Fusion of virtual reality with wearable real-time EEG neurofeedback for mindfulness meditation enhancement: an accessible tool for neurocognitive modulation

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Abstract: Virtual reality (VR) combined with real-time Brain-Computer Interface (BCI) technology is a promising but underexplored area. Neurofeedback-driven VR could revolutionize treatments for mental health and chronic conditions by harnessing immersive experiences and real-time brain activity monitoring. This approach targets the Default Mode Network (DMN), often deregulated in conditions like depression, anxiety, and Alzheimer's disease. Mindfulness-based therapies, known to affect the DMN, are effective but require specialized expertise. This project aims to democratize access with a home-based VR tool, validated by neurophysiological data, to induce and maintain mindfulness through emotional regulation in real time.

Target brain region: Default Mode Network

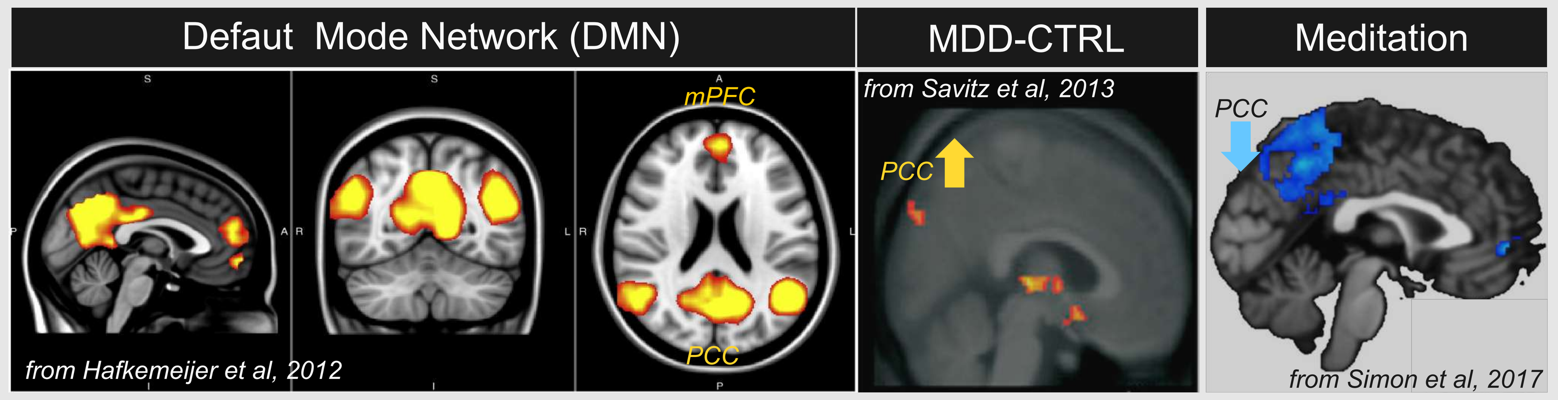


Figure 1: Defaut Mode Network (DMN) includes key regions like the posterior cingulate cortex (PCC), medial prefrontal cortex (mPFC), and the angular gyrus, key nodes implicated in ruminative cognitions. Dysregulation of the DMN is associated with overactivity in depression and anxiety, abnormal connectivity in Alzheimer's, while mindfulness meditation reduces DMN hyperactivity, promoting present-moment awareness.

