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Integrating Virtual Reality and Physiological Measures to study Restorative Environments for Mental Well-Being

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Abstract

This paper explores the integration of virtual reality (VR) environments with physiological sensors to study and enhance mental well-being. Building on research emphasizing the role of restorative environments, this study focuses on designing and optimizing experiment to understand restorative potential of realistic virtual outdoor spaces on VR. By using VR combined with physiological measures (e.g., heart rate and skin conductance), the study aims to move from explicit data collection to more implicit, continuous feedback. Preliminary design considerations, challenges, and methodologies are discussed, highlighting VR's potential for improving mental health.

Index terms: Emotion, Cognition, Physiological signals, Stress.

1 Introduction

Virtual reality (VR) serves as a powerful research tool, fusing the control of lab experimentation with the ecological validity of physical-world environments [3]. Combined with recent advancements in physiological sensing, current levels of fidelity have significantly enhanced the potential of VR for studying environmental factors that affect mental well-being. By integrating physiological sensors, VR enables implicit data collection, offering a deeper understanding of how body and mind respond to different environmental factors [10].

The integration of physiological sensors with VR not only enriches our understanding of human responses but also helps design real-world environments that enhance quality of life. For instance, this approach can foster optimizing green spaces—recognized as restorative environments [32]—to promote well-being in urban settings. The physical environment can play a critical role in shaping mood, creating a bidirectional relationship between the body and mind [5, 4]. Studies [20, 23, 23] have shown that virtual nature, even in videos and images, can have a restorative effect similar to that of real-world environments. VR allows for the creation of controllable natural spaces, where factors such as tree height can be adjusted—something that is difficult or impossible to do in physical environments. By observing emotional and cognitive responses to controlled environmental changes in VR, this study provides preliminary data for how specific design elements, such as tree height and spatial openness, influence psychological well-being for future studies. These insights can be used by urban planners and architects to design real-world environments that promote stress reduction and cognitive recovery. Potential applications include the design of restorative public parks, healthcare facilities, and educational settings. While experimenting in real-world environments is often costly, time-consuming, and sometimes infeasible, VR allows for cost-effective and flexible experimentation.

Ability of VR to closely replicate the restorative effects of real nature, offers a promising platform for developing experimental methods that can eventually be applied to designing restorative physical environments. [3].

Biosignals include physical -associated with body movement and deformation - and physiological - associated with internal bodily functions - markers, such as heart activity, skin conductance, blood pressure, respiration, and body and eye movements [9], offer valuable insights into emotions, arousal, stress, and cognitive load. However, biosignals often exhibit similar responses across different contexts, making their interpretation complex [2, 3, 5]. Despite the potential of integrating physiological sensors with VR for assessment and feedback [1, 4, 6], challenges remain in areas like synchronization, data analysis, and interpretation. Addressing these challenges is key to unlocking the full potential of VR as a tool for research and enhancement on mental well-being.

In this study, we explore the restorative effects of environments using physical, physiological, and behavioural measures in VR, with the goal of addressing the challenges associated with selecting appropriate assessment tools, particularly physiological sensors with VR for mental health applications. To build a comprehensive understanding, we begin by introducing key theories of restoration, which form the foundation for our study of restoration effects of environmental factors on body and mind. Next, we explain the rationale behind selecting specific sensors and assessment methods based on restorative theories, illustrating how these tools are used to capture and analyse changes in physiological and emotional responses. By refining these methods, our research aims to develop practical approaches for evaluating characteristics of physical environments by using VR as a proxy in future studies.

2 Key Theories of Restoration and Their Relevance to VR

Restoration aims to alleviate mental fatigue and negative emotions, promoting relaxation, well-being, and resilience [32]. Two key theories explain the restorative effects of environments: Stress Recovery Theory (SRT), which emphasizes positive emotional responses, and Attention Restoration Theory (ART), which focuses on replenishing cognitive capacity [32]. SRT, introduced by Ulrich et.al [34] in 1991, explains how being in natural, safe environments can help reduce stress. The human body's stress response once was helpful aiding in survival in the face of immediate dangers; however, it can become counterproductive in today's world, often contributing to chronic

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stress. Restorative environments activate the body's relaxation system (Parasympathetic Nervous System), making individuals feel calmer and enhancing their overall mood. If an environment bears characteristics of restoration, stress levels are reduced.

