Virtual Reality-Enhanced Neurofeedback: Training Mechanisms, System Components, and Prospects for Cognitive and Neural Rehabilitation

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Abstract

The integration of virtual reality (VR) with electroencephalography (EEG)-based neurofeedback represents a significant advancement in cognitive training and neural rehabilitation. This article examines the training mechanisms of neurofeedback across key EEG frequency bands, slow cortical potentials (SCP), theta (4–7 Hz), alpha (8–13 Hz), sensorimotor rhythm (SMR, 12–15 Hz), and beta (14–30 Hz) detailing their physiological origins, electrode locations, targeted therapeutic effects, and applications in conditions such as epilepsy, attention-deficit/hyperactivity disorder (ADHD), anxiety, depression, and mild cognitive impairment.

It is demonstrated how VR overcomes the limitations of conventional neurofeedback environments, monotony, low adherence, and limited adaptability, by providing immersive, interactive, and multi-sensory settings that enhance motivation, brain self-regulation, and neuroplasticity. The typical architecture of VR-supported neurofeedback systems is described, including EEG acquisition and processing, VR control module, and real-time feedback delivery.

Reviewed evidence indicates that VR augments specific cortical activation, accelerates neuroplastic changes, and improves outcomes in psychological and neurological rehabilitation, while enabling application in clinical, educational, and home-based contexts. Nevertheless, technical challenges persist, including hardware latency,

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algorithmic precision, and cybersickness.
In conclusion, the VR–neurofeedback synergy constitutes a promising evolution in brain–computer interface applications, offering greater efficacy, accessibility, and personalization. Longitudinal studies and technical refinements are required to fully realize its therapeutic potential.

INTRODUCTION

Virtual reality (VR) is a computer simulation technology that enables users to experience sensations approaching reality in a virtual world (Halarnkar et al., 2012). The integrated virtual environment it generates, encompassing visual, auditory, tactile, olfactory, and gustatory senses, provides users with a highly immersive experience. Compared to traditional computer technologies, VR offers a more natural human-computer interaction method, emphasizing the dominant role of humans in such interactions (Gao et al., 2016). In recent years, with the rapid development of VR technology featuring advantages such as immersion, interactivity, and multi-sensory capabilities, VR has been increasingly applied in medical education, patient analysis, and clinical treatment. The benefits of VR-supported cognitive training and neural rehabilitation are becoming more prominent (Tan et al., 2020) In contrast to traditional simple and monotonous external training environments, VR training scenarios not only provide users with real-time multi-sensory stimulation feedback and visualized training data but also break the limitations of conventional training venues, allowing users to complete training in various locations such as hospitals, schools, and homes (Lüddecke, & Felnhofer, 2022).
Neurofeedback, built on the foundation of brain research and applications, is a form of biofeedback training and has become an important direction in research related to brain-computer interface (BCI) technology (Lalanza et al., 2023) Neurofeedback uses electroencephalography (EEG) signals as feedback control signals, treating the user's brain as the subject of learning and training. Neurofeedback training helps the user's brain learn to achieve its goals in an appropriate manner, with the ultimate objective of reconfiguring the brain's structure and function to improve cognitive abilities such as memory, attention, processing speed, or executive function. These improvements in cognitive abilities can be applied not only to the treatment of psychological disorders such as autism, depression, and anxiety but also to rehabilitation training, inducing neuroplastic changes, and promoting the recovery of damaged neural pathways. Compared to traditional brain function enhancement methods, such as behavioral therapy, medication, and physical stimulation (Tosti et al., 2024) neurofeedback training is more targeted and yields more significant enhancement effects.
Currently, the design of external training environments for neurofeedback systems is relatively simple, mostly using computer screens to provide visual feedback, and the training process is monotonous and tedious, resulting in low user engagement and a considerable proportion of users unable to properly regulate their brain activity. This article analyzes the training mechanisms of neurofeedback technology, summarizes and analyzes the feedback methods of VR technology in neurofeedback training; discusses the advantages and challenges of VR technology in neurofeedback training; and finally points out the future development directions of VR technology in neurofeedback training.