Biomarker collection

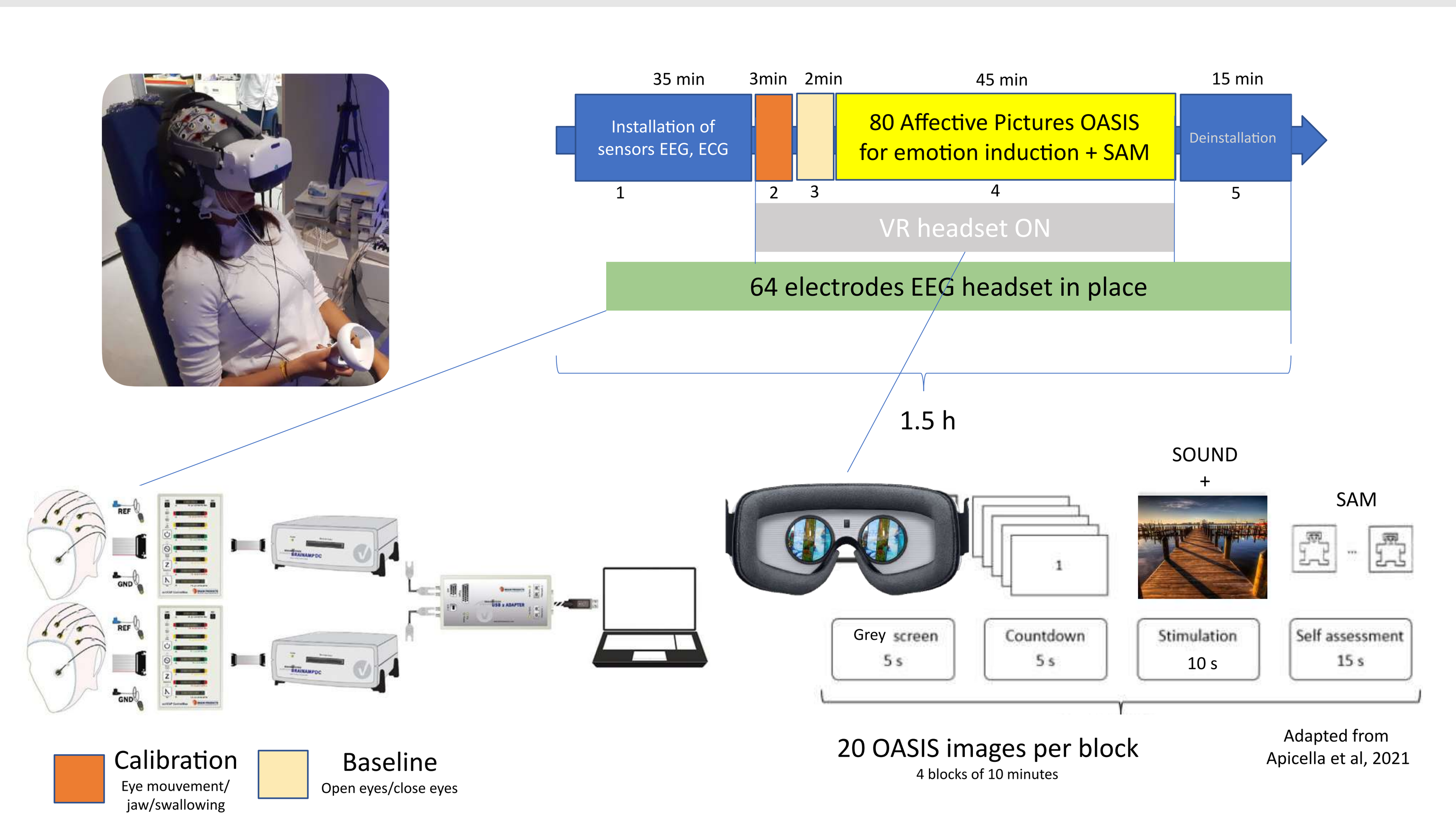
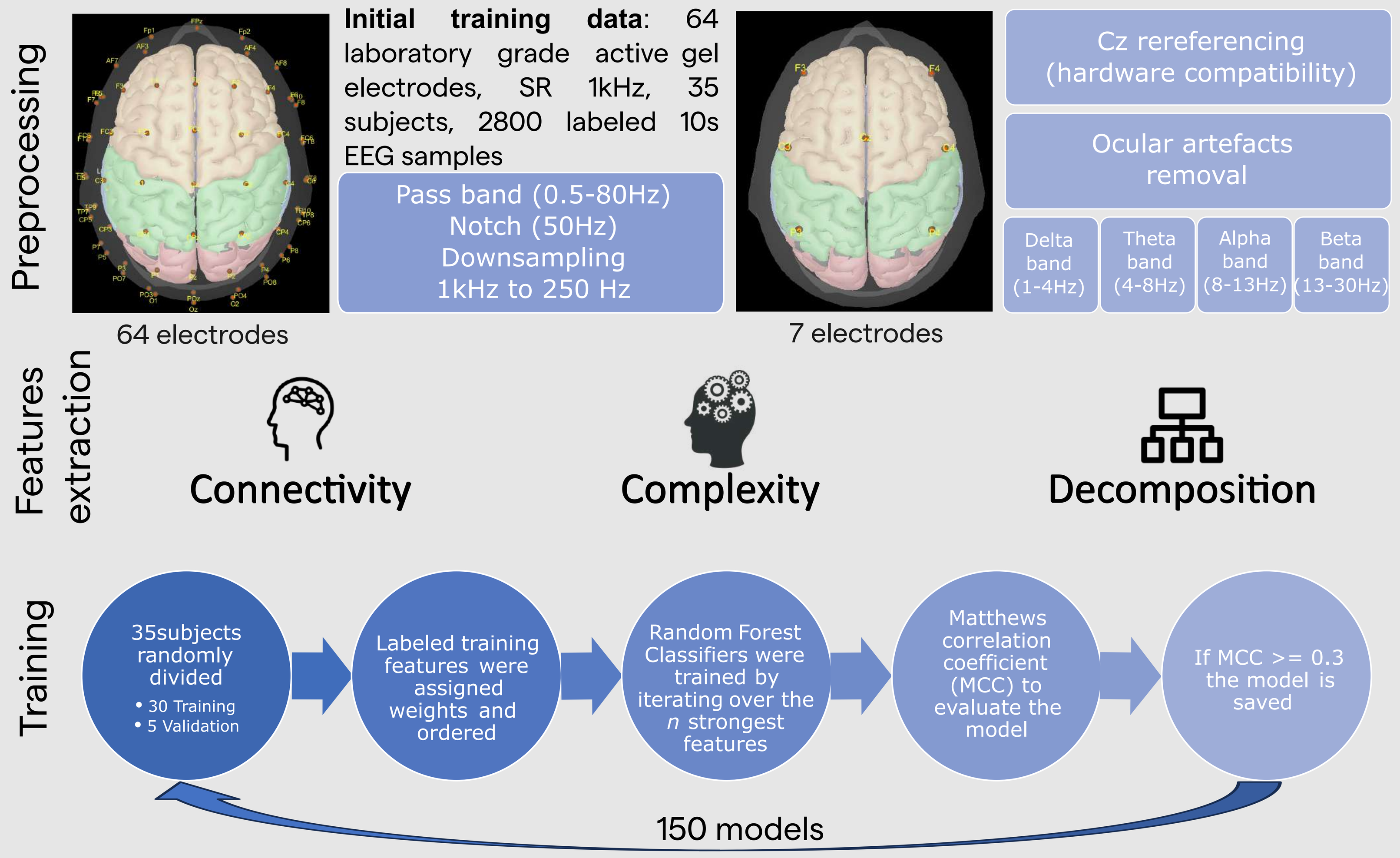