ART was introduced by Kaplan [14] in 1995, and proposes that natural environments help restore mental energy drained by tasks requiring sustained focus. Prolonged concentration can lead to attentional fatigue, but nature offers a way to replenish mental resources particularly selective attention -the ability to focus on important information while filtering out distractions-. Kaplan and Berman [15] suggest that nature can recharge this resource by promoting effortless attention, which occurs when the mind is naturally drawn to the environment without expending mental effort [15]. According to ART, certain criteria are essential for an environment to be restorative. One key characteristic is *fascination*, which involves capturing attention effortlessly and allowing the mind to rest and recover. Additionally, the environment should have *extent*, providing a sense of vastness. Another crucial quality is *being away*, offering an escape from everyday demands and worries, thereby creating a mental break from routine stressors. Finally, *compatibility* is vital, meaning the environment must align with an individual's personal needs and goals. For instance, natural settings, which historically supported human survival, are particularly effective in fulfilling these criteria [24].

Natural environments vary in their ability to provide restorative benefits base on ART criteria [11, 13]. Equally important, the diverse emotional responses individuals have to natural settings suggest that these environments are not always perceived as restorative. For some, the unpredictability of nature may evoke feelings of insecurity or threat, which undermines the sense of safety and comfort emphasized by SRT [11, 3].

VR offers a unique opportunity to study restorative environments to systematically identify factors that make physical-world environments restorative, enabling the development of enhanced VR restorative spaces and providing insights to improve physical-world restorative environments [9, 18, 20]. By understanding the underlying mechanisms of restoration through VR research, we can design better virtual environments while also informing changes to physical-world settings. VR makes environment aligns closely with the criteria of restorative environments. For instance, VR can mimic realistic settings with higher quality and resolution than traditional desktop simulations, effectively fulfilling the ART criterion of *fascination* [18, 23]. *Exten*t is achieved in VR through its larger field of view, enhanced depth perception, and 360-degree field of regard. Tracking sensors further enhance the experience by mapping users' physical movements into the virtual environment, ensuring continuity and immersion as users explore the virtual space [37]. Moreover, VR creates a secure and consistent space for restoration and recovery by eliminating the unpredictability and potential feelings of unsafety that some individuals may associate with real-world environments. In VR, the fully adjustable environment aligns with the *compatibility*, allowing participants to engage with restorative features tailored to their needs and goals. These capabilities makes VR a powerful tool for studying and promoting restoration, offering potential benefits such as stress recovery, relaxation, increased energy levels, and reduced negative emotions [20]. By integrating VR with ART and SRT principles, researchers can systematically investigate and optimize the design of restorative environments in physical and virtual worlds to enhance mental health and well-being.

In our study, we have developed two virtual environments to compare the restorative effects of nature versus urban settings. To evaluate restorative effects, it is essential to assess cognitive processes, positive emotions, and stress, as both ART and SRT emphasize their significance. Selecting appropriate methods for measuring these variables is therefore critical. In the following section, we will first describe the two VR environments, and then we will outline the measurement methods we have chosen, along with the rationale for their selection based on ART and SRT.

3 Design of the VR Environment

In this section, we describe the design process of the two virtual environments developed for this study: a nature environment and an urban environment. The goal was to create immersive, realistic environments that effectively embody the key features of restorative spaces, as defined by ART and SRT. The environments were chosen to allow for a clear contrast in restorative potential, as supported by prior research [3, 18] showing the restorative effects of natural spaces such as forests compared to urban parks. To establish a baseline understanding of the restorative effect, we opted for a highly distinguishable forest environment compared to an urban setting. This decision allows us to explore the fundamental spatial differences contributing to restorative outcomes, minimizing other confounding factors like the presence of moving elements (e.g., people or vehicles). The absence of such dynamic elements helps focus the comparison on the physical design and spatial characteristics of the environments. Both environments include ambient sound to enhance immersion. The forest features wind rustling through trees, while the urban setting includes distant city noise, such as far-off traffic sounds, but no visible vehicles. The focus on visual information in this study allows us to align closely with ART's criteria of fascination and extent, which are highly dependent on the perception of visual complexity and depth. Other sensory modalities, such as haptics and scent, were excluded to ensure experimental control and reduce confounding variables in physiological data analysis.