Neurofeedback Training Mechanisms

To help users enhance brain activity and thereby produce more prominent EEG features, training involves increasing or decreasing activity (maximum amplitude, relative power) in one or more EEG frequency bands or the ratio of activities across different frequency bands at a specific electrode position, serving as a real-time feedback reference for training effects (Cheng et al., 2024) VR technology can present users with varying degrees of multi-channel sensory stimulation in virtual training environments, enhancing/suppressing specific EEG features through repetitive training, activating specific brain cortices, and assisting users in producing transient or even permanent neural functional changes in specific neuronal systems, namely neuroplastic changes, thereby achieving better training outcomes. (Berman et al., 2025) implanted microelectrodes into rat brain neurons and found that VR enhanced specific brain rhythms and altered rat brain neurons, confirming that VR can be used to enhance or control specific EEG features and promote neuroplastic changes. VR technology not only opens new perspectives in the design of neurofeedback training but also provides new ideas in studying human interactions with the external world. It holds significant importance for researching brain rhythms and designing neurofeedback training mechanisms.
This section introduces the characteristics and training mechanisms of individual frequency bands such as slow cortical potential (SCP), theta waves (θ, 4~7 Hz), alpha waves (α, 8~13 Hz), sensory-motor rhythm band (SMR, 12~15 Hz), and beta waves (β, 14~30 Hz), as shown in Table 1.

Table 1: Classification of Neurofeedback System Training Mechanisms

Training Mechanism	EEG Range/Hz	Corresponding Electrodes	Training Effects
SCP	0.01~2	Cz	Healing
θ	4~7	Cz	Calm, relaxation
α	8~13	O1, O2	Relaxation, focus
SMR	12~15	C3, C4, Cz	Healing, sleep
β	14~30	Cz, C3	Alertness, focus

Source: Author's own elaboration (2026)

1.1 SCP Feature Training Mechanism

SCP represents the positive or negative polarization of electroencephalogram changes, originating from depolarization of apical dendrites in the upper cortical layers, induced by synchronous discharge, primarily from thalamocortical sources; consequently, the SCP extracted from EEG signals at the Cz electrode is the most prominent (Patil et al., 2022). The duration of SCP ranges from 0.5 to 10.0 seconds, with a frequency range typically between 0.01 and 2.00 Hz. Functionally, SCP establishes a threshold regulation mechanism for local excitation (negative SCP) or inhibition (positive SCP) within cortical networks. Through SCP training, immediate feedback and positive reinforcement can be provided for self-generated slow potential shifts, enabling individuals to learn autonomous regulation of these potentials. Following mastery of self-regulation for negative SCP, improvements in motor and cognitive performance across various tasks are observed. For instance, in epilepsy treatment training, SCP serves as an indicator of cortical excitability; SCP training can elevate the threshold of the positive SCP reflex, effectively diminishing cortical excitability. Patients with epilepsy, through SCP training, can autonomously induce excitatory cortical inhibition (i.e., positive SCP), thereby interrupting seizure episodes (Orban et al., 2022).

1.2 θ Feature Training Mechanism

The θ rhythm exhibits a frequency of 4 to 7 Hz, with an average amplitude ranging from 10 to 40 μV. As age advances, the quantity of θ waves in the brain gradually diminishes; in healthy adults, electroencephalograms display only minimal θ waves, though they may emerge for nearly 20 seconds during emotional suppression, particularly in states of disappointment or frustration. θ waves increase during fatigue or upon falling asleep, and they constitute common waveforms in senescence and pathological conditions (Liwei, 2024). Accordingly, training typically focuses on suppressing θ rhythms to modulate brain activity. The specific approach involves setting a low neurofeedback threshold; when the subject's θ rhythm reaches this threshold, users are prompted through feedback training to suppress the θ rhythm, ultimately promoting cerebral calmness and cessation of rumination. Furthermore, in patients with mild cognitive impairment or Alzheimer's disease, enhancement of abnormal θ rhythms is associated with greater cognitive deficits; thus, aberrant θ activity can predict the progression of mild cognitive impairment or dementia. Normalization of θ rhythms is also linked to enhancements in cognitive abilities (Lombardo, 2024).

