

Adaptive Cognitive Relaxation through EEG-Based Selection of 360° Real Environments: A Study Using the WAVEX EEG-VR Platform

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Abstract—Chronic stress is a growing global health concern, contributing to mental and physical disorders that reduce quality of life and productivity. In response, this study introduces a novel neuroadaptive methodology for inducing cognitive relaxation through immersive 360° real-world environments, guided by real-time brainwave analysis. Participants wore WAVEX, a custom-designed EEG-VR headset that integrates dry EEG sensors and motion tracking for seamless neurophysiological monitoring within virtual reality. Each participant was exposed to five one-minute 360° videos, during which two neural features—*Relative Gamma (RG)* power and the *Beta/Alpha Ratio (BAR)*—were computed to assess the degree of cognitive relaxation. To enhance detection accuracy and robustness, we further propose a new composite metric, the *Composite EEG Relaxation Index (CERI)*, which combines RG and BAR into a unified measure of mental relaxation. The video associated with the most relaxed brain response, as determined by these metrics, was then replayed for an additional one-minute session. Results from thirty participants demonstrated that the system consistently identified the environment that elicited the lowest arousal and highest relaxation levels. These findings highlight the potential of WAVEX as a brainwave-responsive tool for rapid, personalized stress reduction and cognitive wellness. The technology will be showcased at World Expo Osaka 2025 as a forward-looking demonstration of how neuroadaptive systems can support mental health in everyday settings.

I. INTRODUCTION

Stress and anxiety are prevalent issues worldwide, with anxiety disorders affecting approximately 301 million people in 2019, making them the most common mental health conditions [1]. Beyond individual well-being, the economic repercussions are equally concerning. Lost productivity due to depression and anxiety costs the global economy an estimated US\$1 trillion annually, a figure projected to rise to US\$6 trillion by 2030 [2]. In the United States alone, job-related stress is estimated to cost companies over US\$300 billion per year due to healthcare expenses, absenteeism, and decreased work performance [3]. These alarming statistics underscore the urgent need for effective, scalable, and user-friendly solutions to support mental health and cognitive well-being.

Immersive virtual reality (VR) has emerged as a promising tool to facilitate cognitive relaxation by transporting users to calming, interactive environments. When integrated with physiological monitoring systems such as electroencephalography (EEG), VR can be transformed into a neuroadaptive

platform that responds in real time to the user's mental state. Previous studies have explored the neural correlates of relaxation and mindfulness, identifying specific EEG features that correspond to reduced stress levels [4]. Building on these findings, our research focuses on two EEG-derived features: *Relative Gamma (RG)* power and the *Beta/Alpha Ratio (BAR)*, both of which have been shown to reliably characterize levels of cognitive engagement and relaxation.

RG power, defined as the ratio between gamma and theta-alpha activity, has been associated with meditative and emotionally regulated states [4], [5]. Meanwhile, BAR is a well-established biomarker of arousal and stress, where a lower BAR typically reflects a more relaxed state [6], [7]. Using both metrics in combination allows for a more robust and multidimensional characterization of cognitive relaxation under immersive VR conditions.

A growing body of literature supports the use of VR for stress reduction. Annerstedt et al. [8] demonstrated that exposure to natural environments in immersive VR can significantly reduce cortisol levels and self-reported stress. Tarrant et al. [9] showed that combining VR nature experiences with EEG-based neurofeedback can reduce anxiety symptoms. Navarro-Haro et al. [10] conducted clinical trials showing VR-based relaxation environments were effective in reducing physiological arousal in individuals with generalized anxiety disorder. Additionally, Wiederhold et al. [11] investigated VR-based guided meditation and found improvements in heart rate variability and subjective calmness. While these studies validate the efficacy of VR for stress relief, most employ static or pre-selected content and lack real-time adaptation based on neural responses. This limitation motivates our proposed methodology, which integrates EEG-driven dynamic content selection to personalize and optimize the relaxation experience.

