Examining the Effectiveness of Virtual Reality in Stress Management

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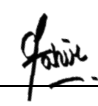
Student Signature: 

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With boundless love and eternal gratitude, I dedicate this thesis to the two remarkable souls whose unwavering support has been the catalyst for every endeavor — my parents.

This achievement is yours as much as it is mine

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I extend my heartfelt gratitude to my peers, Abdullah and Saad, for their invaluable assistance during the tedious data acquisition phase of the experiment. The process would have been quite daunting without their support.

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TABLE OF CONTENTS

LIST OF TABLES

Page No.

LIST OF FIGURES

Page No.

LIST OF SYMBOLS, ABBREVIATIONS AND ACRONYMS

ECG	Electrocardiography
EEG	Electroencphalography
HR	Heart Rate
HRV	Heart Rate Variability
STAI	State Trait Anxiety Inventory
SAI	State Anxiety Inventory

ABSTRACT

Virtual Reality (VR) has emerged as a promising tool in healthcare management, with recent studies exploring its effectiveness in addressing various psychological and physiological disorders. Stress is prevalent in modern society, necessitating effective strategies for its management. While sports and extended reality (XR) gaming have shown promising effects on mental health, this study aims to investigate the effectiveness of VR in reducing stress by comparing conventional and VR-based relaxation techniques using HRV parameters and EEG responses. A total of 40 participants (28 males, 12 females) with a mean age of 25 ± 3.21 years participated in the study. Baseline recordings were obtained, followed by a stress phase induced by a timed IQ quiz. Participants were then randomly assigned to either VR-based relaxation or conventional relaxation techniques. Both relaxation methods significantly improved heart rate variability (HRV) and decreased sympathetic dominance, indicating enhanced adaptability to stress and activation of the parasympathetic nervous system (PNS).However, VR-based relaxation resulted in a more pronounced decrease in heart rate and a significant reduction in the LF/HF ratio compared to conventional relaxation, suggesting a deeper state of relaxation. Furthermore, VR-based relaxation led to a significant increase in the alpha-to-beta ratio, indicating a calmer mental state compared to non-VR relaxation. Notable changes were also recorded in Alpha Power in the frontal channels and Beta Power across all channels, suggesting greater effectiveness in inducing PNS activation and recovery.

Keywords: Mental Stress, ECG, EEG, HRV, Virtual Reality, Relaxation

CHAPTER 1: INTRODUCTION

1.1 Introduction

Mental stress has become a pervasive and widespread issue affecting individuals worldwide, transcending cultural and socioeconomic boundaries. According to the 2021 Gallup World Poll, approximately one-third of adults globally reported experiencing stress, worry, or anger on the previous day, highlighting the pervasive nature of stress in modern society [1]. In Pakistan, a 2019 study by the National Institute of Mental Health (NIMH) found that nearly 40% of the population faces various mental health challenges, with stress being a significant contributor [2]. The prevalence of stress underscores its profound impact on individuals' daily lives and overall well-being.

Chronic exposure to stress is associated with a myriad of detrimental effects on both physical and mental health. Physiologically, prolonged stress can increase the risk of cardiovascular diseases, compromise the immune system, and contribute to conditions such as hypertension and metabolic disorders [3, 4]. Psychologically, stress is linked to higher incidences of anxiety disorders, depression, and burnout, significantly impacting individuals' quality of life and productivity [4].

In response to stress, individuals often resort to traditional coping mechanisms, such as social withdrawal or substance use, which can have negative consequences and exacerbate the underlying stressors [5]. Therefore, effective stress management strategies are crucial for mitigating these adverse effects and promoting overall health and well-being. Such strategies not only aim to reduce stress levels but also improve sleep quality, enhance cognitive function, and foster better emotional regulation [5].

Virtual Reality (VR) technology has emerged as a promising tool for innovative stress management interventions. VR offers immersive and interactive environments that can simulate natural settings, such as forests, beaches, or serene landscapes, to create a therapeutic escape from everyday stressors [6, 7]. These virtual environments aim to induce feelings of relaxation and calmness by engaging multiple senses and providing a sense of presence in a peaceful atmosphere.

Recent research has demonstrated the potential of VR-based relaxation therapies in effectively reducing stress levels. Studies suggest that VR experiences designed to evoke relaxation responses can significantly decrease physiological indicators of stress, such as heart rate variability and cortisol levels [6, 7]. By immersing individuals in calming virtual environments, VR can facilitate mental rejuvenation and emotional resilience, offering a unique approach to stress management that complements traditional therapeutic methods.

Moreover, VR's ability to tailor experiences to individual preferences and needs makes it a versatile tool in mental health care. Users can customize their virtual experiences based on personal preferences, adjusting elements like scenery, sounds, and interactive activities to optimize relaxation outcomes [8]. This personalization aspect enhances engagement and effectiveness, potentially increasing adherence to stress management interventions over time.

In conclusion, amid the growing recognition of stress as a global health challenge, integrating VR technology into stress management practices holds significant promise. By leveraging VR's immersive capabilities and therapeutic potential, healthcare providers and researchers can enhance the effectiveness of stress relief interventions and improve overall psychological well-being on a broader scale. Continued research and innovation in VR-based therapies are essential to further elucidate their mechanisms of action and optimize their use in promoting resilience against stress in diverse populations and settings.].

1.1.1 Definition and Causes

Mental stress is a multifaceted condition characterized by intricate physiological, cognitive, and behavioral responses to perceived threats or demands that exceed an individual's coping capabilities [8]. It is a natural human response to challenges, pressures, or uncertainties encountered in daily life. While moderate stress can sometimes motivate and energize individuals, chronic or excessive stress can profoundly impact overall well-being and health outcomes [8].

The causes of stress are diverse and can stem from various aspects of life. Everyday hassles such as work deadlines, financial strains, traffic congestion, and interpersonal conflicts are common stressors that individuals encounter regularly [8]. Major life events, such as unemployment, serious illness, bereavement, or relocating to a new environment, can also trigger significant stress responses [8]. Moreover, occupational factors like high job demands, tight deadlines, job insecurity, and strained relationships with colleagues or supervisors can contribute significantly to stress levels [8].

Financial difficulties and health concerns represent additional prevalent stressors that can affect individuals profoundly [8]. Certain personality traits, including perfectionism, neuroticism, or a lack of resilience, may predispose individuals to experiencing stress more intensely in response to these triggers [8]. Recognizing these diverse sources of stress is crucial as it enables individuals to identify their specific stressors and develop effective coping strategies tailored to their needs.

Understanding the multifaceted nature of stress facilitates the implementation of proactive measures to mitigate its adverse effects. Effective stress management techniques not only alleviate immediate stress but also promote long-term resilience and psychological well-being. Strategies such as mindfulness practices, relaxation techniques, regular physical activity, and fostering social support networks are proven methods for reducing stress and enhancing overall coping mechanisms [8].

In contemporary society, where stress has become increasingly prevalent, fostering awareness and education about stress management is essential. By empowering individuals with knowledge of stress triggers and coping strategies, healthcare providers and educators can play a pivotal role in promoting mental health and resilience. Furthermore, ongoing research into the physiological, psychological, and social factors influencing stress responses can inform targeted interventions and policies aimed at minimizing the impact of stress on individuals and communities. Efforts to address stress comprehensively contribute to enhancing quality of life and promoting holistic well-being across diverse populations.

1.1.2 Impact on Health and Well-being

Chronic stress profoundly disrupts the body's natural equilibrium, leading to a cascade of detrimental consequences for both physical and mental health. When faced with stress, the body triggers the release of hormones such as cortisol and adrenaline, initiating the "fight-or-flight" response. This physiological reaction is beneficial in acute, short-term situations as it prepares the body to respond to immediate threats. However, prolonged stress keeps these hormone levels elevated, leading to various adverse physiological changes.

One of the primary effects of chronic stress is the continuous elevation of heart rate and blood pressure, which significantly increases the risk of cardiovascular diseases, including stroke and heart attack [9]. The sustained activation of the cardiovascular system can lead to long-term damage to blood vessels and the heart, making stress a major contributor to cardiovascular morbidity and mortality.

Additionally, chronic stress has a detrimental impact on the immune system. The persistent release of stress hormones can suppress immune function, making individuals more susceptible to infections and illnesses [9]. This immunosuppressive effect means that stressed individuals are more likely to catch colds, suffer from recurrent infections, and have slower recovery rates from illnesses and injuries.

