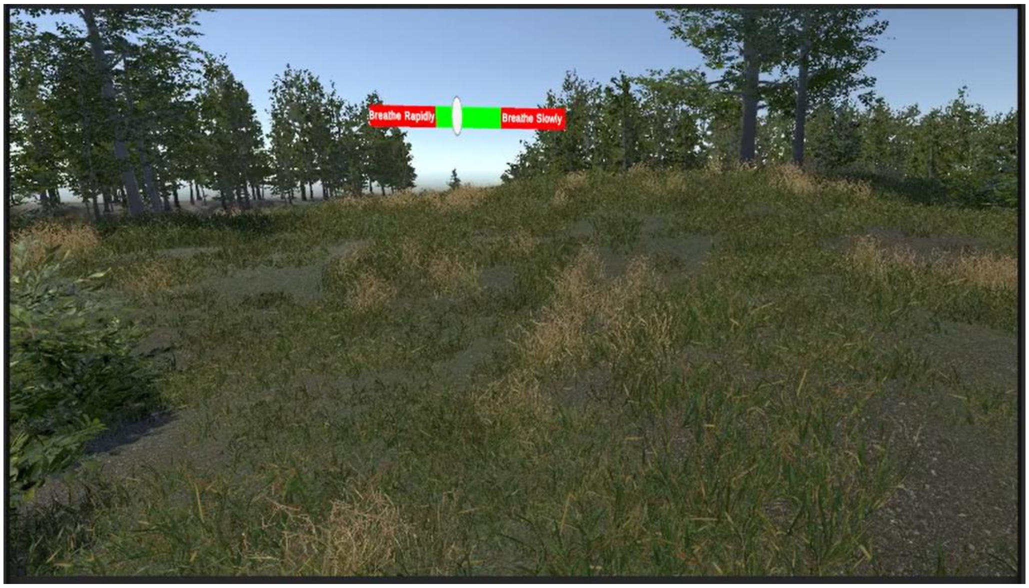

Figure 3: Clear forest environment achieved when the participant's breathing rate is within the 6 BPM range, with the slider positioned in the green zone at the center.

Furthermore, to augment user feedback and involvement, a crucial interactive element was incorporated into the Biofeedback Forest VR Environment. This element takes the form of a visual slider (see figure above) that is presented within the VR interface. The slider is crucial in directing participants toward attaining the ideal breathing rate of 6 breaths per minute, which is vital for inducing relaxation and reducing stress. The slider is designed to be user-friendly and easy to understand. It moves along a scale, and there is a specific red zone that indicates when the participant's breathing rate is not within the ideal range of 5.5 to 6.5 breaths per minute. When the participant's breathing rate falls below 5.5, the slider moves to the red region on the left, and the prompt "Breathe Rapidly" is displayed, indicating the need to increase the speed of breathing. On the other hand, if the rate of breathing goes beyond 6.5, the slider moves to the red area on the right side, and a message saying "Breathe Slowly" appears, instructing the participant to slow down their breathing speed. This visual tool serves two purposes: it allows participants to visually monitor their breathing efficiency and offers clear guidance to correct their breathing pattern. As a result, it enhances the therapeutic effectiveness of VR intervention.

The VR system employs a sliding window logic implemented in Unity to process data. This logic effectively manages Biopac data through web sockets. The system consistently receives data and stores it in a buffer with a capacity of 10 data points. After the buffer is filled, the average value of these points is computed to evaluate the current respiratory condition. The environment adapts in response to this data, ensuring that it remains within the optimal breathing range by modifying factors such as fog density when the average deviates from this range. This approach guarantees that the virtual reality (VR) environment promptly adjusts to the participant's physiological condition every 10 seconds, thereby preserving the immersion and efficacy of the relaxation exercise. The mobility of participants in the Biofeedback Forest VR Environment was meticulously crafted to strike a balance between immersion and the practical constraints imposed by the physical lab space. Participants were given the choice to physically navigate within the virtual reality (VR) environment. However, it was generally advised against due to the restricted space in the laboratory. In order to meet this limitation and improve user satisfaction, navigation within the virtual forest was primarily facilitated using a joystick. This feature enabled participants to navigate seamlessly and instinctively along the virtual pathways in both forward and backward directions.

In order to make turning and orientation adjustments, participants were obliged to physically rotate their bodies, thereby intensifying the feeling of presence and immersion in the virtual realm. This turning technique preserves the natural ambiance of the surroundings while also guaranteeing safety and spatial awareness in the limited laboratory space. It is crucial to mention that the VR setup did not allow for jumping actions, either through physical movements or by pressing a button. The implementation of this restriction was intended to uphold the emphasis on relaxation and prevent any potential disorientation or accidents within the limited area. Additionally, although participants were able to walk along the designated paths and admire the surrounding scenery, which included visually attractive slopes next to the trails, it was explicitly forbidden to climb or traverse these slopes. The purpose of this limitation was to guarantee that the experience was as real as possible, which helped avoid navigational errors that might interrupt the VR experience. The VR environment ensured user safety and control by limiting movement to flat paths and avoiding intricate terrain interactions.

3.2 Virtual Reality Video Intervention

The Parkour VR Video scenario, designed to induce mild stress through exposure to high-paced parkour activities, is complemented by a sophisticated VR Video Player setup. The player environment is styled as a massive room, akin to a theater, where the large screen fills the entire field of view, enhancing the immersion. This virtual theater, however, features no physical chairs and creates the illusion of floating in space from the user’s perspective. Upon entering this environment, participants find themselves equipped with virtual hands that closely resemble human hands, reinforcing the illusion of physical presence within the virtual space. Directly in front of them, an interactive console is presented, featuring Play, Pause, Next, Previous, and Lights buttons, along with a dropdown list for video selection. For the duration of the experiment, this list contains only one video— a specially compiled 5-minute Point of View (POV) parkour sequence. Interaction with this console is facilitated through the VR hands, where pointing at the console emits a ray of light, indicating the selection target.

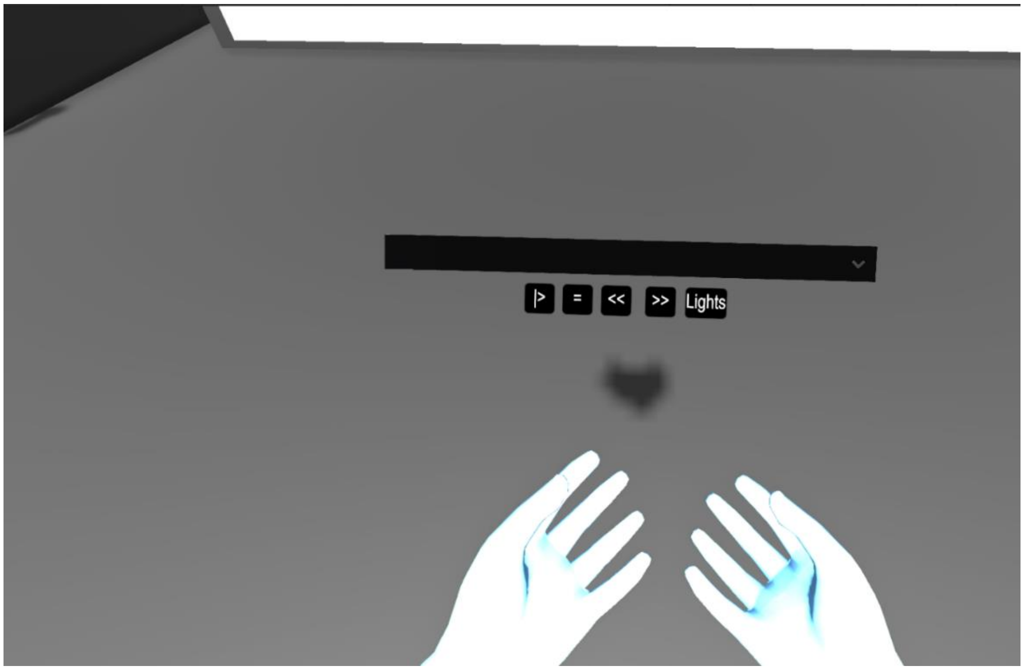

Figure 4: VR Video Player displaying 'Parkour Videos' with virtual hands and interactive buttons for Play, Pause, and other selectable options.

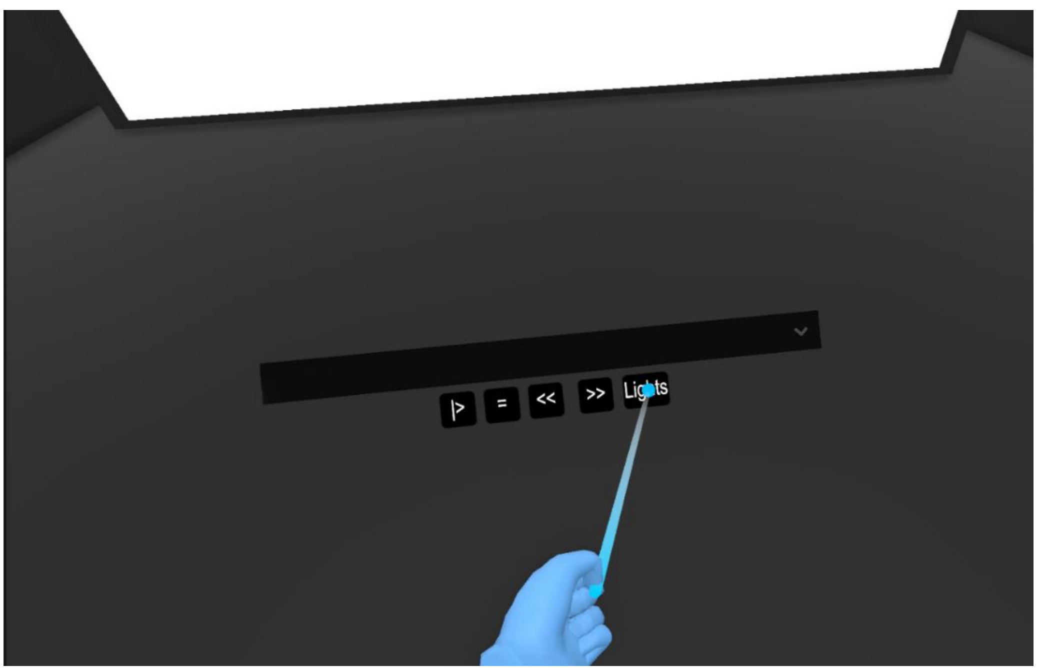

Figure 5: Switching Off Lights in the VR Video Player Room - Parkour Video

Participants use the trigger button on the Meta Quest 2 to interact with the menu, and upon their initial arrival in the VR environment, they are prompted to interact with the Lights button to familiarize themselves with the controls. To enhance realism and prevent inadvertent exploration or movement, additional hand gestures are mapped to corresponding buttons on Quest 2, creating tactile feedback that mimics real-life interactions. The setup ensures that participants remain in front of the console and the screen, minimizing movement within the room. Once adjusted, participants are asked to press the play button, which starts the video and simultaneously initiates the recording of RSP, ECG, and fNIRS data to monitor physiological responses. Throughout the viewing, participants are advised to remain still and silent to ensure accurate data collection. Notably, the video is played without any audio, focusing the stress induction purely on visual stimuli.

This VR Video Player functions as both a medium for delivering the parkour video and as a crucial component in controlling the experiment's environment, ensuring participant engagement, and accurately capturing data. By integrating realistic controls and feedback, the setup enhances the immersive experience, making it an essential component of the stress induction mechanism in the Parkour VR scenario. This design not only provides insights into the physiological impacts of VR-induced stress but also explores the potential of VR in safely simulating stressful situations for research, therapeutic exposure, or stress resilience training.

