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RESEARCH ARTICLE

Analysis of an Integrated QEEG-Neurofeedback System Utilizing Active Stimuli for Non-Pharmacological Intervention in Enhancing Neurobehavioral Function

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Abstract

Quantitative Electroencephalogram (QEEG) and Neurofeedback (NF) are employed in the diagnosis and treatment of neurobehavioral deficits associated with various clinical conditions. These approaches enable the exploration of EEG usage within the context of neurobehavioral electrophysiology. This study aims to elucidate the fundamental evidence supporting NF and to outline strategies for its further development and application in ameliorating neurobehavioral deficits. Numerous research studies have demonstrated the efficacy of NF in enhancing neurobehavioral functions, including attention, language, memory, visuospatial abilities, and executive function. This study intends to develop an NF system that includes the establishment of a robust approach to QEEG transformation and database. The closed-loop QEEG-NF system under development incorporates active visual and auditory stimuli that leverage stochastic phenomena. The efficacy of the QEEG-NF treatment was confirmed with a statistically significant increase in alpha brain wave percentages post-treatment ($p = 0.018$), indicating that the system effectively enhances alpha brain wave production.

Keywords: Neurobehavior, Neurofeedback, Quantitative EEG, Stochastic Resonance

1. Introduction

The electroencephalogram (EEG) is a non-invasive diagnostic tool used to detect brain electrical activity, particularly in the cortex, since its discovery in 1924 by a

German scientist. EEG findings commonly categorize brainwave activity into distinct frequency ranges, including delta (below 4 Hz), theta (4–8 Hz), alpha (8–13 Hz), and beta (13–30 Hz) [1]. EEG provides temporal resolution in the millisecond range, a capability not achievable with CT, PET, or MRI scans, and it is one of the few mobile techniques available. EEG serves as a diagnostic and monitoring tool for various brain-related conditions, including epilepsy, dementia, head injury, concussion, brain tumors, and encephalitis. EEG can also be used during brain surgery or to test the brain activity of someone in a coma. EEG is recorded through electrodes placed on the human scalp, and studies have demonstrated that the biosignals detected through EEG correspond to the postsynaptic potentials of pyramidal neurons [1]. In the past, EEG was a primary diagnostic tool for identifying tumors, strokes, and other focal brain disorders. However, its utilization has declined with the introduction of high-resolution anatomical imaging modalities like CT and MRI. EEG derivatives Incorporate evoked potentials (EP) as part of the assessment, and electrocorticography (ECoG), which involves surgical placement of electrodes, is sometimes called "intracranial EEG".

Electroencephalography (EEG) is a non-invasive technique employed to capture the brain's spontaneous electrical activity by placing electrodes on the scalp. EEG has been used for various purposes, including the diagnosis of epilepsy and the detection of abnormal brain waves. In addition to its diagnostic role in epilepsy, EEG is also used quantitatively, especially by psychologists and psychiatrists, to diagnose Attention Deficit and Hyperactive Disorder (ADHD) through specific wave patterns, which have recently become popular as a brain mapping technique. QEEG is an advancement of conventional EEG, initiated by Dietsch in 1932 through the Fast Fourier Transform (FFT) [2]. Several important findings suggest that QEEG is a relevant method for investigating brain-behavior relationships in children and adolescents, based on the available brain mapping data. Therefore, broader research on brain-behavioral EEG should be conducted in the future, making "neurobehavioral electrophysiology" a new approach [3]. It is important to note that epileptiform or paroxysmal EEG waveforms not associated with clinical seizures have neurophysiological, cognitive, and/or neurobehavioral implications, reaffirming the significance of EEG beyond the diagnosis of epilepsy.

NF is a self-regulation concept that modulates the brain's electrical activity patterns (or brain waves) towards improving behavior as a process that can be learned. NF is designed as a training protocol that develops learning strategies as self-regulation training, mostly with auditory or visual presentation. NF has been used for healthy and pathological subjects as well as clinical and nonclinical purposes. Although often relevant to neurobehavioral function, non-clinical uses may include applications in sports [4], music [5], performing arts [6], and food cravings [7]. An interesting study claims that surgical skills can be honed with NF [8].

The adoption of QEEG and NF techniques has been a subject of contention within the field of neurology. Some have advocated for their use due to observed clinical improvements and their non-invasive nature [9]. NF has been widely used and studied in psychological and psychiatric diagnoses such as Attention Deficit Disorder (ADD), ADHD, Autistic Spectrum Disorder (ASD) [10], and Post Traumatic Stress Disorder (PTSD) [11]. QEEG studies have shown a correlation between psychiatric disorders and changes in brain wave amplitudes. Additionally, QEEG analysis has been used to monitor various conditions and has been shown to improve clinical, cognitive, and psychosocial dysfunctions in patients with schizophrenia. NF training has been found to be beneficial in improving cognitive and behavioral performance in healthy individuals. A retrospective study also assessed the viability of qEEG-guided amplitude NF as a treatment for reducing anxiety symptoms. These findings highlight the potential of QEEG and NF in diagnosing and treating various neurological and psychiatric conditions.