1.3 α Feature Training Mechanism

The α rhythm constitutes the primary frequency in human electroencephalograms and is the most commonly utilized EEG feature in neurofeedback training. The α rhythm spans 8 to 13 Hz, with an average amplitude of 30 to 50 μV; it represents the resting rhythm of the visual system, distributed in the parieto-occipital region, manifesting as sinusoidal waveforms. A characteristic of α rhythm is the emergence of a "peak" in spectral analysis within its frequency range, most evident during wakeful relaxation with eyes closed, and most readily observed in posterior scalp regions (Zaferiou et al., 2025). α rhythm activity correlates with reduced brain activation levels, indicating a relaxed state; thus, α activity was initially regarded as an indicator of relaxation, facilitating the attainment and maintenance of this state to mitigate negative emotional influences such as stress, anxiety, and disappointment. Some studies subdivide α rhythm into high-frequency and low-frequency sub-bands, each selectively responding to distinct task demands. High-frequency α rhythm ranges from 10 to 12 Hz, representing the typical parieto-occipital resting rhythm and reflecting states of relaxation and meditation; low-frequency α rhythm spans 8 to 10 Hz and is associated with emotions of tension, excitement, and vigilance (Khanghah et al., 2023).
The aforementioned research outcomes demonstrate that α rhythm activity in EEG signals correlates with cognitive performance; α rhythm plays a positive role in cognitive processing and self-regulation. Neurofeedback training targeting α features facilitates fuller realization of human creativity and executive capabilities, enhancing cognitive abilities such as working memory, attention, and visuospatial skills. (Jensen & Bonnefond, 2026)

1.4 SMR Feature Training Mechanism

SMR constitutes a highly distinctive oscillatory pattern occurring over the sensorimotor cortex, with a frequency range of 12 to 15 Hz. SMR represents the resting rhythm of the motor system, reflecting the cerebral intent to maintain stillness, measurable at electrodes C3, Cz, and C4 overlying the sensorimotor cortex. Ribeiro et al., (2023) induced SMR rhythm in cats through experiments training feeding behaviors; cats subjected to neurofeedback training became calmer and less active, with EEG measurements revealing a marked increase in SMR rhythm. Subsequently, Pourbehbahani et al., (2023) during investigations into the toxicity of monomethyl hydrazine (MMH), randomly assigned these cats to MMH fuel resistance experiments. MMH fuel induces hallucinations, nausea, and seizures; analysis of training data unexpectedly revealed that ordinary cats exposed to MMH experienced seizures, whereas those trained with SMR neurofeedback exhibited exceptional resistance to MMH toxicity, indicating that SMR training conferred enhanced toxin resistance. This finding inspired the application of SMR training in reducing epileptic seizures. Functionally, SMR aligns with SCP neurofeedback objectives, both elevating the positive SCP reflex threshold to diminish cortical excitation. Patients with epilepsy, through SMR feature training, can reduce cortical excitability, thereby effectively lowering seizure rates. SMR feedback protocols may also improve behaviors in patients with attention deficit hyperactivity disorder (ADHD) and attention deficit disorder (ADD), as well as enhance sleep quality in healthy populations. (Ribeiro et al., 2023)

1.5 β Feature Training Mechanism

The β rhythm is a frequently employed EEG feature in neurofeedback training, with a frequency range of 14 to 30 Hz and an average amplitude of 5 to 30 μV, commonly observed in frontal, temporal, and central regions. Similar to α rhythm, β rhythm can be subdivided into low-frequency and high-frequency sub-bands: low-frequency β rhythm spans 15 to 20 Hz, influenced by psychological activities and emerging during focused attention; high-frequency β rhythm ranges from 20 to 30 Hz, appearing during emotional excitement or tension (Zaferiou et al., 2025). In neurofeedback training, β rhythm is generally combined with EEG features from other frequency bands. Hao et al., (2022) first integrated low-frequency β rhythm with SMR rhythm neurofeedback for attention disorders in children, effectively enhancing attention in ADHD patients. In the neurofeedback training combining β and θ rhythms by Afrash et al., (2023), users' θ and β activities were converted online into graphics and fed back in real time on the screen; users must learn to suppress the progress bar on the left side (representing θ activity) while increasing the right side (representing β activity). Through neurofeedback training, users can master control to enhance β activity and suppress θ activity, entering a relaxed yet focused state.