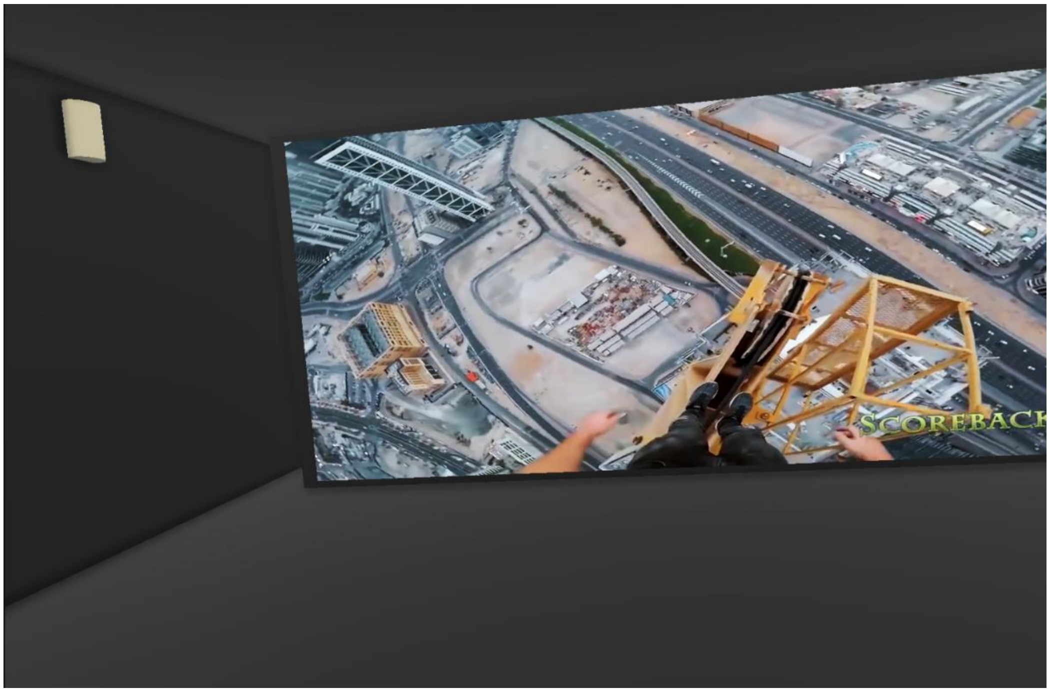

Figure 6: Parkour Video playing within the VR Video Player Room - Parkour Video

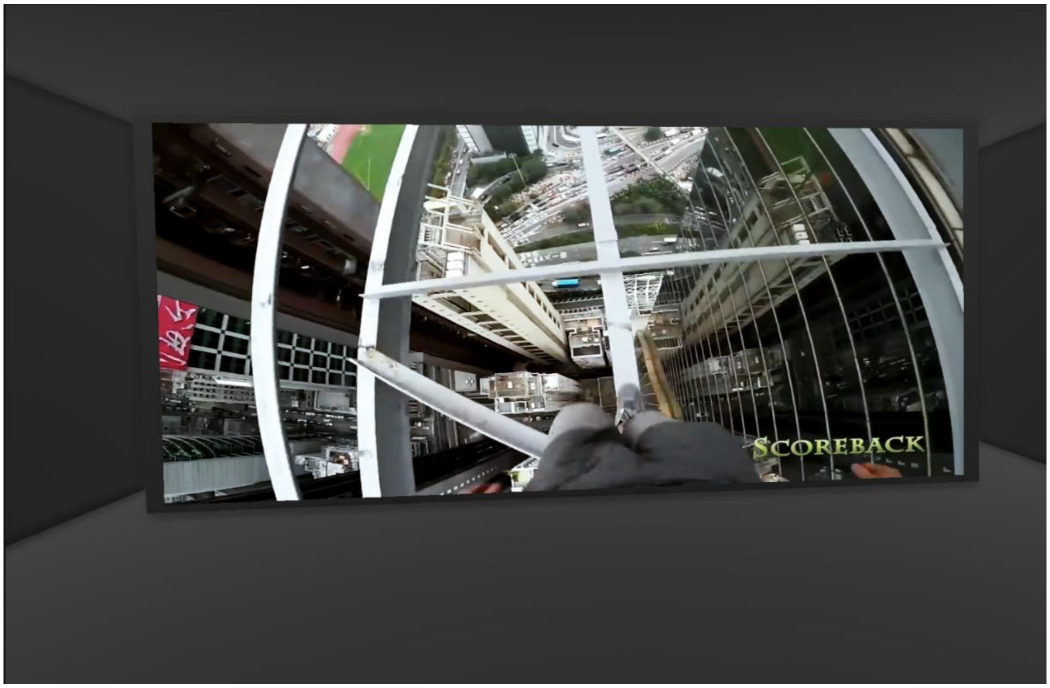

Figure 7: Parkour Video playing within the VR Video Player Room – Parkour Videos

3.3 Richie’s Plank In VR

The Richie's Plank Experiment, created by Toast VR, is a crucial element of our research aimed at inducing anxiety through an extremely immersive virtual reality encounter. Participants are positioned on a simulated plank that is extended from a tall building, creating a strong sensation of being dangerously elevated. In order to amplify this impact, a tangible plank is integrated into the virtual reality configuration, aligning with the virtual measurements and strategically placed to ensure that every participant covers an equal distance before reaching a conclusion. The consistent arrangement guarantees homogeneity in the difficulty encountered by all participants.

Figure 8: Richie's Plank Elevator Entrance

Figure 9: Participant Standing Inside the Elevator Looking Outside from Plank Floor.

Figure 10: Participant's view inside VR while standing inside the Elevator Looking Outside from Plank Floor.

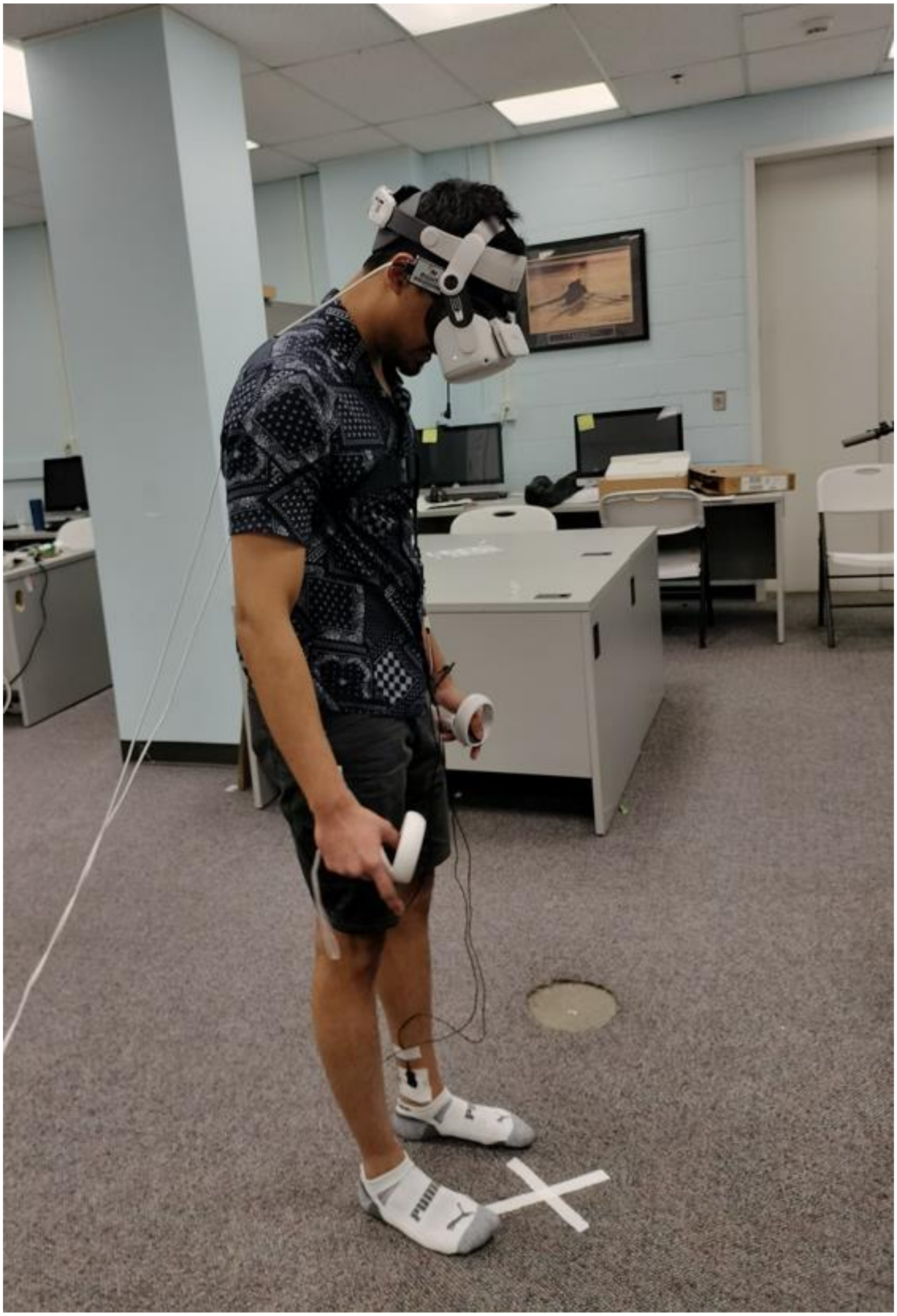

Figure 11: Participant at the end of the plank looking Down.

Figure 12: Participant's view inside VR while standing at the end of the plank looking Down.

Throughout the experiment, the participants underwent the height challenge three times, with each trial lasting about 5.5 minutes. The objective is to consistently measure and compare physiological and psychological responses across all three trials. Prioritizing the safety of the participants, they receive comprehensive instructions on safety protocols before commencing. A researcher is present during the session, providing guidance to participants as they enter the virtual reality scenario and instructing them to press the button that triggers the height challenge. This direct interaction facilitates the management of anxiety and guarantees safety, as the experimenter can communicate with participants and monitor their experience in real-time on a mobile device.

The main goal of incorporating Richie's Plank Experiment in our study is to evaluate the impact of virtual elevations on fear and anxiety reactions. The study offers valuable insights into the impact of high-anxiety virtual reality scenarios on physiological and psychological states by monitoring cardiovascular responses, respiratory patterns, and cerebral oxygenation. This configuration not only enhances our comprehension of fear conditioning and anxiety disorders but also investigates the potential of virtual reality in therapeutic exposure treatments. The incorporation of Richie's Plank Experiment into a wider range of VR scenarios, which include both serene natural settings and exhilarating parkour challenges, provides a comprehensive framework for investigating the full range of human reactions to virtual stimuli. Our research seeks to gain an in-depth understanding of the effects of virtual reality on human psychology by integrating sophisticated physiological monitoring technologies with immersive and controlled virtual reality environments. The practical ramifications of our discoveries have implications for therapeutic interventions, stress management, and entertainment. We utilize Richie's Plank Experiment exclusively for experimental endeavors, and we do not assert any proprietary rights over the software created by Toast VR.

Physiological data collection and analysis are crucial in evaluating the effects of stress and fear induced by virtual reality in the Richie's Plank Experiment. Once participants press the plank button in the elevator to begin their ascent to the virtual plank challenge, our systems immediately start collecting data from respiratory rate sensors (RSP), electrocardiograms (ECG), and functional near-infrared spectroscopy (fNIRS). By activating immediately, we ensure that we capture the complete range of physiological responses when participants face the height challenge. The utmost priority lies in ensuring the well-being of our participants. Consequently, participants are notified in advance that they have the option to withdraw from the experiment at any time if they experience excessive stress or find themselves unable to finish the task. This measure guarantees adherence to ethical standards and upholds the participants' independence, offering them a secure setting to interact with the potentially distressing virtual reality scenario.