Figure 2: Experimental design The emotion induction procedure involved participants passively viewing affective images for 10 seconds in a virtual reality headset, with corresponding ambient sounds played through noise-canceling headphones. Each of the 80 trials, divided into 4 blocks, included image projection followed by self-assessment using the SAM questionnaire to rate valence and arousal. A short countdown was used between images for washout. Images were randomly selected from 900 in the OASIS database to cover the full emotional spectrum, excluding extreme stimuli, to align with future VR solution scenarios. 35 healthy participants (18 women) between 18 and 65 years old were included.

EEG feature extraction via machine learning



Validation of arousal classifiers

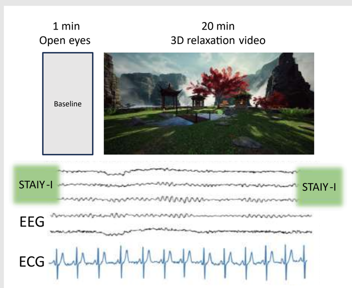
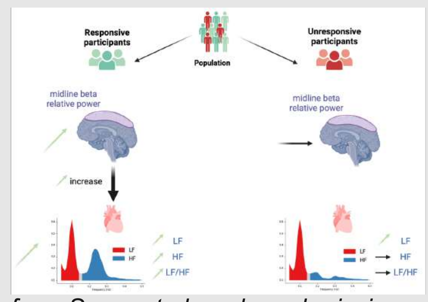


Figure 3: Experimental design Participants viewed a 20-minute immersive 3D VR therapeutic video (Healthy Mind™), with proven anxiety-reducing effects. Before the video, participants underwent a 1-minute open-eye gray screen baseline.

Anxiety levels were assessed using the short form of the State-Trait Anxiety Inventory (STAI-Y1) before and after the video. EEG and ECG data were collected throughout the experiment.



from Sezer et al, under submission

Figure 4: 60% of participants ('responsive') experienced reduced anxiety post-intervention, while 40% ('unresponsive') showed no improvement. All participants displayed increased low-frequency power, but only responders exhibited heightened autonomic tone, midline beta power, and brain-heart connectivity.