In this study, we present a novel brainwave-responsive VR system using WAVEX, a custom-designed EEG-VR headset equipped with dry EEG electrodes and motion tracking capabilities. Participants were exposed to five different 360° real-world immersive environments, each lasting one minute. EEG data was collected in real time, and both RG and BAR metrics were computed for each video segment. The environment that produced the most relaxed brain response was then replayed for an additional minute to reinforce the relaxation state.

The key innovation of this work lies in the integration of neuroadaptive feedback with real 360° environments and the introduction of a new composite EEG-based metric for relaxation. Unlike prior research that predominantly relies

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on static or synthetic VR content, our system dynamically identifies the most effective relaxation environment tailored to the user’s neurophysiological state. In addition to computing Relative Gamma (RG) power and the Beta/Alpha Ratio (BAR), we propose the **Composite EEG Relaxation Index (CERI)**, a unified metric that combines both RG and BAR to enhance the robustness, interpretability, and precision of relaxation detection. This neuroadaptive approach enables rapid personalization and improves the system’s capacity to assess and reinforce cognitive relaxation in real time.

In the following sections, we describe the experimental methodology (Section 2), the EEG signal processing pipeline (Section 3), the obtained results (Section 4), and a discussion of findings and future implications in (Sections 5 and 6).

II. MATERIALS AND METHODS

A. Wavex

The system developed for this study is based on the **WAVEX EEG-VR** platform, a custom-designed headset that integrates electroencephalography (EEG) sensing and immersive virtual reality capabilities into a single wearable device. WAVEX was developed by the Mirai Innovation Research Institute (Osaka, Japan) as a research tool for advancing neurotechnology applications. It has been utilized in a variety of projects spanning wellness (e.g., relaxation and stress management), healthcare (e.g., cognitive training for elderly adults), education (e.g., neurofeedback-based learning), and entertainment (e.g., adaptive content based on cognitive engagement).

The device is equipped with eight dry EEG electrodes positioned according to the international 10–20 system at the following scalp locations: F3, Fz, F4, C3, C4, P3, Pz, and P4. This configuration enables monitoring of key brain regions involved in attention, relaxation, and cognitive processing. EEG signals are acquired in real time and transmitted wirelessly via the Lab Streaming Layer (LSL) protocol to a custom software platform that computes a relaxation metric based on relative gamma (RG) power, the Beta/Alpha Ratio (BAR) and the Composite EEG Relaxation Index (CERI).

The VR environment is developed using the Unity engine and includes five high-resolution 360° panoramic video experiences, each designed to promote a sense of calm and immersion. The available scenes are: (1) a tranquil beach, (2) a lush green forest, (3) a traditional Japanese temple, (4) an underwater marine environment, and (5) a cosmic outer space experience. Participants are exposed to each of the five videos in sequence, with the EEG-based analysis identifying the environment that elicits the highest relaxation response. This selected environment is subsequently replayed for an extended minute to reinforce the cognitive relaxation effect.

B. Subjects

A total of 30 healthy young adults participated in the study (17 males, 13 females; mean age = 25.2 years, SD = 3.1; age range: 20–27 years). All participants reported having normal or corrected-to-normal vision. Only three participants had prior experience using a virtual reality headset. None

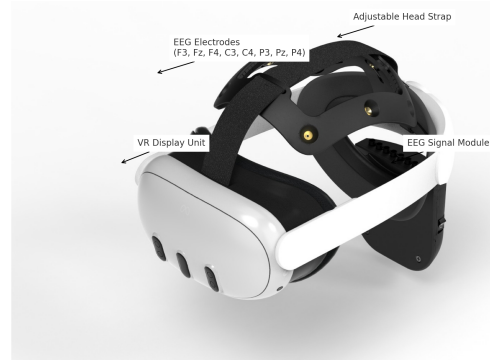


Fig. 1. WAVEX EEG-VR headset developed by Mirai Innovation Research Institute. The system integrates eight dry EEG electrodes (F3, Fz, F4, C3, C4, P3, Pz, P4) into the head strap, allowing real-time brainwave acquisition. The headset includes a VR display unit and a signal module that streams EEG data via the Lab Streaming Layer (LSL) protocol.

of the participants reported any history of neurological or psychiatric disorders, nor were they undergoing medical treatment at the time of the experiment. Informed consent was obtained from all participants, and the study was conducted in accordance with institutional ethical guidelines.