Muscle tension is another common manifestation of chronic stress, leading to physical discomfort such as tension headaches, backaches, and jaw clenching. These symptoms can become chronic conditions themselves, contributing to a cycle of pain and stress that is difficult to break. The physical strain caused by muscle tension can also lead to more serious musculoskeletal problems over time.

Sleep disturbances are a prevalent consequence of chronic stress. Individuals under prolonged stress often experience difficulty falling asleep, staying asleep, or achieving restful sleep. This lack of quality sleep further exacerbates stress, creating a vicious cycle that can lead to chronic insomnia and other sleep disorders. Poor sleep quality affects overall health, cognitive function, and emotional regulation, making it harder for individuals to cope with daily stressors effectively.

Chronic stress can also exacerbate or contribute to digestive problems. Conditions such as irritable bowel syndrome (IBS) and peptic ulcers can be worsened by stress, as the digestive system is highly sensitive to hormonal and nervous system changes. Stress can lead to increased gastric acid production and altered gut motility, resulting in symptoms like abdominal pain, bloating, diarrhea, and constipation [8].

The long-term consequences of chronic stress highlight the importance of effective stress management strategies. By understanding the physiological impacts of stress, individuals and healthcare providers can better address and mitigate these effects. Techniques such as mindfulness, regular physical exercise, adequate sleep, and maintaining social connections are crucial in managing stress and promoting overall health and well-being. Continuous research into the mechanisms of stress and its effects on the body will further enhance our ability to develop targeted interventions to reduce the burden of chronic stress on individuals and society.Importance of Stress Management Techniques

Traditional coping mechanisms for stress, such as social withdrawal or substance use, often have negative consequences. Effective stress reduction techniques are crucial for maintaining overall well-being [5]. These techniques can improve sleep quality, increase focus, and enhance emotional regulation [6].

1.1.3 Need for Effective Strategies

Given the detrimental effects of chronic stress on both physical and mental health, effective stress management techniques are crucial for maintaining overall well-being [8]. These techniques can help individuals:

- Reduce physiological arousal caused by stress hormones [8].
- Improve sleep quality, leading to increased energy and focus [8].
- Enhance emotional regulation, promoting feelings of calm and resilience [8].
- Develop coping mechanisms for dealing with daily hassles and major life stressors [8].

By incorporating stress management techniques into their daily routines, individuals can build their capacity to handle challenges and improve their overall quality of life.

1.2 Virtual Reality: A New Frontier in Relaxation

Virtual Reality (VR) technology has emerged as a promising tool for creating immersive and interactive experiences. VR environments can be designed to evoke feelings of relaxation and calmness, offering a novel approach to stress management [7].

1.2.1 Introduction to VR

VR technology utilizes headsets with two screens, one for each eye, creating a realistic 3D view. These headsets can be paired with hand controllers or full-body tracking systems, allowing users to interact with the virtual environment naturally.

VR experiences come in two main types: pre-recorded and interactive. Pre-recorded experiences offer ready-made simulations, like serene beaches or calming art galleries. Interactive experiences take it a step further, allowing users to explore virtual environments, solve puzzles, or engage in relaxing activities.

This technology is evolving, but its potential for creating immersive experiences is vast.

1.2.2 Potential for Relaxation and Stress Management

VR offers a unique potential for relaxation, meditation, and stress management. Programs offering relaxation interventions are often aimed at immersive relaxation or distraction and sensory focus.

1.2.2.1 Immersive Relaxation

VR environments can transport users to calming settings, offering an escape from everyday stressors [9]. Studies suggest exposure to nature can positively impact mental well-being and reduce stress.

1.2.2.2 Distraction and Sensory Focus

VR experiences provide engaging distractions, shifting focus away from worries [10]. By captivating sight, sound, and sometimes even touch, VR creates a sense of presence that reduces stress by diverting attention.

While VR research in stress management is still emerging, the initial evidence is promising [9]. However, more studies are needed to fully understand its long-term effectiveness.

1.3 Research Question and Study Overview

1.3.1 Research Question

This study investigates the potential of Virtual Reality (VR) as a stress-reduction tool. Our central question is: "*Can exposure to calming VR environments lead to a more efficient reduction in stress levels compared to a conventional technique employing positive thinking approach?*" By analyzing pre- and post-intervention stress levels through self-reported measures and physiological assessments, we aim to compare the effectiveness of VR against a conventional positive thinking approach for stress management.

1.3.2 Participant Groups and Overview

The study employed a randomized controlled trial (RCT) design to assess the effectiveness of VR for stress management. A total of 46 healthy adults were recruited. We ensured a balanced representation within the age range of 20 to 30 years and across genders. Participants were randomly assigned to either a VR group or a control group. The VR group experienced calming virtual environments, while the control group engaged in a positive thinking exercise after both had been exposed to a cognitively challenging timed-mental IQ test. Both groups completed pre- and post-intervention stress assessments to evaluate the impact of the interventions.

1.3.3 Stress Assessment Methods

This study employed a comprehensive approach to assess stress levels. Participants completed standardized self-report questionnaires to measure perceived stress before and after being exposed to the stressor as well as relaxation intervention. Additionally, physiological measures were used to capture objective stress responses. We utilized electrocardiograms (ECGs) to monitor heart rate variability, a key indicator of stress response. Furthermore, electroencephalograms (EEGs) were employed to assess changes in brainwave activity associated with stress levels. This multi-modal approach provided a detailed picture of how VR exposure or the control activity impacted participants' stress states.

CHAPTER 2: LITERATURE REVIEW

2.1 Detecting Mental Stress with EEG and ECG Signals

Mental stress is a growing concern globally, impacting an individual's health and well-being. Early and reliable stress detection techniques are crucial for developing effective stress management strategies. Electroencephalography (EEG) and electrocardiography (ECG) offer promising solutions for non-invasive continuous monitoring of the physiological responses associated with stress [11].

2.1.1 Role of EEG and ECG in Stress Detection

EEG captures the electrical activity of the brain with high temporal resolution, providing insights into neural activity patterns linked to mental states [12]. Studies suggest stress alters specific EEG frequencies [13]. Increased activity in the beta band (13-30 Hz) and decreased activity in the alpha band (8-12 Hz) have been associated with stress responses [14].

ECG measures electrical signals generated by the heart, reflecting heart rate and rhythm variability. Stress can trigger physiological changes like heart rate acceleration and increased heart rate variability [15]. Analysis of these ECG features can provide valuable information about an individual's stress state.

These modalities offer complementary information. EEG reflects central nervous system activity, while ECG captures autonomic nervous system responses [16]. Combining EEG and ECG data can lead to a more comprehensive understanding of the body's stress response [17].

2.1.2 Relevant Features and Stress Response

Analyzing specific features extracted from EEG and ECG data can provide valuable insights into stress levels.

2.1.2.1 ECG Features

- Heart Rate (HR): An increase in heart rate is a common physiological response to stress [18]. However, this measure can be influenced by factors unrelated to stress, such as physical activity.
- Heart Rate Variability (HRV): Heart rate variability refers to the variation in time intervals between heartbeats. HRV generally decreases under stress, reflecting a shift towards a more sympathetic nervous system state [19]. Analysis of specific HRV parameters like Root Mean Square of the Successive Differences (RMSSD) can be informative.

2.1.2.2 EEG Features

- Power Spectral Density (PSD): EEG signals can be decomposed into different frequency bands. As mentioned earlier, changes in the relative power of specific bands like alpha (8-12 Hz) and beta (13-30 Hz) are associated with stress responses. Increased beta and decreased alpha activity are often observed under stress conditions [13, 14].
- Event-Related Potentials (ERPs): These are voltage fluctuations in the EEG waveform that occur in response to specific stimuli. Studies suggest that certain ERPs, such as the P300 component, can be modulated by stress levels [20].
- Functional Connectivity: EEG analysis can also explore the functional connectivity between different brain regions. Increased or decreased connectivity between specific brain areas might be indicative of stress responses [21].

2.2 Virtual Reality-based Interventions for Stress Reduction

Traditionally, stress management techniques have included cognitive behavioral therapy, exercise, and relaxation practices. However, emerging technologies like virtual reality (VR) are offering innovative approaches to stress reduction. VR creates immersive experiences that can transport users to calming environments or provide interactive scenarios for practicing coping mechanisms.