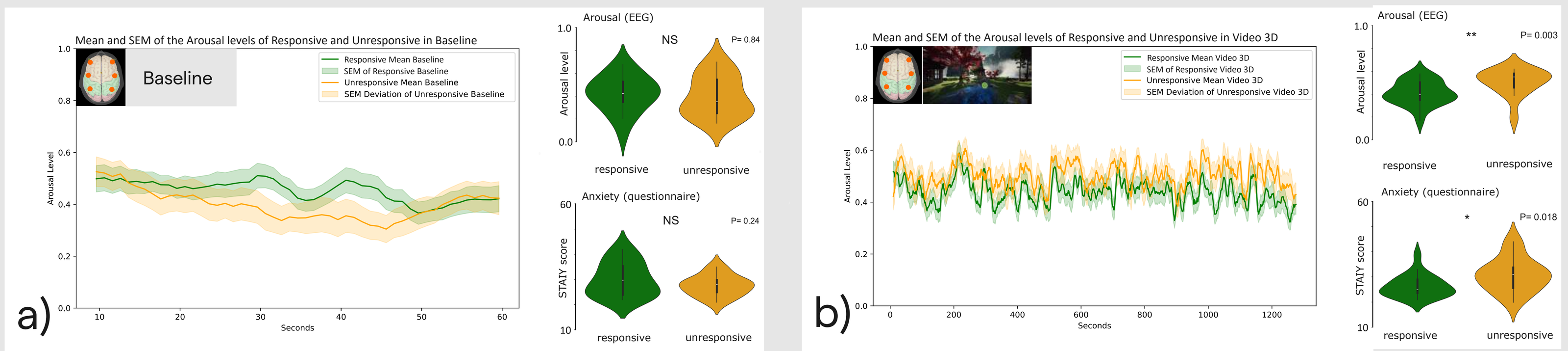


Figure 5: Psychometric validation of EEG based classifiers: (a) predicted baseline arousal is not significantly different between responders (n=20) and non-responders (n=14) matching with the STAI-Y1 questionnaires anxiety results; **(b)** predicted arousal during 3D video significantly decreased for the responders (n=20) compared to the non-responders (n=14) matching with the STAI-Y1 questionnaires anxiety results done right after the video (Mann-Whitney U test)

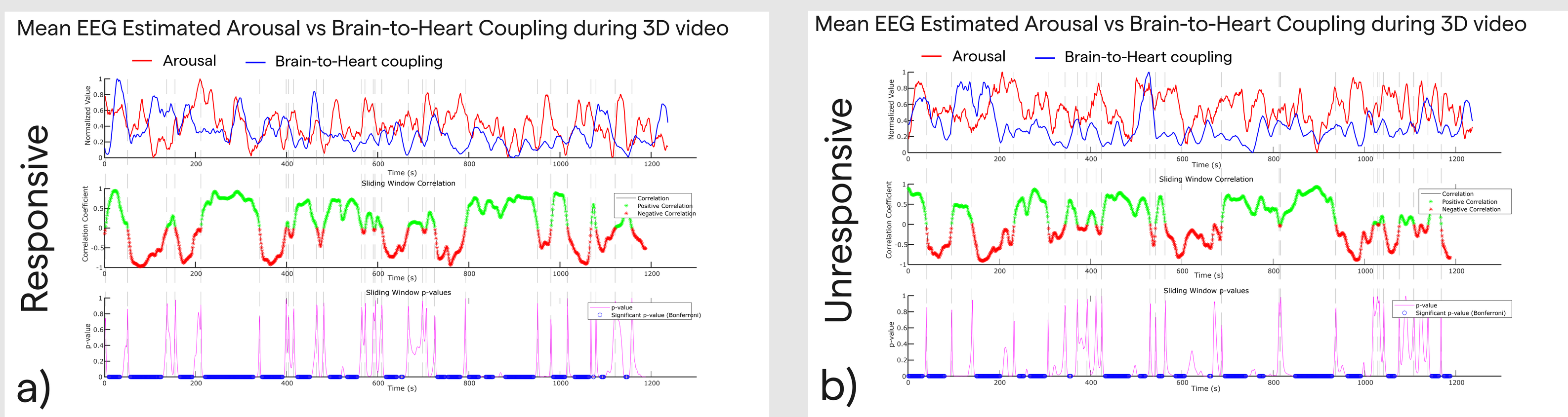


Figure 6: ECG-related validation of EEG-based classifiers: Significant correlation observed approximately 75% of the time between the arousal 6-electrode EEG prediction and brain-to-heart coupling (midline beta to High Frequency HRV) across a 30-second sliding window both for responsive (a) and unresponsive (b) groups. Negative correlation with High Frequency HRV generally coincides with positive correlation with Low Frequency HRV. Pearson correlation coefficients are reported, with Bonferroni correction applied for multiple comparisons.