3.5 Devices

We utilized a wide variety of state-of-the-art biosensors to gather accurate data from ECG, RSP, and fNIRS measurements in our study. This setup was specifically designed to prioritize participant comfort and maintain the highest quality of signal integrity. The BioNomadix BN-ECG2-T wireless transmitter was used to monitor the electrical activity of the heart. This transmitter is attached to participants using a Velcro strap and sends data to the Smart Center. This transmitter is capable of recording from Lead I, and Lead II, and calculating aVR, aVL, and aVF leads. It works together with the BN-RSPEC Transmitter, which records ECG and respiration on a single channel. The ECG electrodes are strategically positioned on the arms, and legs to align with the Lead I, II, and III configurations. They are fastened using adhesive pads or straps to guarantee consistent and high-quality data collection.

Figure 13: Biopac BioNomadix Smart Centre and BN-ECG3-T transmitter

Figure 14: Electrode Placement for ECG on participant

Figure 15: SS5LB transducer placement on Participant

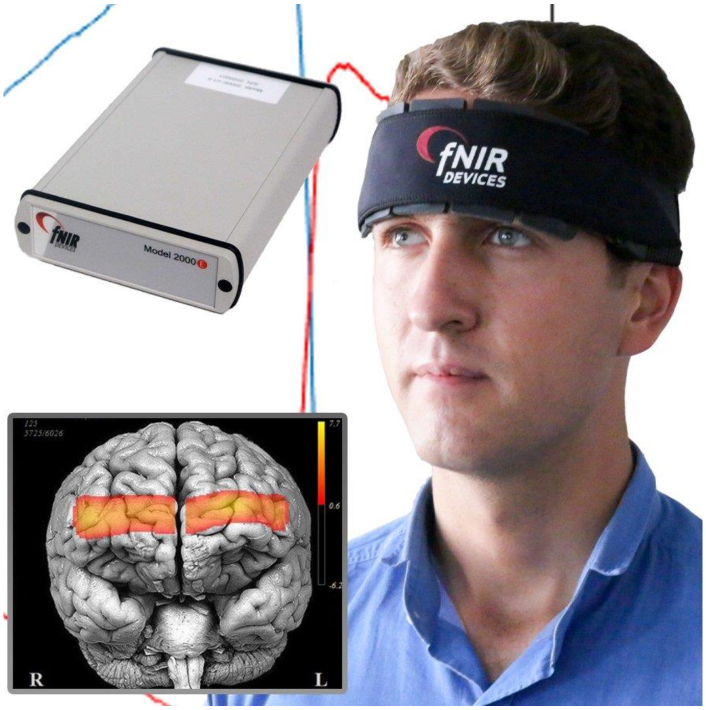

Figure 16: fNIRS placement on forhead for individuals

The SS5LB Respiratory Effort Transducer is essential for analyzing respiratory patterns. The device is positioned around the chest, specifically below the armpits, where the respiratory expansion is greatest. It is slightly tightened to ensure accuracy when the user exhales to their maximum capacity. This configuration is crucial for capturing accurate respiratory data during the experiment.

Participants were outfitted with Biopac RSP-ECG and fNIRS devices. The FNIRS 2000 Device, specifically the FNIR103C models, is used to measure neural activity and hemodynamic responses in the prefrontal cortex using a multi-channel NIRS optical brain imaging technique. Participants utilize a fNIR sensor affixed to their forehead to obtain instantaneous measurements of oxy-hemoglobin and deoxygenated hemoglobin levels while engaging in different activities. This technology not only enables cognitive function assessments to be conducted in a laboratory setting but also facilitates various applications, including neurorehabilitation and human performance assessment.

Figure 17: Participant with BNECG2-T(RSP-ECG), SS5LB transducer, electrodes and fNIRS

For our research utilizing custom Unity environments and Richie's Plank experience, we chose the Meta Quest 2 as our device. To enhance comfort during extended use, we've upgraded the Meta Quest 2 with two additional features: a specialized head strap and a cooling fan. The head strap is engineered to reduce facial pressure by distributing the weight of the device evenly across the head. It features an adjustable design with five nodes to accommodate various head sizes for optimal comfort. These enhancements aim to improve user experience during immersive VR sessions by balancing comfort with functionality, making extended periods of use more manageable and enjoyable.

Figure 18: Meta Quest 2 with two additional features: a specialized head strap and a cooling fan.

The Dell G15 gaming laptop, equipped with high-performance components such as the i9-12900H processor, RTX 3070 ti graphics card, 16GB DDR5 RAM, and a 1TB SSD, was used to create and execute the Unity environment for the experiment, as well as to gather RSP and ECG data. In addition, a secondary computer featuring an Intel(R) Core(TM) i7-6850K CPU, 64.0 GB RAM, and 1 TB HDD was exclusively assigned for the purpose of recording FNIRS data. This computer was connected to three high-definition monitors. This configuration highlights our dedication to utilizing state-of-the-art technology to accurately investigate the physiological and psychological effects of virtual reality environments.

Every device and component, ranging from the 45 cm Electrode Lead wire for ECG connections to the medical tape used for securing electrodes, was carefully selected to guarantee dependability and uniformity in data collection, thereby improving the scientific integrity of our experiment.

3.6 Measures And Analysis

3.6.1 Stress And Anxiety Measures

In order to evaluate the level of anxiety and pain experienced by participants, our study utilized the State-Trait Anxiety Inventory (STAI) and Visual Analog Scales (VAS), which have been validated in previous research(Facco et al., 2013; Hawker et al., 2011; Hornblow & Kidson, 1976; van der Bij et al., 2003). The State-Trait Anxiety Inventory (STAI) assesses anxiety levels by asking participants to rate their emotions, including calm, tense, upset, relaxed, content, and worried, on a scale from 1 to 5. A rating of 1 indicates the least amount of emotional presence. In contrast, the Visual Analog Scale (VAS) employed an 11-point continuum to measure the intensity of pain and anxiety, spanning from 0 (indicating the absence of pain/anxiety) to 10 (representing the utmost level of pain/anxiety).

While it is difficult to measure pain and anxiety objectively, physiological changes can serve as a substitute measure to comprehend differences in objective pain levels (Perlaki et al., 2015; Tracy et al., 2016). In this particular situation, we employed Heart Rate Variability (HRV) as it functions as a gauge for alterations in the sympathetic and parasympathetic nervous systems, which are associated with stress and relaxation states, respectively (Lehrer et al., 2007; Reiner, 2008; McCorry, 2007). The HRV analyses incorporated time and frequency domain metrics verified by previous studies (Malik et al., 1996). The time domain metric, Root Mean Square of Successive RR Differences (RMSSD), was computed. RMSSD is recognized for its correlation with parasympathetic activity and its connection to stress, anxiety, and pain (Ali et al., 2021; Shaffer & Ginsberg, 2017; Tebar et al., 2020). The use of frequency domain metrics helped in comprehending changes in pain. One such metric is the ratio between low-frequency (LF, 0.04–0.15 Hz) and high-frequency (HF, 0.15–0.4 Hz) bands, which serves as an indicator of the balance between sympathetic and parasympathetic nervous system activity (Appelhans & Luecken, 2008; Chalmers et al., 2014; Malik et al., 1996; Malliani et al., 1991). Although HRV has a wide range of applications, recent findings (Moens et al., 2022) suggest that it is not suitable as a proxy for pain, particularly chronic pain, and its use is limited (Girishan Prabhu et al. 2020).

In addition, the respiration rate (RR) was observed and affected by the activities of both the sympathetic and parasympathetic nervous systems. It increases with sympathetic activity and decreases with parasympathetic activity (Glick & Braunwald, 1965; Narkiewicz et al., 2006; Russo et al., 2017). Research and analyses have established a connection between anxiety and an elevated respiratory rate (RR) and have observed that reducing RR can effectively decrease anxiety levels (Leyro et al., 2021; Masaoka & Homma, 1997; Paulus, 2013; Zaccaro et al., 2018). Pain increases respiratory characteristics, including rate, flow, and volume, through neuronal interactions in regions such as the pre-Bötzinger complex, which plays a key role in generating breathing rhythm (Jafari et al., 2017; Liu et al., 2022). Recent systematic reviews indicate that paced, slow breathing can relieve pain by regulating heart rate and blood pressure, thereby modifying the brain's pain perception (Joseph et al., 2022).

3.7 Hemodynamic Response Analysis In Cognitive Neuroscience

The COBI Studio software is employed to collect data from the fNIR imager, which it subsequently saves in a ".nir" file format. This format predominantly captures measurements of luminous intensity. The measurements are then transformed into concentrations of oxygenated and deoxygenated hemoglobin utilizing the Modified Beer-Lambert Law, a widely used approach in near-infrared spectroscopy to estimate the absorption of light in a medium(Delpy et al. 1988; Scholkmann et al. 2014). The converted data is stored in a file with the extension ".oxy", while any event markers recorded during the session are saved in a separate file with the extension ".mrk".

The ".oxy" file, which is crucial for our analysis, includes data from 18 optodes that correspond to 54 unprocessed light channels. The positioning of these optodes adheres to previous studies, wherein Optodes 1 to 16 are assigned to distinct cerebral areas, while Optodes 17 and 18 function as superficial reference points situated in the left and right hemispheres, respectively(Delpy et al. 1988; Scholkmann et al. 2014). This file format precisely documents the hemodynamic responses. The first column contains the time in seconds, while the subsequent columns are organized in pairs. Each pair represents the levels of deoxygenated hemoglobin (HBR) and oxygenated hemoglobin (HBO) from each optode.

After obtaining the data, the ".oxy" file is transformed into a CSV format to simplify subsequent data manipulation and preprocessing. During the preprocessing stage, we guarantee the integrity of the data by eliminating any non-numeric characters and null entries, thus making it ready for thorough analysis.

The 16 optodes are classified into four separate groups for analytical purposes, according to their anatomical positions: left lateral (Optodes 0-4), left medial (Optodes 4-8), right medial (Optodes 8-12), and right lateral (Optodes 12-16). We calculate the average values of oxygenated and deoxygenated hemoglobin for each group. These values are then used in later statistical analyses to investigate regional brain activity and its functional consequences. This methodological approach enables a meticulous evaluation of hemodynamic alterations in reaction to cognitive tasks, facilitating a thorough interpretation of functional brain dynamics.

3.8 Analysis

3.8.1 Participants

The study conducted at UNCC intentionally selected participants solely from the Asian/Pacific Islander demographic using focused outreach efforts to maintain a uniform participant profile for ECG, RSP, and fNIRS measurements. This method was implemented to reduce the variability in genetic factors, cultural influences, and baseline physiological responses frequently observed in a more heterogeneous population. The study aimed to improve the accuracy and dependability of its findings by narrowing its focus to a particular ethnic group. Due to this, we were able to consider any confounding variables that may impact the physiological and psychological reactions to VR, such as environmental factors and social determinants of health. The selection criteria, although more limited, were crucial for attaining a comprehensive comprehension of the influence of VR within this homogeneous group, which could potentially guide the development of more culturally and physiologically appropriate interventions.

Participants were mandated to have a minimum age of 18 years to encompass a wide range of adults while reducing the potential for age-related physiological differences. To participate in the study, it was required that individuals were in good overall health and did not have any known cardiovascular, neurological, or psychiatric disorders that could affect the study results. The study encompassed individuals unfamiliar with Virtual Reality (VR) and those with previous experience with VR to evaluate the influence of VR familiarity on physiological and psychological reactions.