2.2.1 Evidence on VR Applications

Research on VR for stress reduction is a burgeoning field, with studies demonstrating promising results. A 2020 systematic review by Moss and Gordillo [6] found that VR interventions showed positive effects in reducing anxiety. Similarly, Lee et al. (2019) [7] investigated VR forest experiences and reported significant reductions in psychological stress, improved restoration, and increased self-compassion among participants.

2.2.2 Effectiveness of Nature Environment

Building on the potential of VR for stress reduction, research suggests that VR simulations of natural environments are particularly effective. These experiences can evoke positive emotions, promote feelings of calmness and restoration, and ultimately reduce stress levels.

A key study by Bratman et al. (2012) [21] employed a meta-analysis to examine the use of nature exposure, even through virtual simulations, as preventive medicine. The study found that exposure to natural environments resulted in significant reductions in stress and anxiety. This highlights VR's potential to bring the benefits of nature to individuals who may not have easy access to natural settings.

VR nature experiences can provide a break from demanding cognitive tasks, aligning with Kaplan's (1995) [22] Attention Restoration Theory. By immersing users in calming natural scenes, VR allows the mind to "softly focus" and restore its ability to concentrate, leading to reduced stress [23].

The biophilia hypothesis, proposed by Wilson (1984) [24], suggests an innate human connection to nature. VR nature experiences may tap into this inherent connection, triggering physiological responses associated with relaxation, such as lowered blood pressure and heart rate [25].

Well-designed VR nature experiences create a highly immersive environment through high-quality visuals, spatial sound, and even subtle sensory elements like scent. This immersive quality enhances feelings of presence and connection to nature, further promoting stress reduction [26].

Research supports the effectiveness of VR nature experiences. Liu et al. (2020) [27] conducted a study where participants exposed to VR nature environments reported significant decreases in perceived stress compared to a control . Similarly, Baños et al. (2020) [28] found that VR forest experiences led to reductions in cortisol (stress hormone) levels and improvements in mood among participants.

While research is positive, some considerations remain. Further investigation is needed to identify the specific elements within VR nature environments that contribute most to stress reduction. Additionally, individual preferences for natural environments (forests, beaches, mountains) may influence VR experience effectiveness, suggesting the need for personalized approaches [29].

CHAPTER 3: METHODOLOGY

3.1 Controlled Experiment Design

3.1.1 Sample Size and Group Allocation

44 participants (34 males, 10 females) aged between 20 and 30 years were recruited for this study. The participants were comprised of undergraduate and postgraduate students from university premises. A multifaceted recruitment strategy was employed to ensure a diverse participant pool. This strategy included disseminating invitations through university communication channels, such as student platforms and social media groups. Additionally, outreach was conducted during various mass gatherings on campus.

The Experiment Design was a Randomized Controlled Trial and participants were randomly allocated to Experimental and Controlled Groups.

3.2 Participant Recruitment

3.2.1 Inclusion Criteria

Healthy undergraduate and postgraduate students between 20 to 30 years of age with 6/6 vision with or without correction were included in the experiment.

3.2.2 Exclusion Criteria

Participants who showed high levels of baseline anxiety were excluded from the subject pool. Additionally, participants who had an uncorrected vision, any pre-existing medical conditions that could be exacerbated with exposure to stressors, or those who had been consuming prescription drugs/medications that could alter their physiological response and/or effect their Virtual Reality Experience were also excluded. Participants that reported motion sickness or dizziness after exposure to Virtual Reality in the past, were also not included.

3.3 Ethical Considerations

3.3.1 Informed Consent

To ensure participant understanding and ethical conduct, the study employed a transparent consent process. Prior to participation, all subjects provided informed consent and received a briefing on the experiment's general nature. This briefing aimed to strike a balance between transparency and avoiding disclosure of specific details that could potentially influence their responses.

3.3.2 Ethical Guidelines

The research protocol for this study was reviewed and approved by the Institutional Review Board (IRB) at the National University of Science and Technology (NUST), Islamabad to ensure adherence to ethical research principles. This approval guaranteed that the experiment complied with federal regulations and professional guidelines established for the protection of human subjects in research.

3.4 Experimental Procedure

3.4.1 Materials

3.4.1.1 Head Mounted Device (HMD)

The experiment employed the Oculus Quest 2, a virtual reality (VR) platform developed by Meta, to immerse participants in the environment. For enhanced comfort and stability during extended use, the HMD was paired with a separately acquired Halo Headband. This headband's ergonomic design offered secure contact and a rotatable adjustment feature, allowing for individual customization of the viewing angle for each participant. Additionally, the headband's design facilitated the stabilization of the EEG headset, ensuring consistent data quality throughout the experiment. For the relaxation phase, participants engaged in an immersive VR experience available online titled "Liminal." To ensure consistency across participants, the HMD boundaries were set to a fixed position prior to each session.

3.4.1.2 ECG Circuit

A custom-designed, low-power ECG circuit using Arduino UNO and the AD8232 module was employed to capture heart rate data throughout the experiment. This single-lead configuration sampled data at 50 Hz and utilized Exponential Moving Average (EMA) filtering to minimize noise and baseline drift. Signal quality was visually inspected before data acquisition, which was facilitated through Data Streamer software.

3.4.1.3 EEG Headset

A research-grade, 5-channel wireless EEG headset (Emotiv Insight) was used to capture real-time brain activity during the experiment. This system offers faster setup compared to traditional EEG options and features five electrode locations (AF3, AF4, T7, T8, Pz) with two reference electrodes. The headset's built-in filtering capabilities ensured the acquisition of clean EEG data for subsequent analysis.

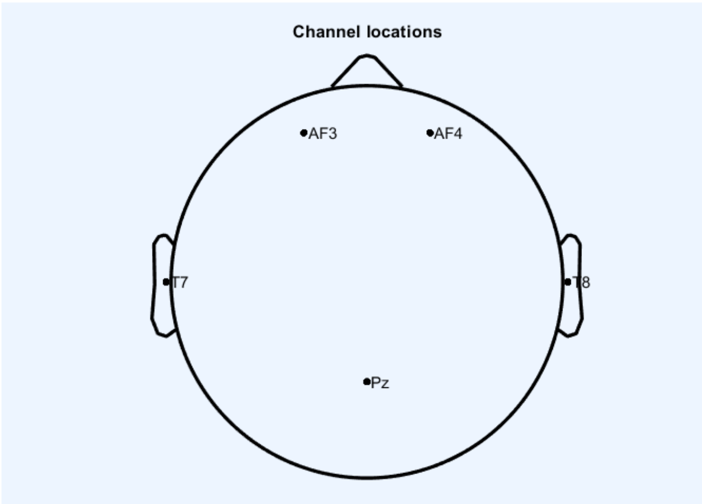

Figure 1 Channel Locations EEG

3.4.1.4 State-Trait Anxiety Inventory (STAI-Y1)

The State-Trait Anxiety Inventory (STAI Y1) is a validated self-report questionnaire widely used to assess temporary anxiety levels (state anxiety) in adults [12]. This inventory distinguishes between state anxiety, which is a transient response to specific situations, and trait anxiety, which reflects a general predisposition to experience anxiety. Given the focus on short-term stress responses in this experiment, only the state anxiety component of the STAI Y1 was employed.

3.4.2 Preparation

To ensure data quality, participants were comfortably seated while disposable ECG electrodes were attached to their left and right wrists and right ankle. Following verification of proper electrode function and signal transmission, a wireless EEG headset was positioned on each participant's head. For optimal EEG signal acquisition, the headset's dry electrodes made secure contact with a clean scalp area. In cases of exceptionally dry scalp, a primer containing primarily glycerol was applied to enhance conductivity. Recording commenced only after both ECG and EEG signal quality were confirmed satisfactory. This preparation process typically took between 5 and 10 minutes.

The entire experiment was continuously recorded for an average duration of approximately 24 minutes.

3.4.3 Baseline Phase

Following the start of the recording, participants remained seated upright and minimized movement while keeping their eyes open for a three-minute baseline period. This phase aimed to establish a reference point for subsequent measurements. After the baseline recording, participants completed the STAI Y1 questionnaire presented on a computer screen using a wireless mouse. This self-report inventory typically took approximately two minutes to finish.