Notably, the success of the aforementioned neurofeedback training mechanisms is determined by whether the average absolute amplitude or power of the target frequency band's EEG features in each training session exceeds the average from the previous round. During each training period, users can adjust baseline settings to ensure the feedback received neither induces frustration nor complacency (Khanghah et al., 2023). The advent of VR technology not only enables users to conduct simulated training under controlled, repeatable conditions, thereby facilitating superior investigation of brain rhythm changes, but also allows users to achieve more pronounced brain electrical activity in complex virtual training scenarios.

2 VR Systems Applied to Neurofeedback Training

VR systems applied to neurofeedback training enable users to intuitively and concretely perceive their real-time status. By integrating adaptive feedback information generated through highly immersive, multi-channel perceptual interfaces in virtual environments, these systems guide users to learn, to a certain extent, to shape brain activity patterns associated with neural activity in desired ways, thereby achieving objectives of cognitive enhancement or neural rehabilitation. This section introduces the advantages of VR technology in the field of neurofeedback training, as well as the basic components of VR systems applied to neurofeedback training.

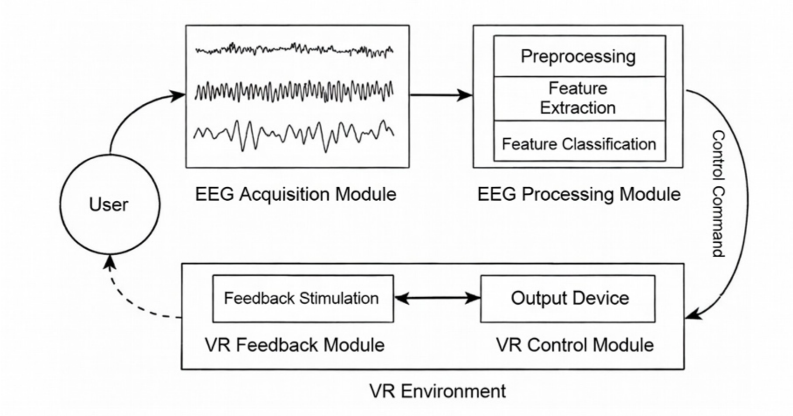
2.1 Advantages of VR Systems Applied to Neurofeedback Training

Traditional neurofeedback training requires users to remain in designated areas equipped with electroencephalography (EEG) devices, which can induce feelings of tension and unease. Moreover, when providing feedback based on users' EEG, it is challenging to promptly adjust the external environment to form targeted training, and these limitations can impact the users' training (Gkintoni et al., 2025). During training, many users may fail to exhibit suitable EEG features in the cerebral cortex due to environmental constraints or external interferences, or may even display brain activity patterns contrary to the intended feedback training. Such occurrences can lead users to receive erroneous feedback prompts from the training system, ultimately resulting in a flawed feedback loop. The emergence of VR technology effectively addresses these issues; it not only provides users with realistic virtual training environments but also allows real-time adjustments to virtual environment settings based on user needs to deliver targeted training content. Furthermore, training content in virtual environments offers greater interest and interactivity, enhancing user comfort and compliance.
Suhaimi et al., (2022) found that incorporating rich feedback mechanisms in training systems, such as images, animations, and sounds, assists users in improving neural activity in the cerebral cortex through self-regulation, yielding superior training outcomes. Liao et al., (2023) developed a VR system for upper-limb motor neural rehabilitation training, which employs real-time virtual scenarios for visual feedback, effectively motivating users and shortening rehabilitation cycles. In recent years, with the rapid advancement of VR technology featuring advantages such as immersion, interactivity, and multi-sensory capabilities, its applications in fields like military training, educational instruction, and clinical treatment have proliferated. The advantages of VR training systems integrated with neurofeedback have become increasingly evident, enabling neurofeedback training supported by VR technology in both medical institutions and home settings, thereby providing convenience and enhancing user adherence.