To avoid any interference with physiological measurements, individuals who had pre-existing cardiovascular, neurological, or severe psychiatric disorders were not included in the study. Individuals who tend to experience motion sickness or previously encountered cybersickness were not included in the study to avoid possible adverse reactions to virtual reality exposure. The exclusion of pregnant individuals was justified due to the potential hazards and physiological differences related to pregnancy. Individuals taking medications known to impact the cardiovascular or central nervous systems such as beta blockers were not included in the study to prevent any disruption to the physiological measurements. Participants underwent a standardized questionnaire screening process to confirm their eligibility based on specific criteria for inclusion and exclusion. This approach aimed to establish a participant pool that was representative and conducive to achieving the study's goals while also ensuring participant safety and the integrity of the data.

The study maintained strict adherence to the utmost ethical standards to safeguard the dignity, rights, and welfare of all participants throughout the research process. The same has received approval from the Institutional Review Board (IRB). The research design included measures to mitigate potential hazards and discomforts related to virtual reality exposure and physiological monitoring. Special emphasis was placed on reducing the likelihood of cybersickness and safeguarding the privacy and confidentiality of participant data.

Participants were given a comprehensive consent form that clearly explained the study's objectives, methods, possible hazards, and advantages during the consent process. The document also outlined the entitlements of the participants, which encompassed the freedom to discontinue their involvement in the study at any point without facing any adverse consequences. The researcher meticulously examined the consent form with every participant, ensuring their comprehensive comprehension of the study's extent and specific responsibilities. Prior to finalizing their signature on the consent form, participants were granted the opportunity to raise any uncertainties they had.

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The final study included a demographic profile of 14 individuals, all between the ages of 22 and 27. The gender distribution consisted of 7 males and 7 females. The participants demonstrated a high level of educational achievement, with the majority having obtained a bachelor’s degree and a significant portion holding a master's degree. All participants self-identified as Asian/Pacific Islander.

Regarding marital status, all the participants were unmarried. Regarding the virtual reality (VR) experience, a range of levels of familiarity exists. Among the participants, the majority were first-time VR users, while a smaller group had some experience using VR a few times. There were no participants who were frequent users. This diverse experience with virtual reality (VR) served as a comprehensive foundation for assessing the effects of the technology on individuals with varying levels of prior exposure.

The experimental design incorporated a randomized controlled trial framework to assign the 14 study participants to distinct sequences of activities, aiming to mitigate selection bias and safeguard the validity of the research results. Participant assignment to the experimental conditions was determined through a random number generation process implemented in Microsoft Excel. The conditions comprised an initial baseline assessment, followed by either immersion in a forest environment or engagement with virtual reality (VR) parkour videos, culminating in Richie's Plank Experience within VR. The alternative sequence reversed the order of the forest environment and the VR parkour video exposure. This randomization was critical to ensuring a balanced representation of participants in each experimental pathway. Enrollment in the research was optional, and subjects had the freedom to withdraw from the study at any point. Subjects were remunerated with a $10 USD gift card upon successful conclusion of the research. Before conducting the study, a power analysis was carried out using G*Power3 software (Faul et al., 2007) in order to ascertain the optimal sample size needed to detect a large effect size (Cohen's d = 0.8) between three repeated groups using an Analysis of Covariance (ANCOVA), with a significance level set at alpha = .05. The analysis revealed that in order to achieve a statistical power of 0.65, a total of 15 participants would be required.

3.9 Study Design

Upon arrival, participants receive the Consent Form, Demographic Questionnaire, and the Prescreening Questionnaire For Health Condition, and Cybersickness Pre-Screening Questionnaire. If a participant answered Yes to any of these questions in the "Prescreening Questionnaire For Health Condition" form, they will not be eligible to participate. The

Cybersickness Prescreening Questionnaire is essential for identifying potential risks associated with using VR head-mounted displays. It screens for conditions such as migraines, claustrophobia, motion sickness, and other health issues that could affect VR tolerance. Participants marking "Yes" to any of the questions are considered at higher risk for cybersickness; those with multiple affirmative responses are excluded from the study to ensure safety. Each Participant must acknowledge their understanding of these risks by initialing and dating the form, which is then attached to their consent form.

Following this, the BioNomadix BN-ECG2-T wireless transmitter and Smart Center are employed for efficient wireless data transmission. The ECG transmitter, secured to participants with a Velcro strap, sends data to the Smart Centre. It records data from Lead I, and Lead II, and can also calculate leads aVR, aVL, and aVF. Additionally, the BioNomadix BN-RSPEC Transmitter captures both ECG and respiration data on a single channel, accommodating scenarios requiring participant mobility. The SS5LB Respiratory Effort Transducer is crucial for respiratory measurements. It must be precisely positioned about 5 centimeters below the armpits, where respiratory expansion is greatest. To ensure accurate readings, the transducer is securely fastened around the chest with slight tension during maximum expiration. This setup guarantees meticulous monitoring of cardiovascular and respiratory functions in a mobile setting. All electrodes and wires on the Participant's body are secured with medical tape to prevent displacement during movement. Finally, the fNIR Model 2000 is attached to the Participant's forehead; this process and the equipment are carefully explained beforehand to ensure participant comfort.

The Participant's experiment can be played out in 2 directions based on Randomization.

1st Baseline, 2nd Forest Environment, 3rd VR Video Player - Parkour videos and last 4th Richie’s Plank, or

1st Baseline, 2nd VR Video Player - Parkour videos, 3rd Richie's Plank and last 4th Forest Environment

Once the participants are equipped with sensors before the baseline starts, they are provided with a sheet called Visual Analog Scale (VAS) for Stress to fill out. The VAS for Stress is a self-assessment tool that quantifies an individual's current level of perceived Stress. Participants are instructed to mark a specific point on a continuous line that ranges from "0-No Stress" to "10-Worst Stress" to fill out based on what best reflects their stress level, providing a straightforward and measurable method for assessing immediate Stress, which helps in the clear interpretation of outcomes. After completing the form, the participants' baseline data are recorded. During this baseline recording, participants must stand still for 5 minutes without talking or moving. Once the baseline is recorded, the participants fill out the VAS sheet again for the post-intervention assessment.

Following the baseline recording, a 6-minute break is given to allow participants' baselines to return to normal. If the Participant is scheduled for the Forest Segment, they are required to complete two forms: the Pre-Intervention VAS for Stress and the State-Trait Anxiety Inventory (STAI: Y-6 item). The STAI, designed to measure an individual's current state of anxiety, consists of six statements reflecting common emotions associated with anxiety, such as tranquility, tension, and apprehension. Participants rate their feelings against each statement on a four-point scale ranging from “Not at all - 1, Somewhat - 2, Moderately - 3, Very much - 4," providing a quick assessment of their current emotional state. Participants are encouraged to respond based on their immediate feelings without overthinking.

After filling out the forms, participants are briefed on the Forest Environment, its fog components, and the function of the status bar, and they listen to an audio cue resembling a submarine sonar beeping every 5 seconds to assist in maintaining a breathing rate of 6 BPM. They are then handed the Meta Quest 2 controller, and adjustments are made to ensure they are comfortable using it. Participants are advised to limit their movement within the VR environment due to space constraints in the room, with designed movements allowing only left-to-right directional motion. After receiving these instructions, participants were put on the VR headset, which had to be adjusted for clear visibility. The experiment began with the auditory cue and then the fog initiation after 30 seconds of the Participant in the environment. Data collection lasts for 6 minutes, excluding the first 30 seconds as the Participant adjusts to the breathing pace.

Following this segment, participants complete the Post-Intervention VAS and STAI forms. They then take a 6-minute break before proceeding to the VR Video Player – Parkour Video segment, where they are briefed on operation instructions. Data collection starts with the video and ends when the video does. The VR headset is then removed, and participants fill out another VAS form. After another 6-minute break, the "Richie's Plank" experiment begins. Participants fill out Pre-intervention VAS and STAI forms, receive a brief on the environment and controls, and are allowed to explore a bit before starting the experiment. Post-experiment, they complete the final VAS and STAI forms. All devices are then removed, and electrode gel is cleaned off, marking the completion of the session.

CHAPTER 4: RESULTS

4.1 Survey Data

4.1.1 Stress - Within Group Comparison

We first performed a within-group (pre-post) comparison of stress levels across four groups. Table 1 below presents the participant's average stress levels before and after for each group, along with the p-value from paired t-tests. When comparing the post-intervention stress scores to the pre-intervention scores, we did not observe any statistically significant differences across the baseline data (t(26) = 1.50, p-value = 0.16) and the biofeedback forest data (t(26) = 1.76, p-value = 0.10). However, across Richie's Plank (t(26) = 2.70, p-value = 0.02) and Parkour Video (t(26) = 2.45 p-value = 0.03), we saw a significant increase in stress cores after the intervention compared to pre-intervention scores.

Table 1: Stress levels Pre-intervention and Post-intervention.

Group	***Pre-intervention***	***Post-intervention***	***p-value***
Baseline	1.8±2.12	1.1±1.61	0.16
Biofeedback Forest	0.8±1.37	1.6±2.10	0.10
Parkour Video	1.1±1.54	2.2±2.19	0.03
Richie's Plank	1.1±1.29	3.4±3.18	0.02

4.1.2 Stress - Across Group Comparison

Next, we performed an across-group comparison of post-intervention stress scores while controlling for the pre-intervention scores. Table 2 below presents participant's stress scores across four groups. There was a significant difference in mean post-intervention stress score (F(3,51) =3.89, p-value = 0.01) between the four groups, as seen in Table 2 below. The p-values in the table represent the condition (Baseline, Biofeedback Forest, Richie's Plank, and Parkour Video) effect on post-intervention scores, controlling for pre-intervention scores where p-values = 0.05 imply a significant difference between at least two conditions.

Table 2: Stress levels before and after intervention.

Measure	**Baseline**	**Biofeedback Forest**	**Parkour Video**	**Richie's Plank**	**p-value**
VAS-10 pre-intervention	1.8±2.12	0.8±1.37	1.1±1.54	1.1±1.29	= 0.01
VAS-10 post-intervention	1.1±1.61	1.6±2.10	2.2±2.19	3.4±3.18	

Post hoc analyses revealed a statistically significant distinction between Richie's Plank and Baseline (p-value < 0.01). No other groups varied significantly. Table 3 and Figure 19 below present the findings from the post hoc tests.

Table 3: Post hoc differences between group levels.