3.4.4 Stress Phase

To induce a multi-modal stress response (visual, auditory, and cognitive), participants completed a timed IQ test. This test consisted of 15 questions, each with a 30-second time limit. An audible beep commenced after 10 seconds into each question, aiming to heighten feelings of unease and nervousness. This design aimed to create a prolonged stress response. Following the test, participants received immediate feedback on their score and pass/fail status.

Following the stressor phase, participants completed the STAI Y1 questionnaire again (post-stressor) to assess changes in self-reported anxiety levels. This was followed by a one-minute "do-nothing" period where participants remained seated upright.

3.4.5 Relaxation Phase

Following the "do-nothing" period, participants were based on their assigned group carried out the relaxation intervention.

3.4.5.1 Experimental Group

Participants in the experimental group were equipped with a Head-Mounted Display (HMD) tailored for maximum comfort and wore in-ear headphones to enhance immersion. They participated in a 5-minute immersive relaxation session presented within a 360-degree virtual environment. Throughout the session, participants were seated to minimize motion artifacts in the EEG data, allowing them to gently move their heads to explore the virtual surroundings. This setup aimed to create an engaging and relaxing experience while maintaining optimal conditions for data collection and analysis of physiological responses to the virtual reality relaxation intervention.

3.4.5.2 Controlled Group

Participants in the control group underwent a seated relaxation protocol where they kept their eyes open and focused on positive thoughts for a duration of 5 minutes.

Following this relaxation phase, all participants completed the STAI Y1 questionnaire for the third time, immediately after the relaxation session, to gauge any changes in self-reported anxiety levels. Subsequently, a final one-minute "do-nothing" period was observed to allow for a brief moment of rest and stabilization before concluding the recording. At this point, the ECG electrodes and EEG headset were carefully removed. Participants were then provided with a debriefing session aimed at addressing any queries or concerns they may have had regarding the study procedures or their experience during the experiment, ensuring a comprehensive conclusion to the session.

CHAPTER 4: DATA ANALYSIS

4.1 EEG Data Analysis

4.1.1 Preprocessing

The raw EEG data underwent a series of preprocessing steps to remove artifacts and prepare the data for further analysis. The preprocessing included the following steps:

- **High-pass filtering:** Slow drifts and power line noise, typically below 1 Hz, were removed.
- **Low-pass filtering:** High-frequency artifacts, such as those from muscle activity typically above 40 Hz, were attenuated.
- **Notch filtering:** Specific frequencies associated with power line interference (60 Hz) were eliminated.
- **Artifact removal:** The signal was visually inspected, and artifacts such as eye blinks and muscle activities were manually removed.
- **Baseline correction:** Slow drifts in the signal were removed by subtracting the average activity during a specific resting period.

4.1.2 Alpha and Beta Band Power

The alpha and beta bands, consisting of frequencies 8-13 Hz and 13-30 Hz respectively, were isolated for further analysis. Spectral analysis of the epochs was conducted using Welch's method, resulting in a Power Spectral Density (PSD) plot that displayed the signal power across frequency bands. The area under the PSD curve within the respective frequencies was integrated to obtain the power for each band. This procedure was applied to all five channels (AF3, T7, Pz, T8, AF4). Additionally, the average alpha power and average beta power across all channels were calculated.

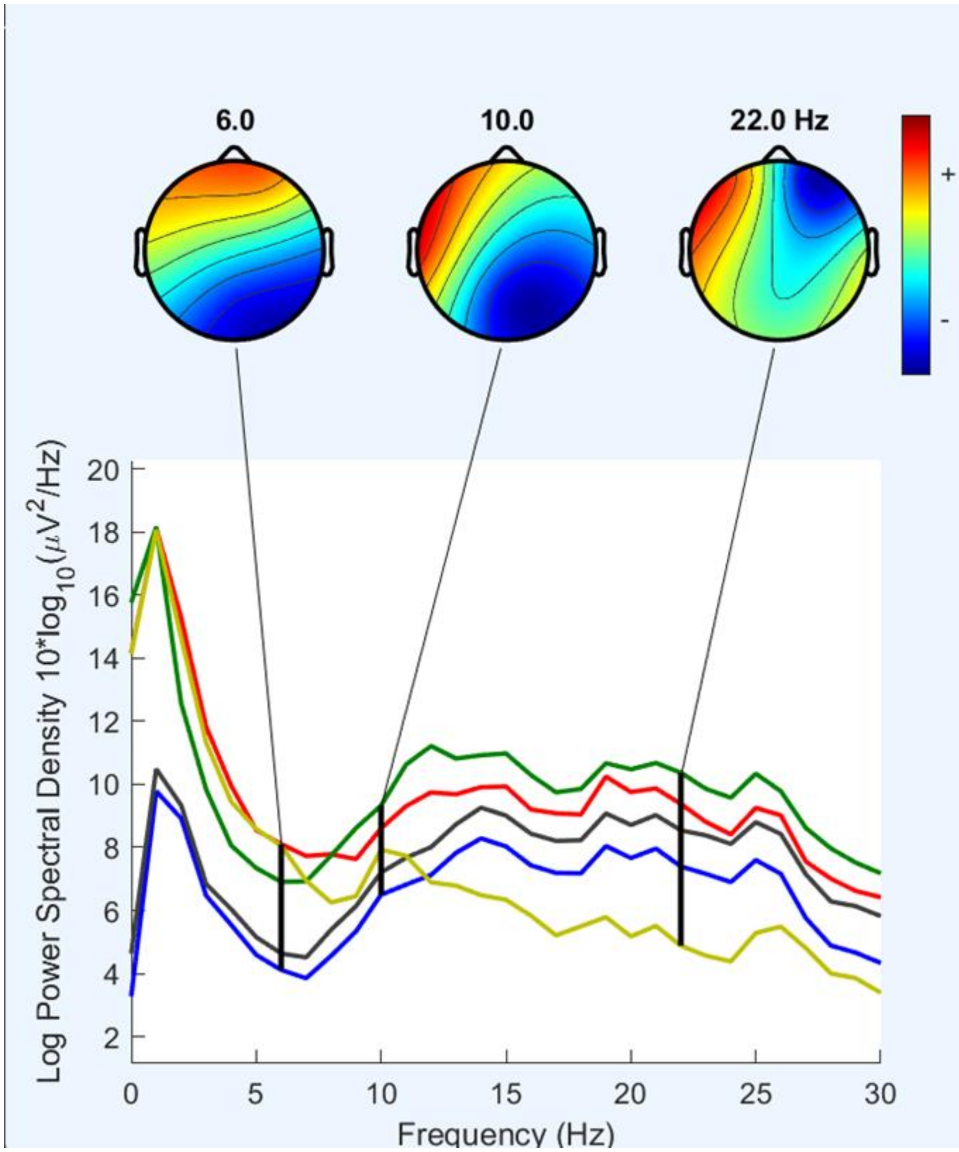

Figure 2 Power Spectral Density Plot obtained at channel AF3 during Baseline phase

4.1.3 Alpha-to-Beta ratio

The ratio of alpha power (8-13 Hz) to beta power (13-30 Hz) was calculated for each epoch, for each channel. A higher α/β ratio indicates a more relaxed state, whereas a lower ratio suggests increased focus or stress.

4.1.4 Relative Frontal Alpha Assymetery

The difference in alpha power between the left and right frontal channels (AF3 and AF4) was calculated for each epoch using an FAA plugin in EEGLAB with MATLAB 2024. A negative Frontal Alpha Asymmetry (FAA), indicating higher left frontal alpha power, is potentially associated with positive emotions and approach motivation. Conversely, a positive FAA, indicating higher right frontal alpha power, may be linked to withdrawal motivation or negative emotions.

4.2 ECG Data Analysis

4.2.1 Preprocessing

Electrocardiogram (ECG) signals obtained from wearable sensors often suffer from various artifacts, including baseline wander and high-frequency noise. To mitigate these effects, a bandpass Butterworth filter with a passband ranging from 0.05 Hz to 15 Hz was applied to the ECG signals. This filter captured the relevant physiological information while attenuating noise outside this range. A third-order filter was used to balance frequency selectivity and phase response.

The ECG signals were segmented into three distinct phases: baseline, stress, and relaxation, each lasting 5 minutes. This segmentation allowed for the analysis of physiological responses during different states of the experimental protocol. Each segment was analyzed independently to extract relevant features and assess heart rate variability (HRV) parameters.