To minimize cybersickness, teleportation was chosen as the primary navigation method in both virtual environments. Free traveling with a controller, while more closely simulating real-world movement, often induces greater cybersickness due to sensory conflicts between visual input and bodily signals related to motion [3, 9]. To reduce this effect while still approximating the experience of walking, we limited teleportation to predefined small circular areas placed at fixed intervals. Participants could only teleport to the nearest circle, encouraging step-by-step forward movement. To help maintain spatial orientation, all teleportation circles remained white and continuously visible throughout the session, forming a guiding path. Participants were seated in a swivel chair and could freely turn, deciding whether to move forward or backward along the designated path. Both environments start at the same location on a circular path to ensure consistency as much as possible in participant experience and control for spatial factors such as height of trees that could influence restorative effects. Participants continue exploring until the 6-minute session concludes. This duration is necessary to ensure the collection of valid biosignal data, as studies suggest a 2-4 minutes is required for reliable physiological measurements for analysing. [2, 5]. (See fig. 1).

3.1 Nature Environment

In the development of the nature environment for this study, we used the demo scene from the "Forest Environment - Dynamic Nature" asset [38] on the Unity Asset Store We made several modifications to the scene, including reducing the elevation changes to create a less ascending and descending terrain to make it similar urban environment as much as possible. Additionally, we illuminated the path with less vegetation to enhance the visibility and ensure a more comfortable and focused navigation experience for participants. These adjustments helped tailor the environment to better suit the study's requirements while maintaining an immersive natural setting.

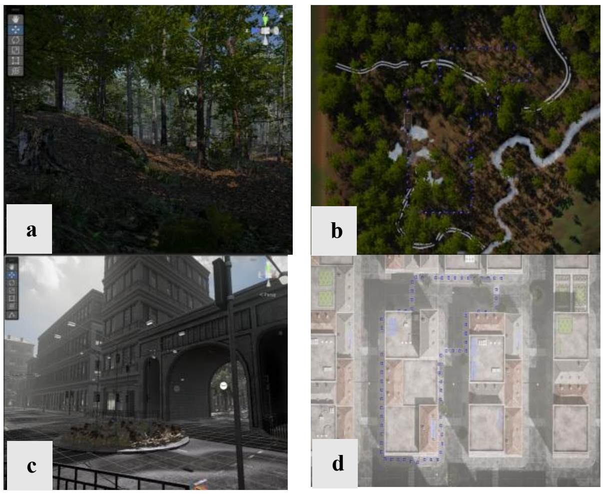

Figure 1: Virtual Reality Forest and Urban Scenes.; a) Forest scene view, b) Forest map view, c) Urban scene view, d) Urban map view.

3.2 Urban Environment

In the development of the urban environment for this study, we used the "City Builder London" asset [39] from the Unity Asset Store. This package has some similarities to the location of the experiment and has some green features in the city. Therefore, this package is similar to participants daily life experience. We used the demo scene as a base and made several modifications, including adding more buildings further along the path to ensure that participants would have a consistent urban view of buildings during navigation.

After developing the environments, the next step is selecting appropriate assessments to measure the effects of restoration and evaluate the differences in restorative effects between the urban and forest environments. In the following section, we will explain reason of choosing assessments, grounded in restorative theories.

CHOOSING THE RIGHT MEASUREMENT METHODS FROM THEORY TO APPLICATION

In this section, we focus on selecting the right measurement tools for assessing the restorative effects of the VR environments. Choosing appropriate evaluation methods is crucial, as VR offers unique possibilities and challenges for data collection, and the validity of different measurement tools can vary. Additionally, the complexity of measuring emotions and cognition, which often overlap, requires careful consideration to ensure accurate and reliable results. We will explore the rationale behind our choices, aligning them with the theoretical frameworks of restoration.