Difference in Group Levels	**Difference of Means**	**Simultaneous 95% CI**	**Adjusted p-value**
Forest - Baseline	1.12	(-1.01, 3.26)	0.51
Richie - Baseline	2.66	(0.56, 4.77)	0.01
Video - Baseline	1.57	(-0.54, 3.68)	0.21
Richie - Forest	1.54	(-0.55, 3.63)	0.22
Video - Forest	0.44	(-1.64, 2.53)	0.94
Video - Richie	-1.09	(-3.18, 0.99)	0.51

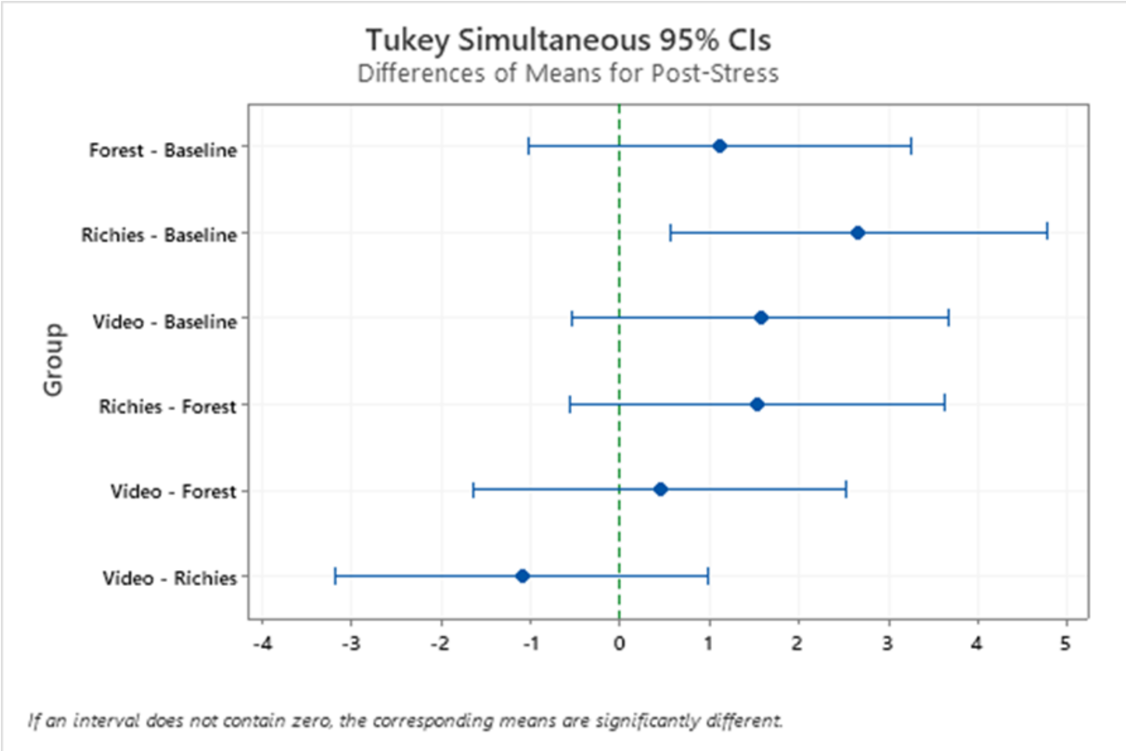

Figure 19: Post hoc differences of mean between group levels.

Finally, from the post hoc tests, we observed that controlling for the pre-intervention scores, the participants reported the highest post-intervention scores after the Richie's Plank experience. Further, we observed that Parkour Video also induces higher stress compared to the relaxing HRV-Biofeedback-based forest environment and baseline scores collected at the beginning of the experiment.

4.1.3 Anxiety - Within Group Comparison

Similar to the within-group (pre-post) comparison performed for the stress levels, we compared the pre-post anxiety scores collected using two instruments (VAS and STAI) across two groups. Unlike stress, there are only two groups considered for anxiety, as we used anxiety instruments only during Biofeedback Forest and Richie's Plank. Table 4 below presents the participant's average anxiety levels before and after for each group, along with the p-value from paired t-tests. For the forest environment, when comparing the post-anxiety scores to the pre-anxiety scores, we did not observe any significant difference across both instruments, VAS (t(26) = 0.49, p-value = 0.63) and STAI (t(26) = 2.09, p-value = 0.06). However, for Richie's Plank, we saw a significant increase in anxiety scores after the intervention compared to pre-intervention scores across both instruments, VAS (t(26) = 2.11, p-value = 0.05) and STAI (t(26) = 2.10, p-value = 0.05).

Table 4: Anxiety levels before and after the intervention.

Group	***Instrument***	***Pre-intervention***	***Post-intervention***	***p-value***
Biofeedback Forest	VAS	1.3±2.09	1.4±1.95	0.63
	STAI	28.1±9.67	32.9±11.39	0.06
Richie's Plank	VAS	1.1±1.46	2.9±3.1	=0.05
	STAI	30.2±10.98	45.7±16.35	=0.05

4.1.4 Anxiety - Across Group Comparison

Table 5 below presents participant's anxiety levels before and after the intervention. On comparing the post-intervention anxiety scores while controlling for the pre-intervention anxiety scores across the two groups, we observed statistically significant differences.

Table 5: Anxiety levels before and after intervention.

Measure	***Biofeedback Forest***	***Richie's Plank***	***p-value***
VAS-10 pre-intervention	1.3±2.09	1.1±1.46	0.05
VAS-10 post-intervention	1.4±1.95	2.9±3.1	
STAI pre-intervention	28.1±9.67	30.2±10.98	<0.01
STAI post-intervention	32.9±11.39	45.7±16.35	

Specifically, across both instruments, we observed that participants reported higher anxiety scores VAS (p-value = 0.05) and STAI (p-value <0.01) post-intervention after experiencing Richie's Plank compared to the Biofeedback Forest.

4.2 Biosensor Data

4.2.1 Cardiac and Respiratory Activity

As discussed in the methods section, we considered various validated metrics that capture the sympathetic and parasympathetic activity to comprehend the levels of stress, anxiety, and relaxation during each intervention. To check for significant differences in the baseline values and the beginning of each intervention (Biofeedback Forest, Richie's Plank, and Parkour Video), we compared the baseline values to the first 45 seconds of the data collected during each intervention. Table 6 below provides the average values of each metric across these scenarios and the p-values. While we used a five-minute break between each intervention to allow for the cardiac and respiratory activity to return to baseline values, this comparison aims to capture any potential learning effect.

Table 6: Initial cardiac and respiratory metrics across four scenarios prior to intervention.

Measure	**Baseline**	**Biofeedback Forest**	**Richie's Plank**	**Parkour Video**	**p-value**
Respiration Rate	17.5±3.61	17.8±2.32	17.4±4.11	17.9±3.20	0.92
RR-Interval	682.2±70.11	691.9±72.34	700.1±78.21	690.2±62.23	0.81
RMSSD	26.7±12.70	27.4±14.31	27.2±11.10	26.9±9.80	0.80
LF/HF Ratio	3.6±2.12	3.8±1.99	4.0±2.56	4.1±2.18	0.43

From the findings in Table 6 above, It is apparent that no statistically significant differences were observed in the cardiac and respiratory activity of participants at the beginning of each scenario. This ensures that any significant differences observed in the cardiac and respiratory activity of participants between the four scenarios are because of the intervention. Next, we compare the different metrics capturing the cardiac and respiratory activity during each intervention to understand the impact of each intervention. Table 7 below presents the different neurophysiology metrics across four interventions, along with the p-value from ANOVA tests.

Table 7: Cardiac and respiratory metrics across four scenarios during interventions.

Measure	***Baseline***	***Biofeedback Forest***	***Parkour Video***	***Richie's Plank***	***p-value***
Respiration Rate	17.2±5.97	11.2±5.90	18.8±6.08	20.6±2.37	<0.01
RR-Interval	675.2±78.77	696.9±80.83	703.7±75.31	692.2±61	0.77
RMSSD	26.3±12.87	39.3±24.03	26.8±10.92	43.7±13.39	0.01
LF/HF Ratio	4.0±3.18	6.2±5.15	2.5±1.51	3.5±3.37	0.05

On comparing the RR-Interval values across four scenarios, there was no significant difference in mean RR-Interval ($F(3,52) = 0.37$, p-value = 0.77), as seen in Table 7 above.

However, on comparing the respiration rate across four scenarios, there was a significant difference ($F(3,52) = 8.23$, p-value < 0.01) in the mean respiration rate. Post hoc analyses revealed a statistically significant distinction between Biofeedback Forest and Baseline (p-value = 0.02), Biofeedback Forest and Parkour Video (p-value < 0.01), and Biofeedback Forest and Richie's Plank (p-value < 0.01). Table 8 and Figure 20 below present the findings from the post hoc tests.

Table 8: Post hoc differences in respiration rate across four scenarios.

Difference of Group Levels	***Difference of Means***	***Simultaneous 95% CI***	***Adjusted p-value***
Forest - Baseline	-5.97	(-11.30, -0.64)	0.02
Richie - Baseline	3.45	(-1.88, 8.78)	0.33
Video - Baseline	1.6	(-3.73, 6.93)	0.86
Richie - Forest	9.42	(4.09, 14.75)	<0.01
Video - Forest	7.57	(2.24, 12.90)	<0.01
Video - Richie	-1.85	(-7.18, 3.48)	0.79

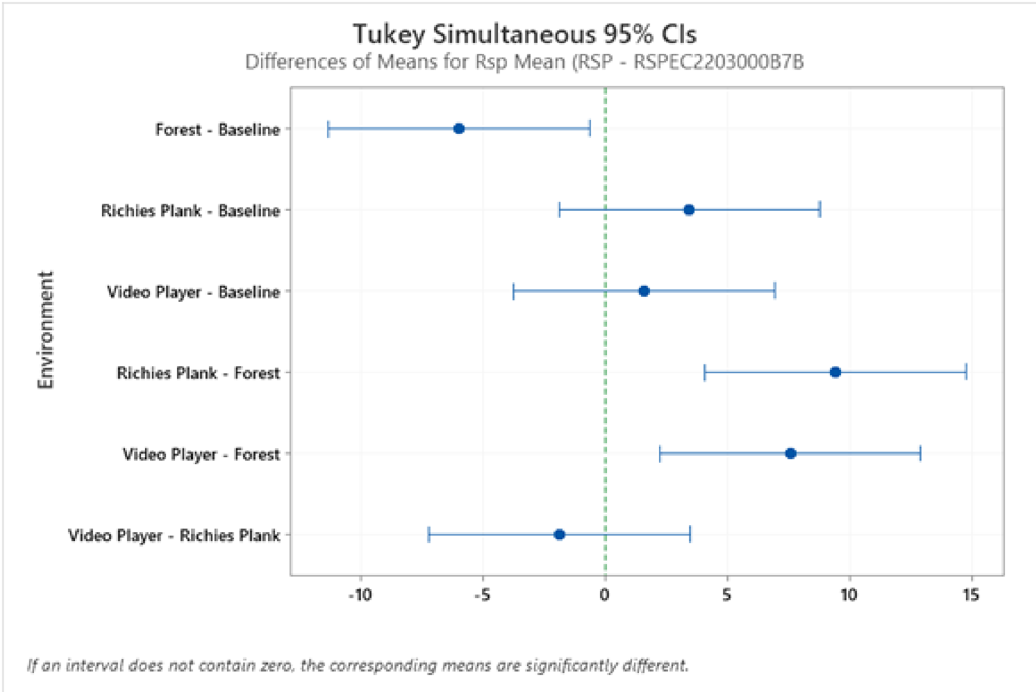

Figure 20: Post hoc differences in mean respiration rate across four scenarios.

Next, on comparing the LF/HF ratio across four scenarios, there was a significant difference (F(3,52) = 2.70, p-value = 0.05) in the mean LF/HF ratio. Post hoc analyses revealed a statistically significant distinction between Biofeedback Forest and Richie's Plank (p-value = 0.04). Table 9 and Figure 21 below present the findings from the post hoc tests.

Table 9: Post hoc differences in LF/HF ratio across four scenarios.