4.2.2 R-peak Detection

R-peaks, marking the onset of ventricular depolarization, were meticulously detected within each ECG segment to compute RR intervals, which are crucial for heart rate variability (HRV) analysis. The process began with visual inspection to ensure accurate identification of R-peaks. Subsequently, the `findpeaks` function was employed, configured with parameters for minimum peak prominence, minimum peak distance, and maximum peak width. This approach ensured robust detection of R-peaks across varying

ECG signals. RR intervals were then computed as the time differences between successive R-peaks, providing a detailed temporal record of heart rate fluctuations. Furthermore, heart rate was calculated using the mean of these RR intervals, offering a straightforward measure of cardiac activity throughout the experimental phases. This methodological rigor in R-peak detection and RR interval computation laid the foundation for precise HRV assessment, facilitating a comprehensive analysis of cardiovascular responses to stress and relaxation interventions.

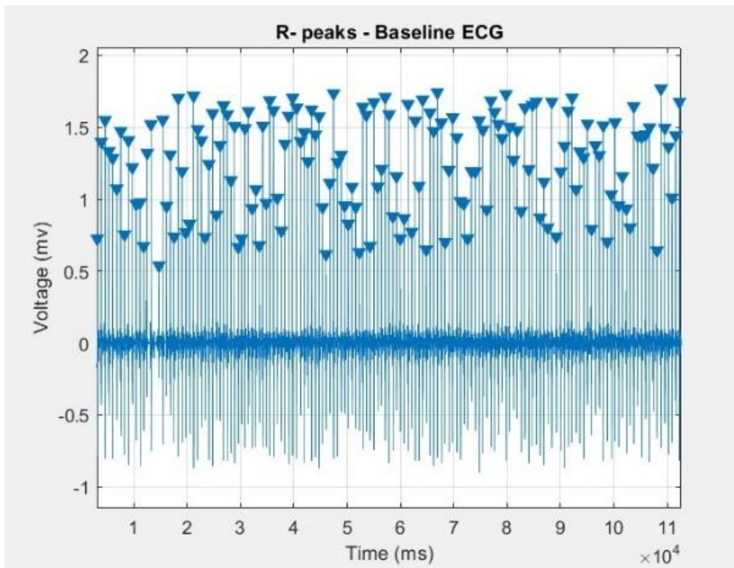

Figure 3 R-peaks Detection in Baseline Phase ECG Sample

4.2.3 Time Domain HRV Features

HRV analysis in this study involved a detailed examination of various time-domain parameters, each offering unique insights into heart rate variability (HRV) and the underlying autonomic nervous system dynamics. Heart Rate (HR) provided a fundamental measure of the average number of heartbeats per minute, serving as a baseline indicator of cardiac activity across different experimental phases such as relaxation and stress.

SDNN (Standard Deviation of NN intervals) was employed to assess overall RR interval variability, encompassing the influence of both sympathetic and parasympathetic nervous systems on heart rate. During relaxation phases, SDNN typically increases, reflecting a broader range of intervals between successive heartbeats as the body shifts into a more relaxed state. Conversely, during stress, SDNN tends to decrease as sympathetic activation leads to a more regular heart rhythm.

RMSSD (Root Mean Square of Successive Differences) quantified short-term variability in RR intervals primarily influenced by parasympathetic (vagal) activity. Higher RMSSD values observed during relaxation indicate increased variability in heart rate due to enhanced parasympathetic tone, suggesting a state of physiological calmness and reduced sympathetic arousal. In contrast, RMSSD decreases during stress as sympathetic dominance leads to a more uniform heart rate pattern.

Furthermore, pNN50 (Percentage of successive NN intervals differing by more than 50 ms) assessed high-frequency variability associated with parasympathetic modulation of heart rate. Higher pNN50 values during relaxation phases indicate greater variability in RR intervals, reflecting increased parasympathetic activity and the body's ability to adapt to environmental and psychological stressors. Conversely, lower pNN50 values during stress signify reduced variability and heightened sympathetic tone, indicative of a more stress-reactive state.

Overall, these time-domain parameters provided a comprehensive framework for understanding HRV dynamics across different physiological states. By examining how HR, SDNN, RMSSD, and pNN50 change with relaxation and stress, this study contributed valuable insights into the autonomic nervous system's response to varying levels of stress and relaxation. These findings underscore the importance of HRV analysis in assessing cardiovascular health, stress resilience, and the efficacy of relaxation interventions in promoting physiological balance and well-being.

4.2.4 Frequency Domain HRV Features

Spectral analysis was performed using Welch's method to estimate the power spectral density (PSD) of RR intervals. This sophisticated approach involves dividing the signal into overlapping segments, computing their periodograms, and averaging these periodograms to obtain a smooth estimate of the PSD. The PSD provides a detailed representation of the distribution of signal power across different frequency bands, offering insights into various physiological processes influencing heart rate variability (HRV).

To evaluate the contributions of different physiological mechanisms to HRV, the power spectrum was partitioned into distinct frequency bands. Specifically, the power in the low-frequency (LF) and high-frequency (HF) bands was calculated. The LF band, spanning from 0.04 Hz to 0.15 Hz, predominantly represents both sympathetic and parasympathetic modulation of the heart. This range provides a comprehensive view of the autonomic nervous system's influence on heart rate, reflecting a mix of both stress-related (sympathetic) and relaxation-related (parasympathetic) activities.

On the other hand, the HF band, covering frequencies from 0.15 Hz to 0.4 Hz, primarily reflects parasympathetic activity and respiratory sinus arrhythmia. This band is particularly significant for assessing the body's relaxation response, as it is closely associated with vagal tone and the calming effects of parasympathetic activation.

The power within each frequency band was computed by integrating the area under the PSD curve within the respective frequency ranges. This integration process allows for a precise quantification of the power in each band, providing a clear picture of the relative contributions of sympathetic and parasympathetic influences on heart rate variability.

Additionally, the LF/HF ratio was calculated to assess sympathovagal balance. This ratio is a crucial metric, with higher values indicating sympathetic dominance and lower values reflecting parasympathetic predominance. By analyzing this ratio, researchers can gain insights into the overall balance between stress and relaxation responses in the body, offering a comprehensive understanding of autonomic regulation.

All ECG and HRV analyses were conducted using MATLAB 2024, ensuring precise and reliable data processing. The use of MATLAB, a powerful tool for numerical computation and visualization, allowed for sophisticated analysis and accurate interpretation of the HRV data. This methodological rigor ensures that the findings are robust and can be confidently used to draw conclusions about the effectiveness of different relaxation interventions.

In summary, the use of Welch's method for spectral analysis, coupled with the partitioning of the power spectrum into LF and HF bands, provided a detailed and nuanced understanding of the autonomic mechanisms influencing heart rate variability. The computation of the LF/HF ratio further enriched the analysis, offering insights into the balance between sympathetic and parasympathetic activity. The rigorous analytical approach, supported by MATLAB 2024, underscores the reliability and precision of the study's findings.

4.3 Self-Reported Stress (SAI Scores)

The State-Trait Anxiety Inventory Y1 (STAI-Y1) questionnaires were meticulously analyzed to determine the State Anxiety Scores (SAI) for each participant. This involved a detailed scoring process where each question was graded on a scale from 1 to 4. Questions that referred to the absence of anxiety were reverse-graded to ensure accurate reflection of anxiety levels. For instance, a low score on an absence-of-anxiety question would contribute to a higher overall anxiety score, whereas a high score would indicate lower anxiety. Table 2 illustrates the specific scoring guide used in this analysis, detailing the approach for each type of question.

This method allowed for a comprehensive assessment of participants' current state of anxiety, providing valuable data on their psychological responses in different experimental conditions.

#	Question	Not at all	Somewhat	Moderately so	Very Much
1	[I feel calm.]	4	3	2	1
2	[I feel tense.]	1	2	3	4
3	[I feel at ease.]	4	3	2	1
4	[I am presently worrying about misfortunes.]	1	2	3	4
5	[I feel frightened.]	1	2	3	4
6	[I feel nervous.]	1	2	3	4
7	[I feel jittery.]	1	2	3	4
8	[I feel relaxed.]	4	3	2	1
9	[I feel worried.]	1	2	3	4
10	[I feel steady.]	4	3	2	1

Table 1 The scoring guide used to calculate cumulative SAI Score

4.4 Statistical Analysis

The initial statistical comparison was conducted within subjects, comparing phases within the same group. To analyze the data, a repeated measures ANOVA was performed to compare parameters across the three phases (Baseline, Stress, Relaxation) within each group (experimental and control). This method allowed for the assessment of within-subject effects over time and the identification of any significant changes across phases.