Prototype and interface

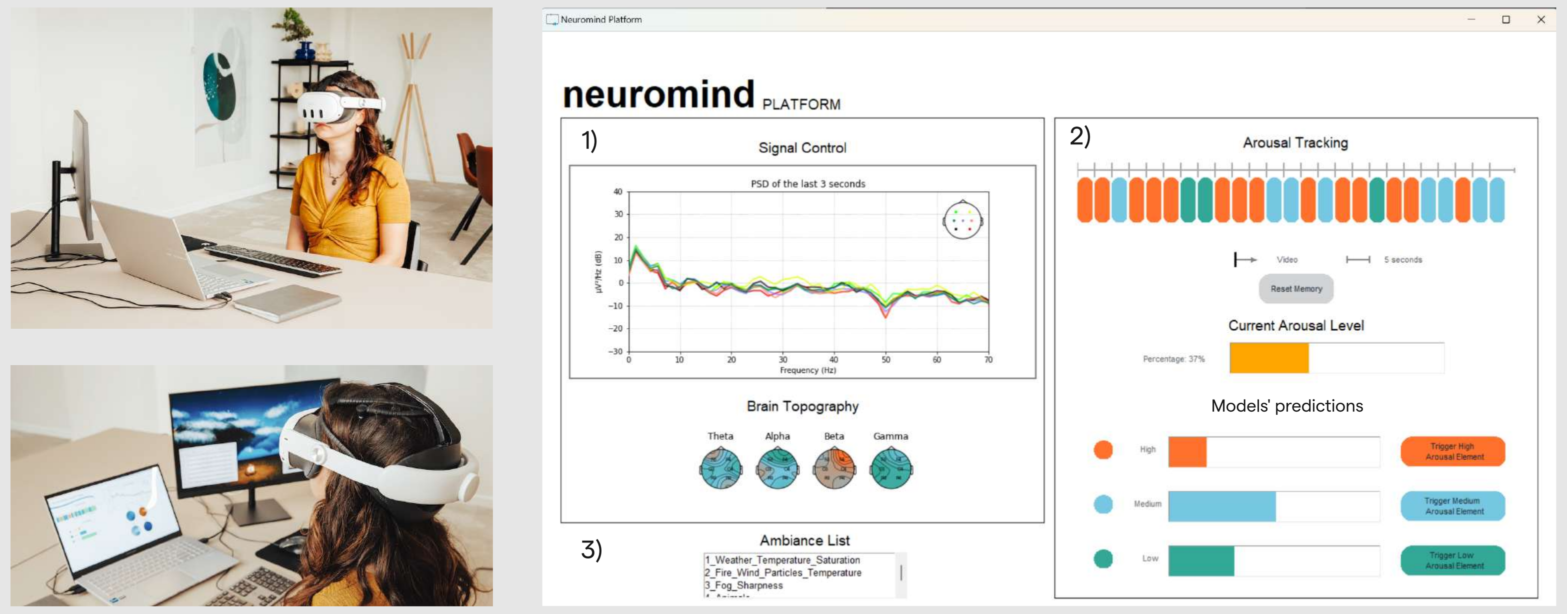


Figure 7: The Neuromind prototype consists of three synchronized hardware components: EEG headset (X.On, Brain Products™), VR headset (Oculus), and a PC. The software includes an AI-based interface with three main components: ① signal quality control and preprocessing, ② brain state tracking and interpretation, and ③ virtual environment management.

VR active feedback elements

Arousal levels: low medium (target state) high

Figure 8: dynamic ambiances and active feedback elements
The 3D immersive VR environments are modulated every 5 seconds based on real-time EEG-based arousal estimation over the previous 10 seconds.
Feedback elements reflect the user's current arousal state, with the most balanced environment corresponding to the target medium arousal state.
To optimize engagement and arousal control, the environments are divided into dynamic ambiances with distinct feedback elements. Transitions between ambiances depend on the user's ability to reach and maintain the target arousal state.

State induction elements (boosters)

To induce arousal levels:
low medium (target state) high

Figure 9: Arousal inducing stimuli
In addition to active neurofeedback control of arousal, stimuli can be introduced to the 3D environment to induce specific arousal states: a breath control sphere to decrease arousal, a focused attention element to induce medium arousal, and a sudden surprising element to increase arousal.

Conclusion: Our study demonstrates the feasibility of using neurofeedback-driven VR based on real-time estimation of arousal states from low-density EEG. By integrating emotional reactivity monitoring with immersive VR environments, we developed a compact tool capable of inducing and sustaining a target attentional state. This system offers a scalable and accessible solution for both addressing mental health conditions linked to DMN dysregulation, such as depression and anxiety, and for research protocols studying neurocognitive modulation. These findings underscore the potential of VR-BCI technology for neuromodulation in mental health treatments and cognitive research.

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