C. Experiment Setup

1) *Preparation*: Before the experiment began, each participant was comfortably seated in a quiet, dimly lit room to minimize external distractions. Participants were fitted with the WAVEX EEG-VR headset, ensuring proper electrode contact at the eight designated locations. The headset was adjusted for comfort and stability using the built-in adjustable straps (Fig.2).

Participants received a detailed verbal explanation of the experimental procedure, including the purpose of the study, the use of EEG and VR technologies, and the sequence of tasks involved. They were instructed to relax, minimize body movements, and remain as still as possible during recordings to reduce motion artifacts. The system was calibrated, and a brief test was conducted to ensure signal quality and participant readiness before proceeding with the experimental protocol.

2) *Collection of EEG Signals*: EEG signals were collected from electrodes positioned according to the international 10–20 system at the following locations: F3, Fz, F4, C3, C4, P3, Pz, and P4. The sampling frequency was set to 250 Hz. Reference electrodes for each channel were placed on the left and right mastoids. Electrode impedance was maintained below 5 k Ω for all channels. Participants were instructed to minimize abrupt head movements and rapid eye-blinking to reduce noise and motion artifacts.

3) *Data Processing*: EEG data acquired from the WAVEX headset were pre-processed to remove noise and physiological artifacts. A notch filter at 60 Hz was applied to eliminate power line interference, followed by a bandpass filter between 0.5–60 Hz to remove high-frequency noise and slow signal drifts. To reduce contamination from eye movement and other non-cerebral sources, Independent Component

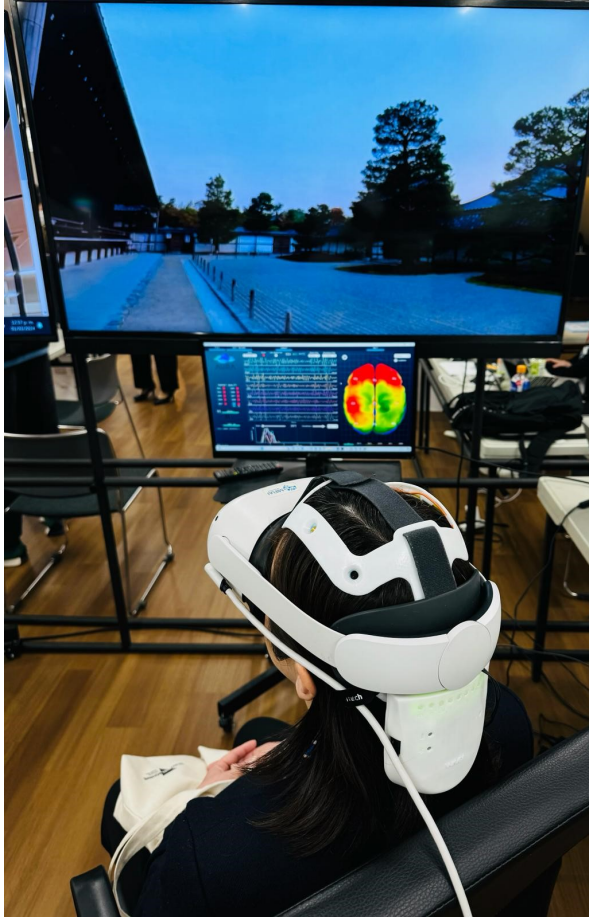


Fig. 2. WAVEX setup: The participants were fitted with the WAVEX EEG-VR headset, ensuring proper electrode contact at the eight designated locations. The headset was adjusted for comfort and stability using the built-in adjustable straps.

Analysis (ICA) was performed. Components corresponding to electrooculogram (EOG) artifacts—typically characterized by high energy in the low-frequency band and symmetric distribution across the prefrontal region—were identified and removed.