3.3 Measuring Affective Responses: Applications of SRT

Considering that SRT focuses on stress reduction and the enhancement of positive emotions, studying affect—defined as the experience and expression of emotions—can provide valuable insights to understand restoration mechanism. Russell's circumflex model of affect [8] categorizes emotions on a circular scale with two axes. The first axis, *valence*, represents the emotional quality, ranging from unpleasant to pleasant. The second axis, *arousal*, reflects the physiological intensity of emotion, ranging from deactivation to activation. Typical methods to measure affect involve interviews and questionnaires such as Self-Assessment Manikin (SAM) [3] and the Positive and Negative Affect Schedule (PANAS) [35]. These methods are *subjective*, as the data is often gathered after the experiment and may be influenced by fading memories or reconstructed events [12]. As an alternative, physical and physiological signals can serve as implicit, *objective* methods for studying affect [12] Physical signals reflect muscle activity and include pupil size, eye movements, blinks, head and body movements, and facial expressions. Physiological signals are closely linked to vital bodily functions, such as cardiac activity, brain function, exocrine activity, and muscle excitability [9]. Next, we will explain measurement for arousal and valance which we used for our study based on SRT and ART.

3.3.1 Arousal measurements

According to Ladakis and Chouvarda (2021) [17], ElectroDermal Activity (EDA) and Heart Rate Variability (HRV) are particularly useful for affect measurement, especially arousal levels and stress. EDA stands out due to its rapid physiological shifts that align with the pace of the peripheral nervous system [17]. EDA includes two components: 1) Skin Conductance Level (SCL) which changes slowly representing average skin conductivity over time, indicating psychophysiological activation, and 2) Skin Conductance Response (SCR) which result is in short-term fluctuations in response to stimuli or triggers, reflecting event-related reactions [9]. Since EDA is influenced solely by the sympathetic nervous system, it serves as a reliable stress indicator, unlike other physiological measures that are influenced by both the sympathetic and parasympathetic nervous systems therefore, SCL is the most effective stress correlate compared to HRV, Respiratory signal, and Electromyography [9].

HRV refers to the variation in time intervals between consecutive heartbeats, also known as interbeat intervals (IBIs). It reflects the dynamic interplay between the sympathetic and parasympathetic branches of the autonomic nervous system in regulating cardiac activity. Therefore, HRV is a key physiological indicator used to measure arousal and stress response, providing valuable insight into the restorative effects of VR. HRV is analysed through time-domain methods, like Root Mean Square of Successive differences between heartbeats RMSSD, which reflect parasympathetic activity, and frequency-domain methods, which decompose signals into high-frequency (parasympathetic) and low-frequency (mixed autonomic) bands [7]. Traditional HRV measurement relies on electrocardiography (ECG), which detects electrical signals of the heart and identifies peaks in the ECG waveform. An alternative is photoplethysmography (PPG) [9], a non-invasive optical method often employed in wearable devices [7, 16].

As a result, we decided to use these two tools since EDA focuses on parasympathetic activation, while HRV includes both parasympathetic and sympathetic activation. By having two different sensors, we can separate sympathetic and parasympathetic activation, allowing us to gain a more comprehensive understanding of the body's response to the environment. Additionally, these two sensors can be integrated into a single kit, which makes it more convenient and efficient for data collection. For our study, we selected the Shimmer's mobile EDA sensor kit and an integrated PPG sensor (fingertip), which allowed for easier setup and enhanced portability while reducing the need for additional sensing devices. These features make it an ideal choice for real-time monitoring in dynamic environments.

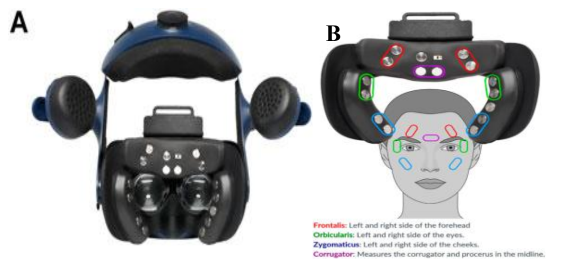

Figure 2: A) EmteqPRO inserts are mounted onto HTV pro B) Mapping between EmteqPRO sensors and facial, muscles (adapted from Gnacek et al., (2021) [10]).