Following the repeated measures ANOVA, a post hoc analysis using Tukey's Honestly Significant Difference (HSD) test was conducted to determine pairwise differences between groups. Tukey's HSD test provided a critical value against which mean differences between groups were compared. Mean differences were calculated for all pairs of groups, and if the absolute difference in means between any two groups exceeded the critical value obtained from Tukey's HSD test, it was considered statistically significant.

The second statistical comparison involved between-subjects analysis, comparing different groups within the same phase. For example, the relaxation phase of the control group was compared to the relaxation phase of the experimental group to establish whether VR-based relaxation was more effective than conventional relaxation.

Before investigating the effectiveness of VR-based relaxation, independent-sample t-tests were conducted to establish baseline phase equivalence and stress phase equivalence between the control and experimental groups. This involved comparing HRV and EEG parameters during both the baseline and stress phases, ensuring no statistically significant differences existed. This step verified the equivalence of the groups prior to the relaxation intervention. Only if the groups exhibited no significant differences during these initial phases could any observed relaxation effects be confidently attributed to the VR intervention.

Finally, independent samples t-tests were conducted to compare relaxation parameters between the control and experimental groups.

CHAPTER 5: RESULTS AND DISCUSSIONS

5.1 EEG Findings

5.1.1 Within-subjects Comparison

For within-subjects comparison, Alpha power was computed to be significantly different across all phases (Baseline, stress, and relaxation) for both groups (experimental and control). This was further confirmed by Tukey's HSD. The table. shows the summary of Repeated ANOVA conducted for Alpha power values for the experimental and control group.

Experimental Group			
Alpha Power	f	P value	fcrit
Alpha- AF3	72.0166	0.0018	3.244
Alpha- T7	48.458	0.0350	3.244
Alpha – Pz	98.730	0.021	3.244
Alpha- T8	85.4712	0.0085	3.244
Alpha – AF4	95.536	0.0015	3.244
Control Group			
Alpha Power	f	P value	fcrit
Alpha- AF3	38.076	0.00096	3.244
Alpha- T7	154.664	0.00052	3.244
Alpha – Pz	153.449	0.0063	3.244
Alpha- T8	77.504	0.000389	3.244
Alpha – AF4	78.11701	0.000345	3.244

Table 2 ANOVA Results - Alpha Power

Beta power also significantly differed across all phases (Baseline, stress and relaxation) for both groups (experimental and control). This was also confirmed by Tukey's HSD. The table. shows the summary of Repeated ANOVA conducted for Beta power values for the experimental and control group.

Experimental Group			
Beta Power	f	P value	fcrit
Beta - AF3	166.146	0.000164	3.244
Beta - T7	170.5226	0.0005	3.244
Beta – Pz	146.3183	0.00141	3.244
Beta - T8	105.2035	0.0032	3.244
Beta – AF4	136.791	0.00435	3.244
Control Group			
Beta Power	f	P value	fcrit
Beta - AF3	226.524	0.00076	3.244
Beta - T7	199.650	0.00069	3.244
Beta – Pz	236.449	0.00078	3.244
Beta - T8	115.855	0.000674	3.244
Beta – AF4	145.117	0.00015	3.244

Table 3 ANOVA Results - Beta Power

The alpha-to-beta ratio showed significance across phases for both the experimental and control groups. This finding indicates that there were notable changes in this ratio, which is often used as a marker for relaxation and cognitive states, across different phases of the study.

However, further analysis using Tukey's Honest Significant Difference (HSD) test, a post-hoc test, revealed more specific differences. For the experimental group, significant differences were observed specifically between the stress and relaxation phases and between the relaxation and baseline phases. This indicates that the VR-based relaxation had a distinct impact on altering the alpha-to-beta ratio during these transitions, reflecting changes in brain activity associated with stress reduction and relaxation.

In contrast, the control group exhibited significant differences in the alpha-to-beta ratio across all phases. This comprehensive change suggests that the conventional relaxation method also effectively modulated this ratio, but the pattern of changes was different from that observed in the experimental group.

The summary table of the repeated measures ANOVA for the overall alpha-to-beta ratio highlights these findings. The repeated ANOVA confirmed that there were significant variations in the alpha-to-beta ratio across the different phases for both groups, but the specific phase-to-phase comparisons provided by Tukey's HSD post-hoc test offer deeper insights into the nuances of these changes.

These results underscore the impact of both VR-based and conventional relaxation techniques on brain activity, as measured by the alpha-to-beta ratio. For the experimental group, the significant differences between stress and relaxation, and relaxation and baseline, suggest that VR relaxation may facilitate more pronounced shifts in brain states associated with relaxation. Meanwhile, the control group's significant differences across all phases indicate a broader, yet equally effective, modulation of brain activity through conventional relaxation methods.

In summary, the alpha-to-beta ratio's significance across phases, coupled with the detailed insights from Tukey's HSD post-hoc test, provides a comprehensive understanding of how both VR-based and conventional relaxation techniques influence brain activity. These findings contribute to the growing body of evidence supporting the effectiveness of VR in stress reduction, while also affirming the value of traditional relaxation methods.

Experimental Group			
alpha-to-beta ratio	f	P value	fcrit
Overall	22.380	0.031	3.244
Control Group			
alpha-to-beta ratio	f	P value	fcrit
Overall	90.6359	0.0345	3.244

Table 4 ANOVA Results - Alpha-to-Beta ratio

The FAA within-subjects, for both the groups showed significant difference in Stress vs Relaxation and Relaxation vs Baseline. The Tukey's HSD confirmed FAA values showed no significant difference in Baseline vs Stress. The table. shows the summary of the repeated ANOVA for the FAA values.

Experimental Group			
FAA	f	P value	fcrit
AF3-AF4	10.378	0.00025	3.244
Control Group			
FAA	f	P value	fcrit
AF3-AF4	13.519	0.000036	3.244

Table 5 ANOVA Results - FAA index

In order to analyze whether virtual reality (VR) based relaxation is more effective in reducing stress, an independent samples t-test was utilized. Prior to applying this statistical test to the relaxation parameters across both the experimental and control groups, it was essential to ensure equivalence in the baseline and stress phases for both groups. This preliminary step was crucial for validating that any observed differences in relaxation outcomes could be attributed to the intervention rather than pre-existing disparities.

The results of these preliminary checks revealed no significant differences in parameters between the two groups during the baseline and stress phases. This finding is important as it establishes that both groups started from a comparable state, ensuring that any subsequent differences observed during the relaxation phase can be confidently attributed to the effects of the VR-based relaxation intervention.

The lack of significant differences in baseline and stress phase parameters between the groups provides a robust foundation for the study, supporting the validity of the comparison between VR-based and conventional relaxation techniques. This equivalence suggests that both groups were equally stressed initially and responded similarly to baseline conditions, thereby enhancing the reliability of the results.

By confirming that the groups were comparable at the outset, the study can more accurately assess the efficacy of VR-based relaxation. This careful methodological approach ensures that any findings regarding the superiority of VR relaxation in reducing stress are well-founded and not influenced by initial group disparities. Consequently, the study is well-positioned to contribute valuable insights into the effectiveness of VR as a stress reduction tool.

Overall, these preliminary equivalence checks underscore the rigor of the study design, allowing for a more accurate and credible comparison of the relaxation techniques. This meticulous approach highlights the potential of VR-based relaxation to provide significant benefits in stress reduction, setting the stage for further exploration and validation of these findings in diverse populations and settings.

5.1.2 Between-subjects Comparison

For between-subjects, Alpha power at the frontal lobe specifically, AF3 ($t(38)=3.18$, $p=0.0038$)and AF4 ($t(38)=3.18$, $p=0.027$) were significantly higher in the experimental group than the control group indicating a more relaxed state in VR-based relaxation. The Alpha-power did not show any significant differences across other channels.

The results demonstrated a significantly higher α/β ratio (t(38)=3.18, p=0.019) during VR relaxation. These findings suggest that VR relaxation techniques promote a more relaxed state of mind, as evident by the increase in alpha-to-beta ratio. VR relaxation appears to be more effective in inducing this shift towards alpha dominance.