Power Spectral Density (PSD) analysis was conducted using the short-time Fourier transform (STFT), enabling time-resolved frequency analysis across five standard EEG bands: delta (δ , 1–4 Hz), theta (θ , 4–8 Hz), alpha (α , 8–12 Hz), beta (β , 12–30 Hz), and gamma (γ , 30–60 Hz). Spatial normalization was applied to each channel by rescaling PSD values between 0 and 1, ensuring comparability across participants and sessions. Electrodes at prefrontal (FP), temporal (T), and occipital (O) sites were excluded due to their known susceptibility to ocular, auditory, and visual artifacts, respectively.

Three EEG-derived metrics were computed to quantify relaxation:

(1) Relative Gamma (RG) Power:

$$RG = \frac{AvgPower(25-45 \text{ Hz})}{AvgPower(4-13 \text{ Hz})}$$

This ratio compares gamma-band activity with combined

theta–alpha activity, highlighting the balance between cognitive engagement and relaxed attention. It has been validated in previous studies involving meditation and mindfulness as a reliable indicator of reduced cognitive effort and enhanced calmness [4], [5].

(2) Beta/Alpha Ratio (BAR):

$$BAR = \frac{AvgPower(13-30 \text{ Hz})}{AvgPower(8-12 \text{ Hz})}$$

This metric captures the relationship between beta-band activity (typically associated with alertness, stress, or anxiety) and alpha-band activity (often linked to calm and relaxed states). A lower BAR has been associated with reduced arousal and improved emotional regulation in stress detection studies [6].

Together, these two metrics provide complementary views of relaxation: RG captures reductions in cognitive workload and attentional demand, while BAR reflects reduced physiological arousal. By combining them, the system enhances sensitivity to diverse manifestations of cognitive relaxation during VR exposure.

(3) Composite EEG Relaxation Index (CERI):

To enhance the robustness and sensitivity of cognitive relaxation detection, we propose a novel combined metric: the **Composite EEG Relaxation Index (CERI)**. This metric integrates two complementary EEG features—Relative Gamma (RG) and the Beta/Alpha Ratio (BAR)—into a single, unified index:

$$CERI = \frac{1}{2} \left(\frac{1}{RG} + \frac{1}{BAR} \right)$$

This combined index offers several advantages over the use of RG or BAR alone:

- **Complementary Sensitivities:** RG captures the balance between gamma activity (associated with cognitive effort) and theta–alpha rhythms (linked to relaxed attention), while BAR reflects arousal via beta and alpha power. CERI combines both to account for cognitive and affective dimensions of relaxation.
- **Noise Robustness:** EEG signals are prone to artifacts in specific frequency bands (e.g., gamma muscle artifacts or beta EMG contamination). By averaging inverses of both ratios, CERI provides redundancy and increases stability in the presence of noise.
- **Interpretability:** The inverse formulation ensures that higher CERI values consistently represent greater relaxation. This simplifies thresholding for real-time classification in neuroadaptive applications.
- **Computational Efficiency:** The metric is simple to compute and well-suited for real-time implementations on systems like WAVEX.

Overall, the Composite EEG Relaxation Index serves as a holistic and interpretable metric for detecting relaxation states during immersive VR, supporting both precision and real-time adaptability in neurofeedback-driven environments.