Difference of Group Levels	***Difference of Means***	***Simultaneous 95% CI***	***Adjusted p-value***
Forest - Baseline	2.19	(-1.36, 5.74)	0.37
Richie - Baseline	-1.49	(-5.05, 2.06)	0.68
Video - Baseline	-0.51	(-4.06, 3.04)	0.98
Richie - Forest	-3.68	(-7.23, -0.13)	0.04
Video - Forest	-2.7	(-6.25, 0.86)	0.20
Video - Richie	0.98	(-2.57, 4.54)	0.88

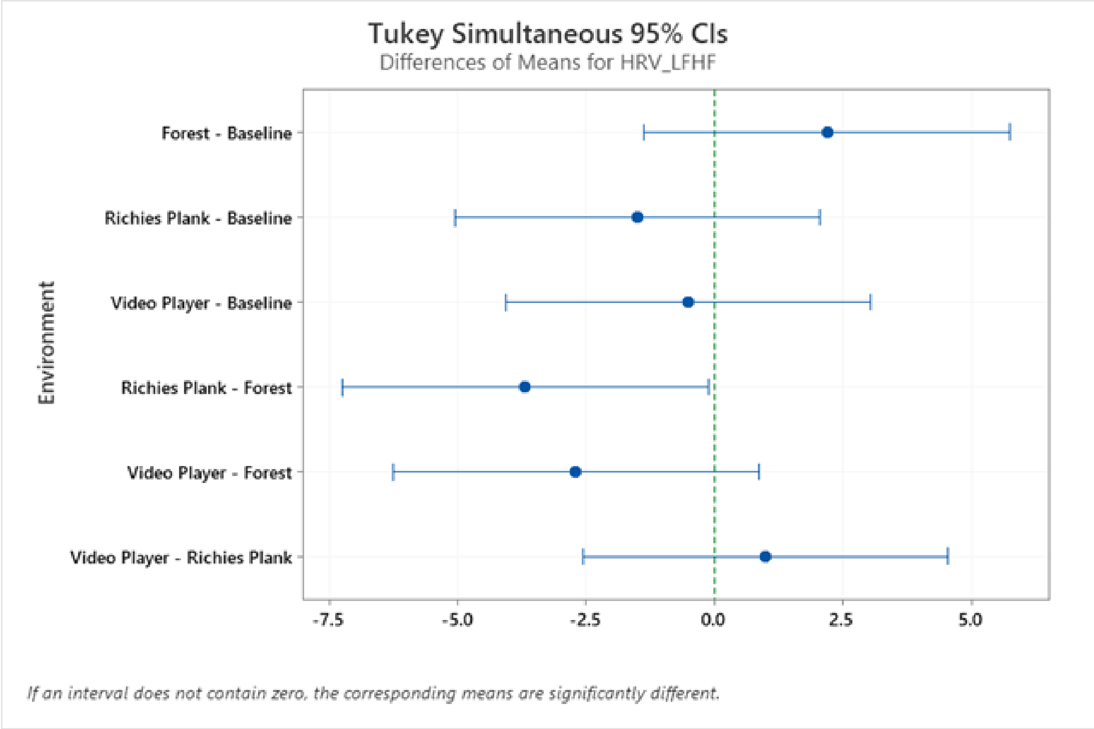

Figure 21: Post hoc differences in mean LF/HF ratio across four scenarios.

Finally, on comparing the RMSSD values across four scenarios, there was a significant difference in mean RMSSD (F(3,52) = 4.19, p-value = 0.01). Post hoc analyses revealed a statistically significant distinction between Parkour Video and Richie's Plank (p-value = 0.04). Table 10 and Figure 22 below present the findings from the post hoc tests.

Table 10: Post hoc differences in RMSSD across four scenarios.

Difference of Group Levels	***Difference of Means***	***Simultaneous 95% CI***	***Adjusted p-value***
Forest - Baseline	13.01	(-3.16, 29.18)	0.16

Richie - Baseline	17.38	(1.21, 33.55)	0.03
Video - Baseline	0.46	(-15.71, 16.63)	1.00
Richie - Forest	4.37	(-11.80, 20.54)	0.89
Video - Forest	-12.55	(-28.72, 3.63)	0.18
Video - Richie	-16.92	(-33.09, -0.74)	0.04

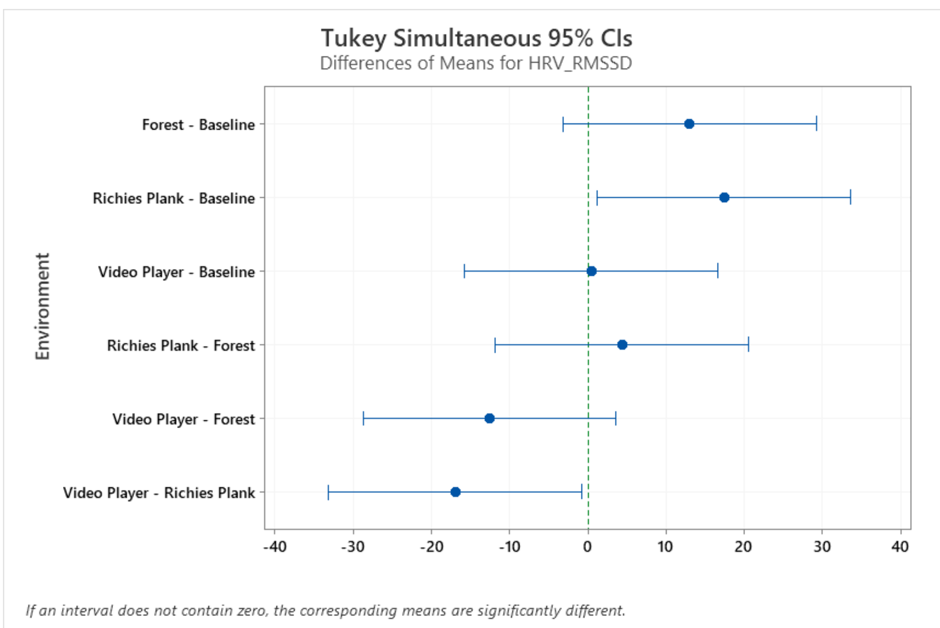

Figure 22: Post hoc differences in mean RMSSD across four scenarios.

4.2.2 Brain Activity

Similar to the analysis performed for the cardiac activity, we first compared the baseline values to the first 45 seconds of the data collected during each intervention. As mentioned in the methods section, we divided the fNIRS data into four sections of the prefrontal cortex and calculated the HbO and HbR for each section. The average values of HbO and HbR for each section across four scenarios were observed, and there were no statistically significant differences in the HbO and HbR activity of participants at the beginning of each scenario. Again, while we used a five-minute break between each intervention to allow for the brain activity to return to baseline values, our observation ensured that any significant differences observed in the fNIRS activity of participants between the four scenarios were because of the intervention.

Next, we compare the different metrics capturing the cardiac and respiratory activity during each intervention to understand the impact of each intervention. Table 11 below presents the different neurophysiology metrics across four interventions, along with the p-value from ANOVA tests.

Table 11: fNIRS (HbO and HbR) activity for four scenarios during interventions.

Brain Area	Measure	Baseline	Biofeedback Forest	Parkour Video	Richie's Plank	p-value
Left Lateral	HbO	0.8±1.13	0.6±0.92	0.7±1.07	2.8±1.97	<0.01
	HbR	0.9±1.40	0.6±0.70	0.0±1.75	-0.6±2.00	0.06
Left Medial	HbO	1.3±1.47	0.3±1.42	0.0±1.10	3.2±1.89	<0.01
	HbR	1.1±1.16	1.3±1.24	0.5±1.02	-0.2±2.02	0.03
Right Medial	HbO	1.0±1.12	0.1±1.28	-0.1±1.80	3.3±1.61	<0.01
	HbR	0.8±1.25	1.0±1.14	0.6±1.69	-0.4±1.70	0.07
Right Lateral	HbO	0.9±1.06	-0.1±1.07	0.6±1.19	2.5±2.38	<0.01
	HbR	0.8±1.14	0.9±0.80	0.7±1.04	-1.2±2.84	<0.01

4.2.3 Oxyhemoglobin (HbO)

On comparing the HbO values across four scenarios within each brain area, we observed significant differences (see Table 11 above). In the left lateral area, there was a significant difference in mean HbO (F(3,52) = 8.41, p-value < 0.01) across four scenarios. Post hoc analyses revealed a statistically significant distinction between Richie's Plank and Baseline (p-value < 0.01), Richie's Plank and Parkour Video (p-value < 0.01), Richie's Plank and Biofeedback Forest (p-value < 0.01), and Baseline and Biofeedback Forest (p-value < 0.01). Figure 23 below presents the findings from the post hoc tests. Specifically, we observed HbO to be highest during Richies's plank and least during Biofeedback Forest.

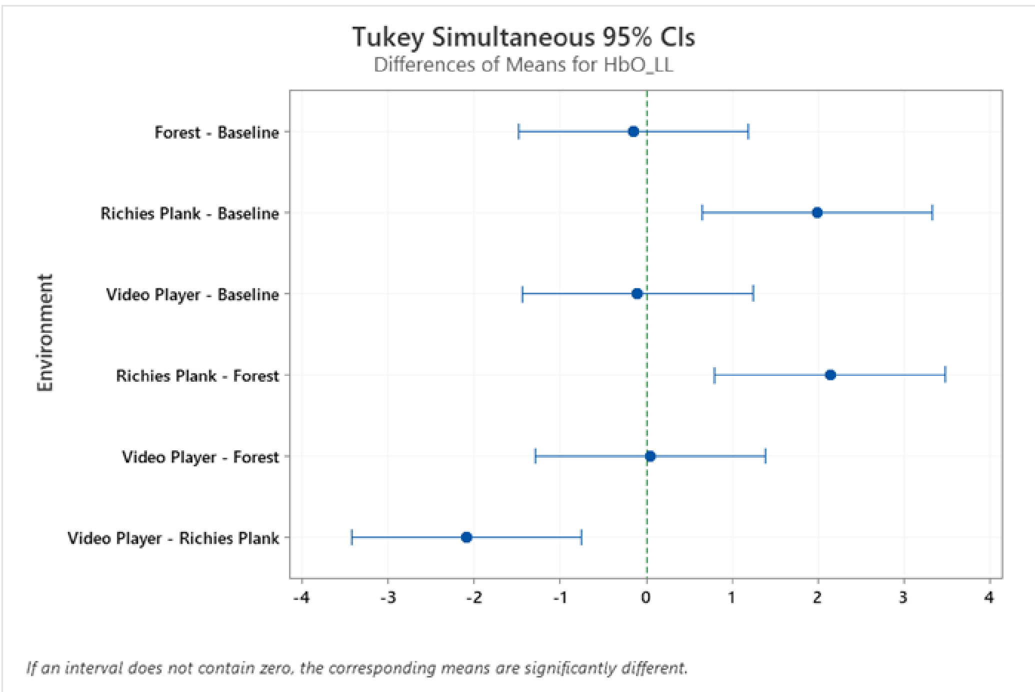

Figure 23: Post hoc differences in mean HbO activity in the left lateral area across four scenarios.

In the left medial area, there was a significant difference in mean HbO (F(3,52) = 12.9, p-value < 0.01) across four scenarios. Post hoc analyses revealed a statistically significant distinction between Richie's Plank and Baseline (p-value = 0.01), Richie's Plank and Parkour Video (p-value < 0.01), Richie's Plank and Biofeedback Forest (p-value < 0.01), and Baseline and Biofeedback

Forest (p-value = 0.01). Figure 24 below presents the findings from the post hoc tests. Similar to the left lateral area, we observed HbO to be highest during Richie's plank and least during Biofeedback Forest.