This observation aligns with previous research linking alpha waves to relaxation and alertness [3]. A higher α/β ratio suggests a predominance of alpha activity, indicating a calmer and more relaxed mental state. VR technology might be particularly effective in achieving this state by providing an immersive and engaging environment that promotes disengagement from stress and facilitates mindfulness.

The beta power across all five channels showed a significant decrease. Further supporting the hypothesis that VR relaxation led to reduction in physical arousal and anxiety. The AF3 (t(38)=3.18, p=0.0023), AF4 (t(38)=3.18, p=0.001), and Pz (t(38)=3.18, p=0.001) showed very strong significant difference. While, the lateral channels, T7(t(38)=3.18, p=0.003) and T8 (t(38)=3.18, p=0.0036) showed comparatively lesser yet strong significant differences.

There were no significant differences in FAA between VR relaxation and non-VR relaxation. This suggests that both techniques might have similar effects on the relative activity between the left and right frontal lobes. However, VR relaxation exhibited a significantly higher α/β ratio as explained earlier, compared to stress, which might indicate a shift towards a more relaxed state of mind, even if the specific distribution of alpha activity across the frontal lobes (reflected by FAA) didn't show a significant difference.

5.2 Heart Rate Variability (HRV)

5.2.1 Within-subjects Comparison

For within-subjects comparisons, heart rate (HR) significantly differed across the Baseline vs. Stress and Stress vs. Relaxation phases for both the experimental (f=17.233, p=0.0000471, f_crit=3.245) and control groups (f=5.069, p=0.011185, f_crit=3.245). The lack of significant HR differences between the Baseline and Relaxation phases suggests a return to calmer physiological states in both groups.

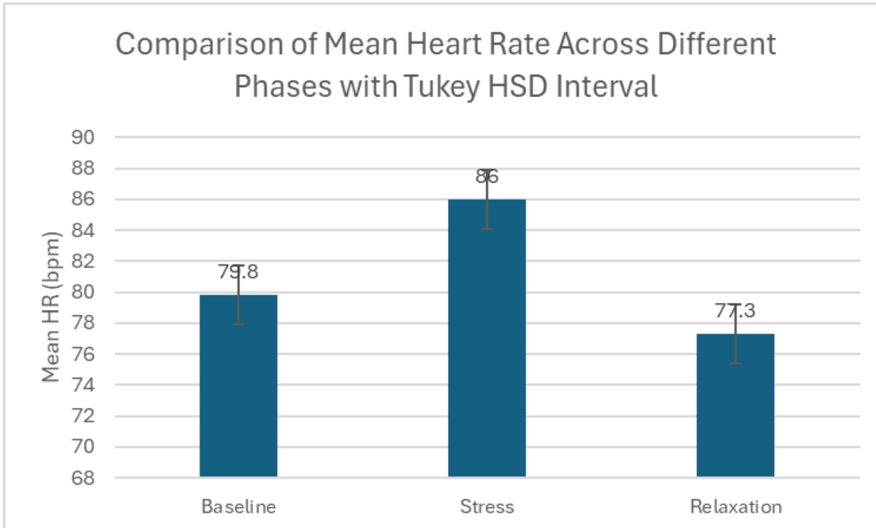

Figure 4 Mean Heart Rate across phases

The standard deviation of normal-to-normal intervals (SDNN) showed marginally significant differences between the Baseline and Stress phases for the experimental group (f=3.262, p=0.0492, f_crit=3.245).

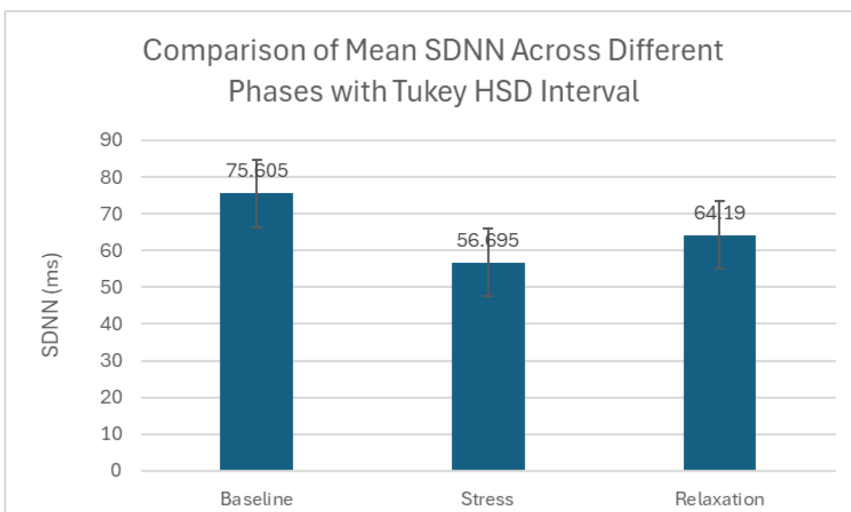

Figure 5 Mean SDNN across phases

The percentage of successive RR intervals differing by more than 50 ms (pNN50) also showed significant differences across all phases in the experimental group (f=11.160, p=0.00015, f_crit=3.245).

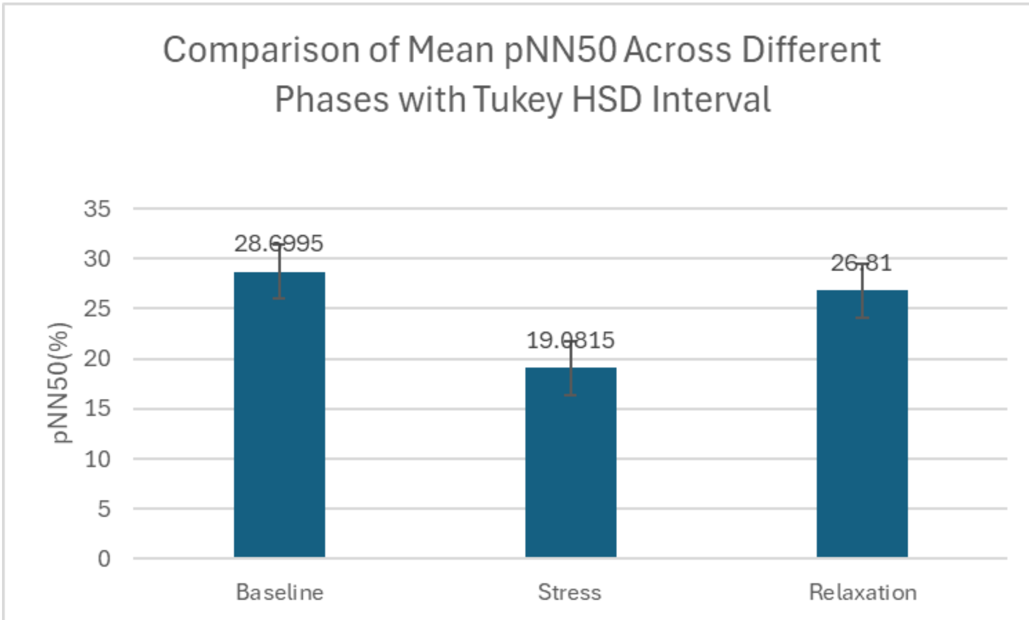

Figure 6 Mean pNN50 across phases

These changes in HRV parameters within subjects provide evidence that the stress phase successfully induced a state of physiological arousal, while the relaxation phase appeared to promote a return to a more parasympathetically dominant state for both groups.

5.2.2 Between-Subjects Comparison

Between-subjects comparisons revealed that heart rate (HR) was significantly lower in the experimental group than in the control group during the relaxation phase (t(38)=2.0259, p=0.0032), indicating a more relaxed state in the virtual reality (VR)-based relaxation. This finding suggests that VR-based relaxation may be particularly effective in reducing heart rate compared to traditional methods. However, it is important to note that none of the other time-domain parameters showed significant differences in relaxation between the two groups, suggesting that the observed HR difference might be specific to the VR intervention.

In terms of heart rate variability (HRV), the standard deviation of normal-to-normal intervals (SDNN) increased during both conventional relaxation and VR relaxation compared to the stress phase, indicating increased HRV in these states. This finding aligns with previous research suggesting that HRV increases during relaxation and can be a marker of improved adaptability to stress. This increase in SDNN during relaxation phases reinforces the idea that both conventional and VR relaxation techniques can enhance physiological responses associated with stress recovery.