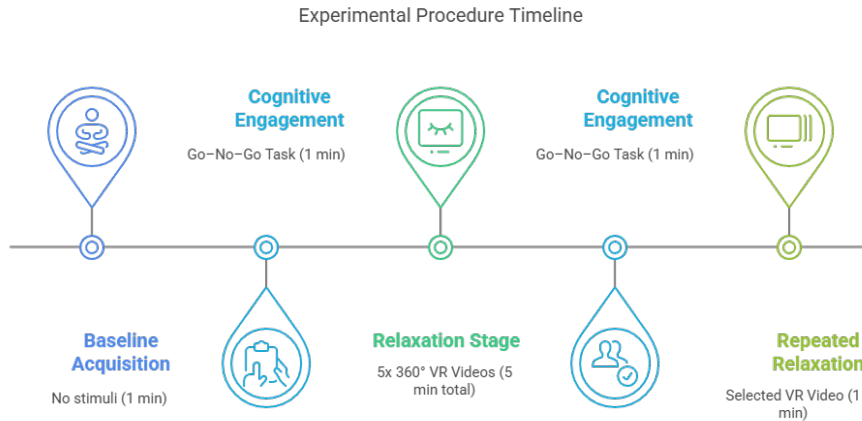


Fig. 3. Experimental protocol timeline illustrating the five sequential stages used in the study: (1) Baseline Acquisition with no stimuli, (2) Cognitive Engagement I using a Go–No–Go task to stimulate attention, (3) Relaxation Stage with exposure to five different 360° VR environments (beach, forest, Japanese temple, underwater, and space), (4) Cognitive Engagement II using the Go–No–Go task to reintroduce attentional demand, and (5) Repeated Relaxation using the VR environment that elicited the most relaxed EEG response based on Relative Gamma (RG) and Beta/Alpha Ratio (BAR) metrics.

D. Experimental Protocol

Participants underwent a structured experimental protocol designed to elicit distinct mental states and assess the effectiveness of EEG-based environment selection for inducing relaxation. The protocol consisted of five consecutive stages shown in Fig. 3.

- 1) **Baseline Acquisition:** Participants sat quietly with their eyes open while no external stimuli were presented. This stage served as a reference to capture natural resting-state EEG activity.
- 2) **Cognitive Engagement I:** Participants performed a Go–No–Go task using PsyToolKit [12], a well-established paradigm designed to stimulate cognitive control and attentional demand. In this task, participants were instructed to respond as quickly as possible to “Go” stimuli while inhibiting responses to “No–Go” stimuli, engaging frontal regions associated with executive function and response inhibition.
- 3) **Relaxation Stage:** A 360° immersive virtual reality environment was presented through the WAVEX system. Participants experienced five natural and calming panoramic scenes—beach, forest, Japanese temple, underwater, and space—each lasting one minute and shown in a pre-defined order. EEG features, including Relative Gamma (RG) and Beta/Alpha Ratio (BAR), were calculated for each scene in real time. The environment producing the most relaxed EEG signature was selected for replay.
- 4) **Cognitive Engagement II:** Participants performed a second round of the Go–No–Go task, identical in structure to the previous engagement stage. This was intended to reintroduce cognitive load and allow assessment of how relaxation exposure may influence neural patterns during subsequent cognitive activity.

- 5) **Repeated Relaxation:** The video identified as most relaxing in the earlier VR stage was replayed for an additional one-minute session, enabling evaluation of short-term relaxation reinforcement following re-engagement.

This protocol was designed to systematically modulate participants’ cognitive and affective states, alternating between rest, engagement, and relaxation phases. The inclusion of two cognitive engagement sessions allowed us to examine pre- and post-relaxation neural responses under identical cognitive load conditions. This approach supports a more robust analysis of WAVEX’s ability to induce measurable relaxation effects, identify optimal environments based on EEG features, and promote short-term cognitive recovery through personalized VR exposure.

III. RESULTS

To evaluate the effectiveness of EEG-based relaxation detection in our neuroadaptive VR system, we analyzed three metrics: Relative Gamma (RG), Beta/Alpha Ratio (BAR), and our proposed Composite EEG Relaxation Index (CERI). Each metric was computed across nine experimental conditions: Baseline, Cognitive Engagement I, Video 1–5, Cognitive Engagement II, and the Selected Video, which was determined by the system as the most relaxing.

The results are presented as boxplots for each metric, offering a visual comparison of their distribution and central tendency across participants and conditions. This format was selected to emphasize inter-individual variability and to identify trends in relaxation and engagement levels over time.