3.3.2 Valance measurement

To measure affective changes in VR experiences, effective assessment methods for both arousal and valence dimensions were explored. While HRV and EDA primarily focus on arousal levels and stress, assessing the valence dimension is also essential for a more complete understanding of emotional states [12]. Based on previous research exploring valence detection approaches in VR [20, 35], we also utilized facial electromyography (f-EMG) to capture facial muscle contractions, as the face is a key source of emotional information. Facial muscle activation reflects responses to affective stimuli, and many studies utilize EMG and/or computer vision assess valence levels by recording these activations. However, VR headsets often cover the face, limiting the use of traditional facial expression recognition methods. To overcome this challenge, we use the Emteq Pro, a specialized mask designed to capture facial muscle activity while seamlessly integrating with VR headsets for accurate facial expression measurement in VR environments. Additionally, the VIVE Pro Eye headset features built-in eye-tracking capabilities, making it an ideal candidate for high-accuracy eye-related data recording in VR [1, 8].

As mentioned earlier, our approach emphasizes incorporating objective measurements to better capture emotional responses. Complementing this, a shift from explicit to implicit methods can further reduce biases associated with subjective reporting. Direct questioning, often used in subjective measures, carries the risk of socially desirable responses or inaccuracies due to participants' limited self-awareness [12]. One such implicit approach we have suggested is using time perception as a proxy for emotional states. Time perception has long been studied as an indicator of cognitive and emotional processing. For example, research [29] shows that unpleasant emotions such as fear, anxiety, or stress can significantly distort our perception of time (feel time passes slowly). This effect is thought to arise from the brain's heightened attentional focus on the environment, leading to an overestimation of time duration [13]. In the context of our study, we use time perception as a proxy to understand unconscious emotional states. For this reason, after exposure to the environment, we asked participants to estimate how long they were in the VR environment. These subjective estimations can offer indirect insights into their emotional states, as deviations from actual time (e.g., overestimating, or underestimating duration) may reflect the underlying emotional experience.

3.4 Evaluating Cognitive Restoration: Applications of ART

By focusing on ART, measuring cognitive capacity is essential to understand the effect of restorative environments. Typically, cognitive capacity is measured before and after exposure to stimuli using cognitive tasks. However, finding a suitable cognitive task that accurately measures the effect of restoration on specific cognitive domains is challenging [26]. To address this, we selected the Trail Making Test B (TMTB) to assess changes in attention capacity before and after restoration based on the review by Ohly et al. [26] on experimental designs for understanding restorative effects. Their findings highlight three dimensions of directed attention that should guide task selection: cognitive demand, direction of attentional focus, and locus of distraction. A task with high cognitive demand, balanced internal and external attentional focus, and clear external distractions is most sensitive to detecting restorative effects. TMTB aligns closely with these criteria, as it involves high cognitive demand through rule-switching while maintaining internal representations. The task engages both external (visual stimuli) and internal (rule sets) attentions, with primary distractions being external (irrelevant visuals) but also allowing for internal distractions.

A more dynamic and real-time approach compared to pre-post cognitive tasks involves using eye-tracking to monitor eye movements, providing valuable insights into visual attention, cognitive load, and arousal levels without disturbing the user's experience [1]. Eye tracking objectively assesses where users look and what captures their attention within virtual environments. By measuring eye movements such as saccades (rapid shifts) and fixations (sustained focus), eye tracking enables researchers to analyse patterns that reflect cognitive processes. For instance, highly fascinating scenes are often associated with more prolonged fixations, while less fascinating scenes typically result in more frequent eye movements as users scan their surroundings [24]. Additionally, pupil size—another measure obtained through eye tracking—serves as an indicator of arousal levels, providing insight into the user's physiological state in alignment with SRT. This can complement other methods of measuring arousal, as explained earlier, to offer a more comprehensive understanding of emotional responses in restorative environments [1].