2.2 Basic Components of VR Systems Applied to Neurofeedback Training

A typical VR system applied to neurofeedback training, as illustrated in Figure 1, consists of an EEG acquisition module, an EEG processing module, a VR control module, and a VR feedback module. This system decodes EEG signals reflecting changes in users' cerebral cortical activity into control signals for the VR environment and transmits them to VR devices, enabling interaction in the virtual world.

Figure 1 Workflow of VR System Applied to Neurofeedback Training



Source: Author's own elaboration (2026)

The EEG Acquisition and Processing Modules serve as the foundational stages of the neurofeedback system, primarily utilizing non-invasive methods to record raw brain signals due to their broad clinical and rehabilitative applicability. Once captured, these microvolt-level signals undergo rigorous preprocessing, including filtering, artifact removal, and downsampling, to eliminate physiological and environmental noise. This is followed by feature extraction and classification using sophisticated algorithms such as Fast Fourier Transform (FFT), Wavelet Transform (WT), and increasingly, Deep Learning architectures. These techniques allow for the dimensionality reduction and categorization of EEG data, accurately identifying the user's cognitive intent or brain state in real time. (Rajaby, & Sayedi, 2022)

The VR Control Module acts as the interface between processed neural data and the virtual environment, translating classified brain signals into specific execution commands. By establishing a direct communication link with hardware such as VR headsets, controllers, and data gloves, this module ensures that the user's mental activity is manifested as functional operations within the simulation. This stage is crucial for maintaining the "brain-to-device" loop, as it converts abstract electrical information into tangible interactions, allowing the system to respond dynamically to the user's underlying neurological patterns. (Antal et al., 2022)

Finally, the VR Feedback Module constitutes the most critical component for neurofeedback efficacy, as it provides the multisensory stimuli necessary for neural plastic change. Unlike traditional methods, VR environments offer synchronized visual, auditory, and tactile feedback that is more immersive and ecologically valid, significantly shortening the training duration required for users to learn self-regulation of specific brain rhythms. By integrating these three stages, acquisition, control, and feedback, the system creates a comprehensive closed-loop architecture that effectively activates targeted cerebral cortices and optimizes neurofeedback training outcomes.

CONCLUSIONS

The integration of virtual reality (VR) with biofeedback, particularly in its neurofeedback variant, represents a paradigmatic advance in the treatment of phobias and other anxiety disorders, by combining immersive environments with real-time physiological feedback mechanisms. Throughout this essay, it has been explored how VR facilitates controlled exposure therapy, simulating phobic scenarios with a high degree of sensory immersion, while biofeedback, through the monitoring of signals such as electroencephalography (EEG), allows users to autonomously regulate their emotional and cognitive responses. The training mechanisms in specific EEG bands, such as SCP, θ, α, SMR, and β, demonstrate how this technology not only suppresses dysfunctional brain activity patterns but also promotes lasting neuroplastic changes, improving functions such as attention, relaxation, and emotional resilience.

VR systems applied to neurofeedback overcome the limitations of traditional approaches, offering adaptive, interactive, and multisensory environments that increase patient adherence and training effectiveness. Evidence from reviewed studies indicates that this synergy accelerates habituation to anxiogenic stimuli, reduces symptoms in conditions such as social anxiety, post-traumatic stress disorder, and specific phobias, and extends its applicability to clinical, educational, and home contexts. Nevertheless, technical challenges persist, such as hardware latency and the need for more precise algorithms for EEG signal processing, which require future research to optimize personalization and scalability.

Ultimately, this technological convergence not only enriches therapeutic practice by democratizing access to innovative interventions but also empowers individuals as active agents in their mental recovery. By fusing virtual immersion with neurophysiological self-regulation, it positions itself as an essential pillar in the evolution of mental health, promising more effective, inclusive, and sustainable outcomes in the management of phobic and cognitive disorders.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest regarding the development or disclosure of the research results.

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