Figure 4 shows the distribution of RG values, with lower values indicating higher relaxation. Figure 5 displays BAR, where again, lower values are expected in more relaxed conditions. Figure 6 illustrates the CERI metric, where

higher values reflect enhanced cognitive relaxation ($p < 0.015$) compared to previous metrics.

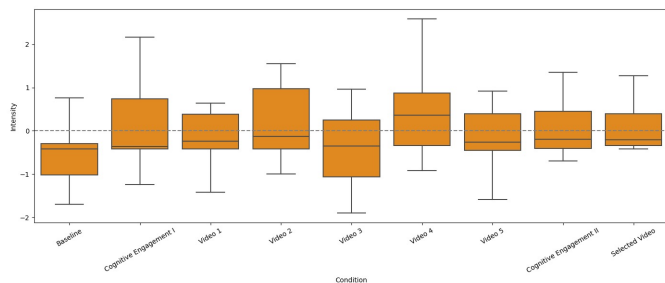


Fig. 4. Distribution of Relative Gamma (RG) values across experimental conditions. Lower RG values indicate increased relaxation.

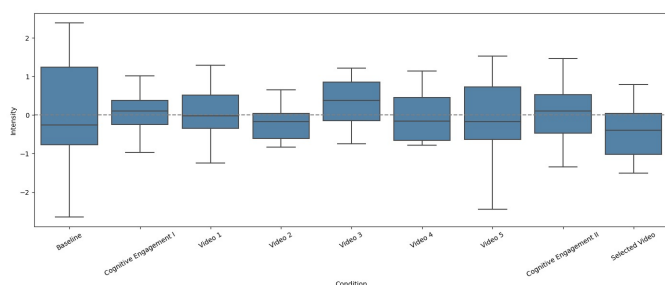


Fig. 5. Distribution of Beta/Alpha Ratio (BAR) across conditions. Lower BAR values are associated with lower arousal.

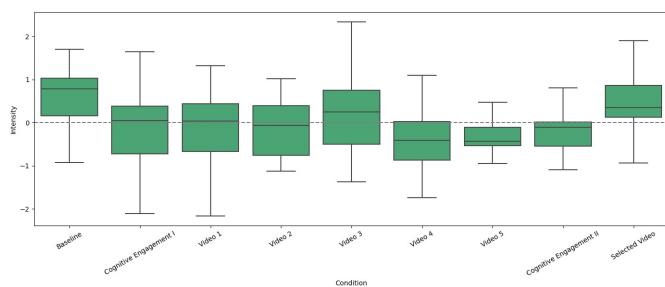


Fig. 6. Distribution of Composite EEG Relaxation Index (CERI) across conditions. Higher values indicate increased relaxation.

IV. DISCUSSION

The results show that the Selected Video condition consistently yielded the lowest RG and BAR values and the highest CERI score. This confirms the effectiveness of our system in selecting the most relaxing environment based on EEG dynamics.

While both RG and BAR independently demonstrated sensitivity to task-related changes in cognitive load and arousal, they also presented variability across conditions. CERI, by combining both indicators into a unified metric, offered more robust and consistent detection of cognitive relaxation. The higher CERI values in the Selected Video condition align with our hypothesis that a composite index improves interpretability and real-time application.

In conclusion, the CERI metric provided a clearer and more reliable assessment of relaxation, especially when compared across diverse VR environments and participant responses. These findings support the integration of composite EEG metrics into adaptive neurotechnology systems for personalized stress reduction.

V. CONCLUSION

This study demonstrated the feasibility of using a neuroadaptive system to induce cognitive relaxation through immersive VR, guided by real-time EEG analysis. By introducing the Composite EEG Relaxation Index (CERI), which combines Relative Gamma and Beta/Alpha Ratio, we achieved a more robust and interpretable metric for evaluating short-term relaxation.

Our findings highlight the value of EEG-based personalization in selecting relaxing environments and support the integration of real-time neurofeedback in mental wellness technologies. The consistently higher CERI values for the Selected Video condition validate the potential of adaptive VR systems to deliver effective relaxation experiences tailored to individual brain responses.

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