Additionally, the relaxation phase showed an increase in the high-frequency (HF) band compared to the baseline, further supporting the activation of the parasympathetic nervous system (PNS) during relaxation. The activation of the PNS is typically associated with relaxation and recovery processes. However, VR relaxation did not exhibit a statistically significant increase in HF compared to non-VR relaxation, suggesting that both techniques might have similar effects on PNS activation. This indicates that while VR relaxation is effective, it may not necessarily outperform conventional relaxation in terms of HF band increases.

Interestingly, the low-frequency to high-frequency (LF/HF) ratio showed a significant decrease in VR-based relaxation compared to conventional relaxation ($t(38)=2.0259$, $p=0.0022$). This suggests that VR might be more effective in inducing PNS activation and recovery, as a lower LF/HF ratio is often interpreted as a sign of greater parasympathetic activity and reduced sympathetic dominance. This significant finding highlights a potential advantage of VR-based relaxation in enhancing the body's recovery mechanisms more efficiently than traditional relaxation methods.

Despite these significant findings, the rest of the parameters, although exhibiting expected patterns consistent with relaxation and stress recovery, did not show any significant differences between the groups. This lack of significant differences in other parameters suggests that while certain aspects of physiological response to relaxation can be enhanced by VR, the overall impact on a broader range of physiological measures might be similar between VR and conventional relaxation techniques. Thus, VR-based relaxation offers specific benefits, particularly in reducing HR and modifying the LF/HF ratio, but further research is needed to explore its effects on other physiological markers of relaxation.

5.2.3 Self-Reported Stress (SAI Scores)

The analysis revealed that the Relaxation State Anxiety Inventory (SAI) scores were markedly lower than the Stress SAI scores across both groups, underscoring the effectiveness of the relaxation interventions in reducing anxiety levels. However, a notable difference emerged between the experimental and control groups. In the experimental group, the Relaxation SAI scores not only decreased significantly from the Stress SAI scores but also fell below their Baseline SAI scores. This suggests a state of hyper-relaxation, where participants achieved a level of calm and relaxation beyond their initial baseline state. In contrast, the control group's Relaxation SAI scores, while lower than their Stress SAI scores, remained comparable to their Baseline SAI scores, indicating that their relaxation did not surpass their initial resting state. This disparity highlights the enhanced relaxation effect experienced by the experimental group, possibly due to the immersive and engaging nature of the VR-based relaxation intervention.

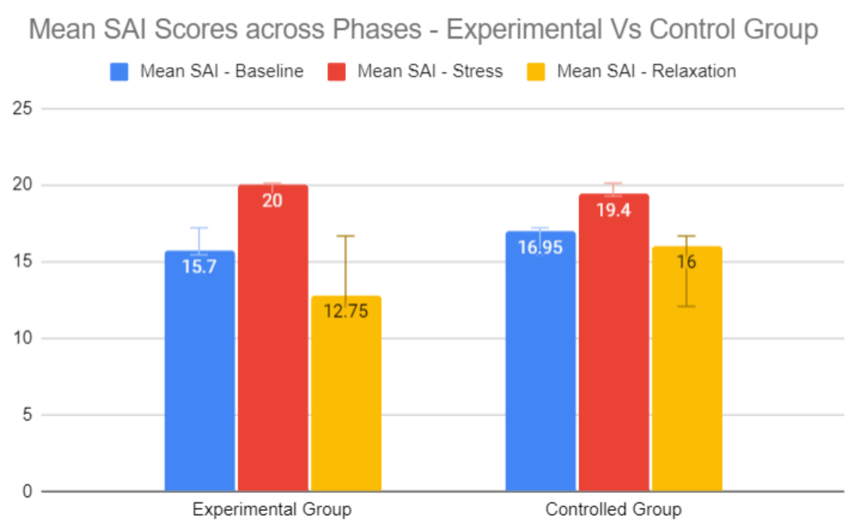

Figure 7 TAI Scores across phases, for Experimental and Control Group

CHAPTER 7: CONCLUSIONS AND FUTURE RECOMMENDATION

7.1 Conclusions

This study investigated the effectiveness of virtual reality (VR) relaxation compared to conventional relaxation techniques in promoting stress recovery. Both VR and conventional relaxation methods significantly improved heart rate variability (HRV) and decreased sympathetic dominance, indicating enhanced adaptability to stress and activation of the parasympathetic nervous system (PNS). These changes suggest that both methods are effective in facilitating a relaxation response, which is crucial for stress recovery.

However, VR relaxation demonstrated additional benefits in promoting relaxation. Specifically, VR relaxation led to a more pronounced decrease in heart rate, highlighting a deeper state of relaxation compared to conventional methods. The significant reduction in the low-frequency to high-frequency (LF/HF) ratio further supports the superiority of VR relaxation in promoting PNS activation. This suggests that VR might be more effective in achieving a state of physiological calm and balance between the sympathetic and parasympathetic nervous systems.

Moreover, the study found that VR relaxation resulted in increased alpha power, particularly in frontal brain regions. This finding supports existing research indicating the prefrontal cortex's involvement in responding to acute mental stress. The enhanced calmness and focused attention observed during VR relaxation may be attributed to the immersive and engaging nature of VR environments, which effectively distract users from external stimuli and promote deeper relaxation. This immersive quality of VR relaxation might be a key factor in its ability to enhance relaxation responses more effectively than conventional techniques.

Additionally, VR relaxation showed a stronger reduction in physiological arousal compared to conventional relaxation. This was evident from a significant decrease in beta power across all brain regions, suggesting that VR has a widespread influence on brain areas involved in attention and processing. The significantly higher alpha-to-beta ratio observed in VR relaxation indicates its effectiveness in promoting a relaxed state with increased alpha dominance, which is associated with calmness and reduced arousal.

Despite these significant findings, it is important to note that both VR and conventional relaxation techniques had similar effects on frontal asymmetry (FAA), suggesting that both methods are equally effective in balancing left and right frontal brain activity. This balance is often linked to emotional regulation and stress resilience.

Overall, these findings highlight VR relaxation's potential as a valuable tool for promoting stress recovery. The enhanced physiological relaxation, focused attention, and more robust reduction in arousal observed with VR relaxation underscore its effectiveness. By providing an immersive and engaging environment, VR relaxation may facilitate a deeper and more comprehensive relaxation response, making it a promising approach for managing stress and enhancing overall well-being. The study underscores the importance of exploring innovative relaxation techniques like VR to address the growing need for effective stress management solutions.

7.2 Future Recommendations

Future research could focus on dynamic virtual reality (VR) interactions. Incorporating dynamic scenarios would enable capturing real-time responses to stress, offering a more comprehensive understanding of how individuals react to varying stressors in a VR environment. This approach could provide deeper insights into the immediate and evolving physiological and psychological responses to stress and relaxation techniques.

Expanding participant diversity to include various age groups, cultural backgrounds, and socioeconomic statuses can significantly strengthen the external validity of research findings. By encompassing a broader demographic, studies can provide a more inclusive understanding of stress reduction experiences and identify potential differences in how diverse groups respond to VR and conventional relaxation techniques. Additionally, exploring gender-specific responses to stress and relaxation could reveal valuable insights if distinct patterns emerge during analysis, further tailoring stress reduction interventions to individual needs.

Longitudinal studies that track the same participants over extended periods would be particularly beneficial in exploring the sustained effects of stress reduction interventions. By following participants over time, researchers can assess the long-term efficacy of VR relaxation and other stress management techniques. These studies could identify lasting benefits or potential drawbacks, contributing to a more comprehensive understanding of how these interventions impact stress resilience and overall well-being in the long run.

Overall, future research should aim to enhance the realism and applicability of VR relaxation studies by incorporating dynamic interactions, expanding participant diversity, and conducting longitudinal analyses. These approaches will contribute to a more nuanced and complete understanding of stress responses and the effectiveness of various relaxation techniques, ultimately leading to more effective and personalized stress management solutions.various age groups, cultural backgrounds, and socioeconomic statuses can strengthen external validity and provide a broader understanding of stress reduction experiences. Additionally, exploring gender-specific responses to stress and relaxation could offer valuable insights if patterns emerge during analysis.

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