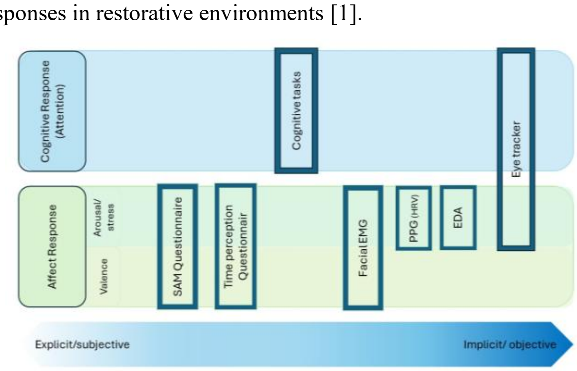

Figure 3: Illustrating measurement methods based on Restoration Theory: Cognitive and Affective Responses

In summary, the measurement tools used in our study are illustrated in Fig. 3. Sensor calibration is essential, as each application has specific requirements beyond the scope of this paper. However, it's important to note that EDA, PPG, and fEMG require baselines due to individual differences. Before the VR experience, all participants undergo at least 3 minutes of resting baseline for EDA and PPG and 2 minutes for fEMG. four emotional states—laughter, surprise, anger, and neutral—are recorded as baselines prior to the experiment. After selecting appropriate tools, data collection was completed, and the collected data will be analysed to identify key findings. While we will address the challenges encountered during the design and implementation phases, additional challenges may emerge as we delve deeper into the analysis. In the next section, we first discuss the challenges faced and then propose directions for future development

4 Challenges and Future Development

Our study faced several challenges, including integrating multiple physiological sensors with VR applications to ensure accurate and seamless data collection. Aligning subjective self-reports with objective physiological data also proved critical for validating findings. Additionally, inducing stress or cognitive load in a controlled manner and selecting suitable cognitive tasks required careful consideration. The design of the VR experiment itself posed challenges, particularly in balancing realism with experimental control.

Isolating the visual modality enables a focused exploration of restorative design principles before expanding into multisensory research. However, balancing realism and immersion is challenging, as sensory inputs like touch, and scent enhance VR presence. Future research could examine how these modalities interact with visual elements to improve restorative outcomes and enrich environmental design.

Finally, individual variability in emotional and physiological responses highlighted the need for adaptive methods to account for user differences. Future work should focus on refining sensor integration, enhancing subjective-objective alignment, and developing more adaptive, scalable, and multisensory experimental designs.

5 Conclusion

This study is designed to explore the restorative effects of a forest and an urban VR setting through the lens of two well-established theories: ART and SRT. Our primary objective is to develop an experiment that can effectively measure restorative effects, focusing on the spatial characteristics of the environments while leveraging biosignals to gauge participants' affective and cognitive responses. This study aims to offer a method for evaluating restorative features in VR before real-world implementation.

The chosen virtual environments have the potential to provide a controlled setting for isolating spatial features that are believed to influence well-being. This study also intends to identify the most effective biosignals to track physiological responses, such as heart rate variability, skin conductance, facial contraction and eye movements or a combination of which may correlate with restorative effects. The ability of VR to systematically manipulate spatial features provides a unique opportunity to examine how specific changes in a space affect emotional and physiological responses. The controlled nature of VR experimentation offers a cost-effective and flexible way to explore how environmental design influences well-being. This study serves as a foundation for future research, with findings guiding the creation of restorative physical spaces in urban and institutional settings. By testing environmental elements in VR before real-world implementation, stakeholders such as urban planners, architects, and healthcare professionals can make informed decisions about space design to promote mental health and well-being. We strive to provide a deeper understanding of how environmental design can impact human well-being and contribute to the growing field of environmental psychology.

Figure Credits

Figure 1 image credit: Layla Farmahini Farahani / VR Scenes
Figure 2 EmteqPRO adapted from Gnacek et al., (2021) [10]
Figure 3 image credit: Layla Farmahini Farahani / Summary of Methods

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