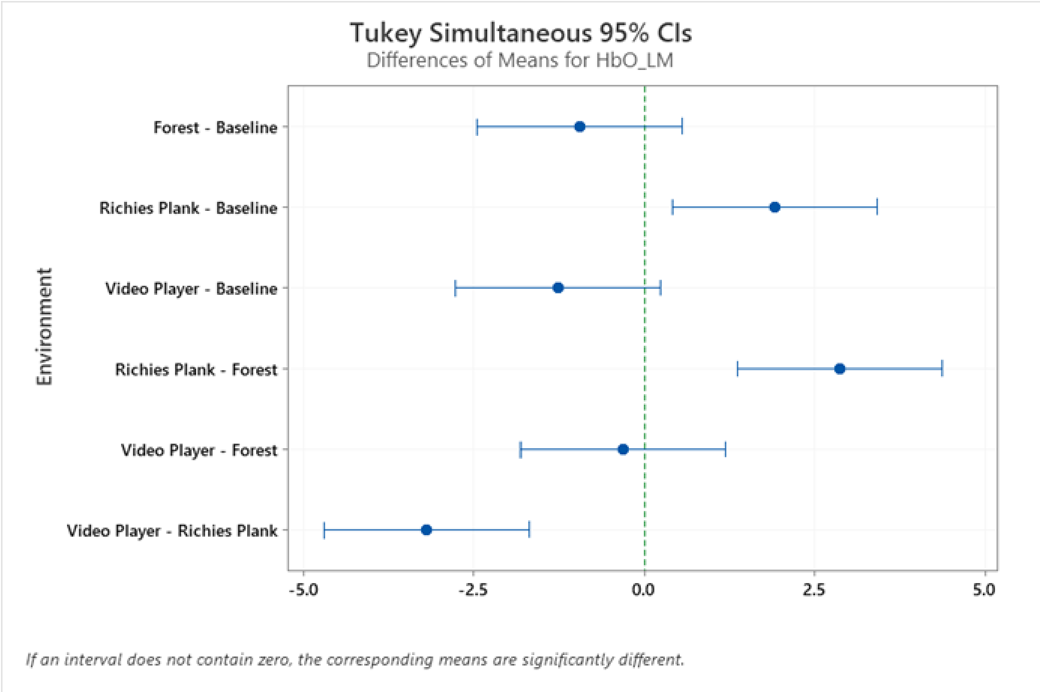

Figure 24: Post hoc differences in mean HbO activity in the left medial area across four scenarios.

In the right medial area, there was a significant difference in mean HbO (F(3,52) = 16.0, p-value < 0.01) across four scenarios. Post hoc analyses revealed a statistically significant distinction between Richie's Plank and Parkour Video (p-value < 0.01), Richie's Plank and Biofeedback Forest (p-value < 0.01), and Richie's Plank and Baseline (p-value < 0.01). Figure 25 below presents the findings from the post hoc tests. Similar to prior scenarios, we observed HbO to be highest during Richie's plank and least during Biofeedback Forest.

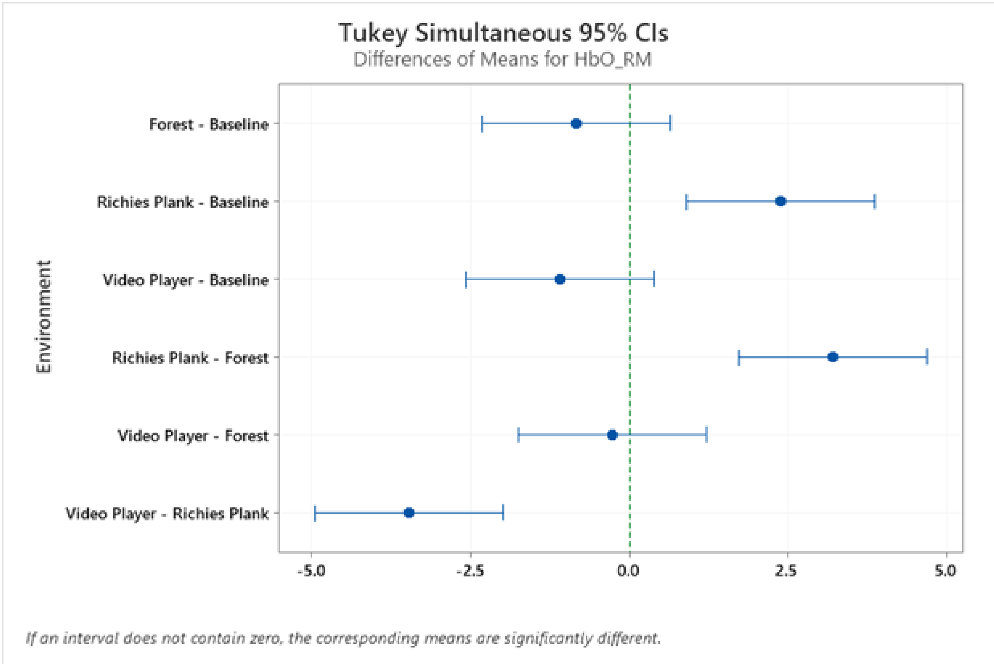

Figure 25: Post hoc differences in mean HbO activity in the right medial area across four scenarios.

Finally, in the right lateral area, there was a significant difference in mean HbO (F(3,52) = 7.10, p-value < 0.01) across four scenarios. Post hoc analyses revealed a statistically significant distinction between Richie's Plank and Baseline (p-value = 0.03), Richie's Plank and Parkour Video (p-value = 0.01), and Richie's Plank and Biofeedback Forest (p-value < 0.01). Figure 26 below presents the findings from the post hoc tests. Similar to all three prior areas, we observed HbO to be highest during Richies's plank and least during Biofeedback Forest.

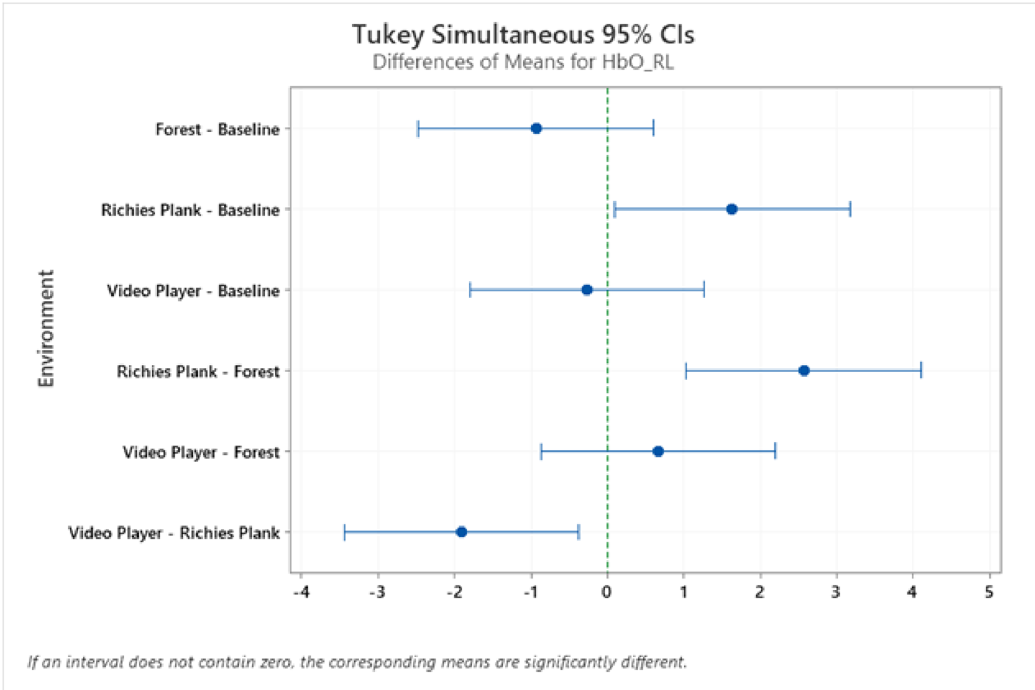

Figure 26: Post hoc differences in mean HbO activity in the right lateral area across four scenarios.

4.2.4 Deoxyhemoglobin (HbR)

On comparing the HbR values across four scenarios within each brain area, we observed significant differences between the two areas (see Table 11 above). In the left lateral area, there was no significant difference in mean HbR ($F(3,52) = 2.7$, p-value = 0.06) across four scenarios. Similar to that, no significant differences were observed in mean HbR ($F(3,52) = 2.5$, p-value = 0.07) across four scenarios in the right medial area.

However, in the left medial area, there was a significant difference in mean HbR ($F(3,52) = 3.2$, p-value = 0.03) across four scenarios. Post hoc analyses revealed a statistically significant distinction between Richie's Plank and Biofeedback Forest (p-value = 0.04). Figure 27 below present the findings from the post hoc tests. Specifically, we observed HbR to be higher during Biofeedback Forest compared to Richie's plank.

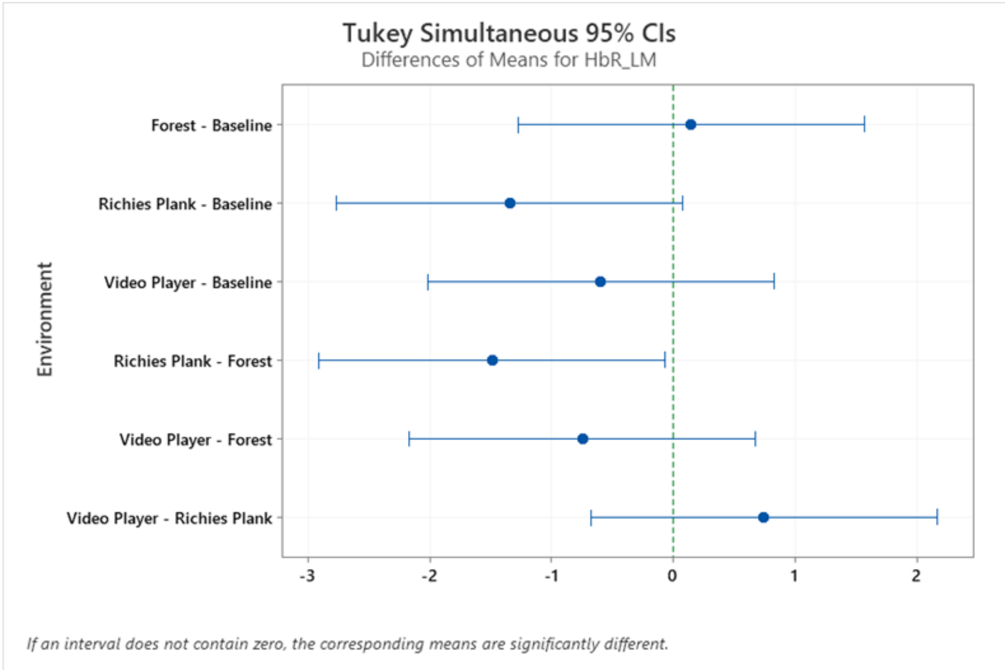

Figure 27: Post hoc differences in mean HbR activity in the left medial area across four scenarios.

Similarly, in the right lateral area, there was a significant difference in mean HbR (F(3,52) = 4.9, p-value < 0.01) across four scenarios. Post hoc analyses revealed a statistically significant distinction between Richie's Plank and Baseline (p-value = 0.01), and Richie's Plank and Biofeedback Forest (p-value = 0.01). Figure 28 below present the findings from the post hoc tests. Similar to the left lateral area, we observed HbR to be higher during Biofeedback Forest compared to Richie's plank and Parkour Video.

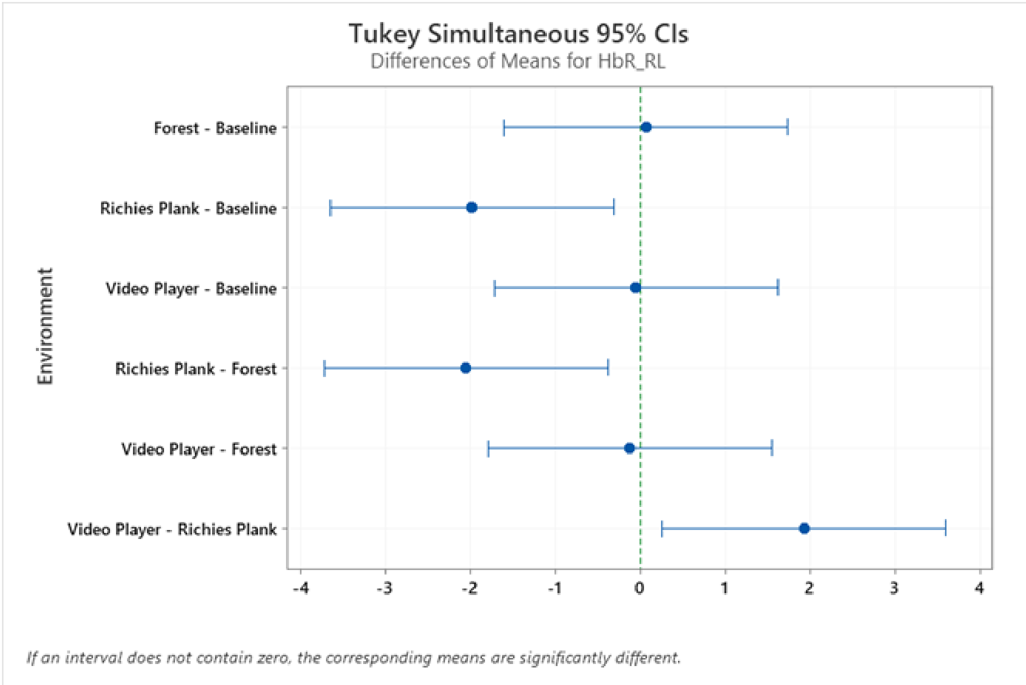

Figure 28: Post hoc differences in mean HbR activity in the right lateral area across four scenarios.

CHAPTER 5: DISCUSSIONS & CONCLUSIONS

Understanding neurophysiological changes while interacting with VR in different scenarios is crucial for understanding the full potential of this VR technology. As VR immerses users in simulated environments, it's essential to comprehend how the brain and cardiac activities adapt and respond to these different stimuli. The neurophysiological effects of VR can be far-reaching, influencing our perception, attention, memory, and emotional regulation. Without a deep understanding of these changes, we risk overlooking critical factors that can impact the effectiveness and safety of VR applications. For instance, VR-induced motion sickness can be a major obstacle to user adoption, while VR-mediated emotional experiences can have unintended consequences on mental health. Moreover, the brain's neural plasticity allows it to reorganize and adapt in response to VR experiences, which can have long-term implications for cognitive development and behavior. By studying neurophysiological changes in various VR scenarios, we can optimize VR experiences to enhance learning, therapy, and other outcomes while minimizing potential negative effects. Furthermore, this knowledge can inform the development of new VR applications, such as treatments for neurological disorders, and improve our understanding of human cognition and behavior. Overall, understanding the neurophysiological changes that occur during VR interactions is essential for responsible and effective use of this technology and for unlocking its full potential to transform and improve human experiences. Although prior studies have investigated the effect of VR on cardiac activity and brain activity in different studies, none of them have investigated the effect of cardiac activity and brain activity at the same time while experiencing relaxing and stress-inducing environments.

By conducting a repeated measures study with 30 participants who experienced HRV Biofeedback enhanced nature-based VR environment, stress-inducing Richie's Plank Experience, and Parkour video, we observed several significant differences in stress and anxiety compared to the baseline data.

In regards to stress, we observed that participants reported a significant increase in stress after experiencing the Richie's Plank (p-value = 0.02) and Parkour Video (p-value = 0.03) reported using the VAS questionnaire. However, no significant change (increase or decrease) in stress was observed after experiencing the HRV biofeedback-based VR nature environment. Further, an across-group comparison of post-intervention stress levels showed that stress levels were significantly higher after Richie's Plank and Parkour Video, and they varied significantly from the post-intervention stress levels after experiencing the HRV biofeedback-based VR nature environment.

Similar to stress data, for anxiety, we observed that participants reported a significant (p-value =.05) increase in anxiety after experiencing Richie's Plank on both survey instruments. However, no significant change (increase or decrease) in anxiety was observed after experiencing the HRV biofeedback-based VR nature environment. In this study, we used anxiety measurements only after these two interventions, as Parkour Video did not aim to induce anxiety. An across-group comparison of post-intervention anxiety levels showed that anxiety levels were significantly higher after Richie's Plank and varied significantly from the post-intervention stress levels after experiencing the HRV biofeedback-based VR nature environment.

Overall, the observations from survey responses align with prior studies where a stress-inducing environment increases post-intervention anxiety and stress. Additionally, a significant difference was observed in the post-intervention scores during an across-group comparison, where Richie's Plank and Parkour Video group reported higher stress and anxiety compared to the HRV biofeedback-based VR nature environment. However, a within-group (pre-post) comparison of stress and anxiety scores after experiencing the HRV biofeedback-based VR nature environment showed that there were no significant differences. Again, while the former observations align with prior research, the latter observation deviates from prior research studies, which have reported that participants often experience lower stress and anxiety after the HRV biofeedback experience in VR. One potential explanation for this could be the already low levels of anxiety among the participants prior to the intervention. Unlike most studies in literature, which were conducted in a healthcare setting or with participants with a clinical diagnosis of anxiety, this study population was healthy adults. Another potential reason could be gathered from the anecdotal comments made by the respondents, who mentioned it was challenging to breathe at 5.5-6 BPM to maintain and achieve the HRV biofeedback goals.

5.1 Summary and Interpretation of Main Findings

By conducting a repeated measures study with 30 participants who experienced HRV Biofeedback enhanced nature-based VR environment, stress-inducing Richie's Plank Experience, and Parkour video, we observed several significant differences in stress and anxiety compared to the baseline data.

In regards to stress, we observed that participants reported a significant increase in stress after experiencing the Richie's Plank (p-value = 0.02) and Parkour Video (p-value = 0.03) reported using the VAS questionnaire. However, no significant change (increase or decrease) in stress was observed after experiencing the HRV biofeedback-based VR nature environment. Further, an across-group comparison of post-intervention stress levels showed that stress levels were significantly higher after Richie's Plank and Parkour Video, and they varied significantly from the post-intervention stress levels after experiencing the HRV biofeedback-based VR nature environment.

Similar to stress data, for anxiety, we observed that participants reported a significant (p-value =.05) increase in anxiety after experiencing Richie's Plank on both survey instruments. However, no significant change (increase or decrease) in anxiety was observed after experiencing the HRV biofeedback-based VR nature environment. In this study, we used anxiety measurements only after these two interventions, as Parkour Video did not aim to induce anxiety. An across-group comparison of post-intervention anxiety levels showed that anxiety levels were significantly higher after Richie's Plank and varied significantly from the post-intervention stress levels after experiencing the HRV biofeedback-based VR nature environment.

Overall, the observations from survey responses align with prior studies where a stress-inducing environment increases post-intervention anxiety and stress. Additionally, a significant difference was observed in the post-intervention scores during an across-group comparison, where Richie's Plank and Parkour Video group reported higher stress and anxiety compared to the HRV biofeedback-based VR nature environment. However, a within-group (pre-post) comparison of stress and anxiety scores after experiencing the HRV biofeedback-based VR nature environment showed that there were no significant differences. Again, while the former observations align with prior research, the latter observation deviates from prior research studies, which have reported that participants often experience lower stress and anxiety after the HRV biofeedback experience in VR. One potential explanation for this could be the already low levels of anxiety among the participants prior to the intervention. Unlike most studies in literature, which were conducted in a healthcare setting or with participants with a clinical diagnosis of anxiety, this study population was healthy adults. Another potential reason could be gathered from the anecdotal comments made by the respondents, who mentioned it was challenging to breathe at 5.5-6 BPM to maintain and achieve the HRV biofeedback goals.

Observations from the cardiac and respiratory biosignals support and align with the subjective data metrics where we observed that the participant's respiration rate increased significantly during the Richie's Plank and Parkour Video and varied significantly from the respiration rate during the HRV biofeedback-based VR nature environment. Additionally, we observed that participants showed a significant decrease in their respiration rate while experiencing the HRV biofeedback-based VR nature environment compared to their baseline respiration rate. Similarly, we also observed that the LF/HF ratio increased significantly while experiencing the HRV biofeedback-based VR nature environment and varied from the LF/HF ratio recorded during Richie's Plank and Parkour Video. These observations suggest that the two stress-inducing videos were successful in increasing stress and anxiety. Moreover, the cardiac and respiratory activity also suggests that the HRV biofeedback-based VR nature environment was successful in reducing anxiety and stress.

Finally, on analyzing the brain activity data collected using the fNIRS signals, we observed that the HbO activity increased significantly across all four areas of the prefrontal cortex of the brain during the Richie's Plank and Parkour Video and varied significantly from the HbO activity during the HRV biofeedback-based VR nature environment. Furthermore, we observed that the HbR activity increased while experiencing the HRV biofeedback-based VR nature environment in the left and right lateral prefrontal cortex of the brain and varied significantly from the HbR activity during the Richie's Plank and Parkour Video. Similar to the cardia activity observations, these findings observed in the brain data suggest that the two stress-inducing videos were successful in increasing stress and anxiety, and the HRV biofeedback-based VR nature environment was successful in reducing anxiety and stress.

5.3 Limitations

The study, while insightful, encounters several limitations that merit consideration. To begin with, the sample size was comparatively limited to a specific demographic group (Asian/Pacific Islanders), which may restrict the generalizability of the findings across different populations with varied cultural and physiological backgrounds. Future studies should aim to include a more diverse participant pool to enhance the applicability of the results.

Secondly, the study's reliance on self-reported measures for assessing stress and anxiety introduces the possibility of subjective bias. Participants' responses might be influenced by their personal perceptions or the desire to conform to perceived expectations of the experiment.

Thirdly, the VR environments used, while immersive, still do not completely replicate real-world conditions, which might affect the ecological validity of the findings. The artificial nature of VR might limit the translation of these results to real-world scenarios. Additionally, the duration of exposure to each VR scenario was relatively short, which might not capture long-term effects of VR exposure on neurophysiological or psychological states. Longer-term studies could provide deeper insights into the sustained impacts of VR.

Technical challenges also posed significant limitations. The need for extended cables due to the original short wires of the equipment, issues with data transmission if the ACQ Smart Centre and the transmitter were not in sight, and sensitivity to Unity software versions, which could disrupt project continuity if updated, all affected the consistency of the experimental setup.

The VR headset's weight caused discomfort and headaches for some participants, suggesting the need for more ergonomic designs in future VR equipment. The physical space constraints for VR experiments also limited participant movement, potentially affecting the naturalness of their interactions within the virtual environment.

Connectivity issues with the Meta Quest headset and the need for a high-speed Wi-Fi connection to ensure smooth operation of VR and Unity projects highlighted the technical dependencies and potential for data loss or lag during the experiments.

The setup of biosensors also introduced challenges; the electrodes for the ECG had to be taped securely to prevent data corruption from loose connections, the RSP transducers required precise positioning to ensure accurate readings, and the FNIRS device, worn on the forehead, could cause discomfort or nausea over long periods.

Despite these limitations, the study significantly contributes to the emerging field of VR research, particularly in understanding how different types of VR content can distinctly affect human neurophysiology and psychological states. Further research addressing these limitations could enhance our understanding and application of VR technologies across various fields, including mental health therapy, educational training, and beyond.

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