This paper aims to outline the evidence base of NF and plans to deepen its development and application to correct neurobehavior deficits with a combination of active stimuli that exploit stochastic phenomena. The neurophysiology and central nervous mechanisms of NF remain to be confirmed, especially for use in neurology.

1.1 Neurofeedback and Neurobehavior

In the realm of neurological diagnostic foundations, neurologists typically establish etiological diagnoses, such as vascular, tumor-related, infectious, metabolic, or degenerative causes. Across all etiologies, one or more neurobehavioral deficits may manifest as clinical diagnoses, with or without concurrent neuroclinical diagnoses like motor, sensory, facial nerve paralysis, etc. Neurobehavior is traditionally categorized into five cognitive functions: attention, language, memory, visuospatial, and executive functions. Some previous works in NF have linked this non-invasive treatment to improvements in these functions.

1.1.1 Attention

A substantial body of work has been undertaken to evaluate the effects of NF on attention enhancement, particularly in the context of conditions such as Attention-Deficit/Hyperactivity Disorder (ADHD) [12].

Randomized controlled trials have demonstrated that NF's efficacy exhibits an additive effect when combined with pharmacological treatments for ADHD [13]. Larger-scale studies (n = 102) employing randomized controlled trial methods, have been conducted, indicating that NF with Theta/Beta protocols is an effective treatment for ADHD [14]. Reports indicate reductions in inattention, impulsivity, and hyperactivity.

1.1.2 Language

Language has not been extensively reviewed in association with NF. One closely related approach involves studies linking NF using auditory stimuli to auditory discrimination.

1.1.3 Memory

Intensive and brief alpha and theta NF protocols have been shown to enhance working memory [15]. Research conducted on a healthy aging population compared the results of NF interventions with conventional cognitive training. Significant outcomes from this study suggest that NF interventions can be applied to the elderly population.

1.1.4 Visuospatial

While not a direct correlation, previous research claims that NF training efficacy extends to improving alcohol dependence syndrome, which may encompass visuospatial abilities [16].

1.1.5 Executive Function

NF, in conjunction with cognitive training, has demonstrated an improvement in executive function after a relatively short training period [17]. Executive function improvements are reflected in various tests, including Letter–Number Sequencing (LNS), Trail Making Test (TMT), and the Color-Word Interference Test (CW).

1.2 The Role of QEEG & NF in Neurology

NF comprises a brain-computer interface (BCI) that essentially connects the brain to an external device. BCI has rapidly evolved for the treatment of neurological conditions and even for enhancing brain function.

Recent investigation has elucidated specific neurophysiological mechanisms underpinning the enhancement of impulsivity in Attention-Deficit/Hyperactivity Disorder (ADHD) through theta/beta NF [18]. This study integrates diverse experimental measures encompassing behavioral and neurophysiological domains, employing high-density electroencephalogram (EEG) recordings coupled with source localization analysis utilizing standardized low-resolution brain electromagnetic tomography (sLORETA). The efficacy of NF appears rooted in the modulation of inhibitory processes within the medial frontal cortex.

Hypotheses positing a robust association between NF and neuroplasticity have persisted. Recent empirical findings provide initial evidence of neuroplastic alterations subsequent to natural brainwave training through NF [19]. Notably, a mere thirty minutes of voluntary control over brainwave frequencies has demonstrated the capacity to induce enduring changes in cortical stimulation and intracortical function. This is evidenced through transcranial magnetic stimulation apparatus and electromyographic (EMG) metrics. The modulation of plasticity is considered achievable through stimulation at specific brainwave frequencies.

1.3 Active Stimuli with Visual & Auditory Stochastic Resonance

Noise pervades various systems and electrical signal environments, encompassing bioelectrical signals. Conventional viewpoints perceive its existence as detrimental to system performance and accuracy. Consequently, diverse analytical methodologies, specialized instrumentation, and an array of analog and digital filters have been devised to alleviate noise-induced random fluctuations in measured quantities, thereby facilitating the extraction of the genuine values of the targeted signals.

In the context of brain physiology, noise emanating from random neuron firing influences brain behavior [20]. This stochastic neural activity impacts decision-making, memory processes, as well as the stability of short-term memory and attentional mechanisms [21]. Additionally, cognitive functions are subject to stochastic variations in N-methyl-D-aspartate receptor-activated synapses, affecting both memory stability and short-term attention. Moreover, synaptic ion changes contribute predictably to the probability of the system erroneously transitioning to a pathologically heightened state of activity [20].

Noise of specific magnitudes has been observed to either enhance or facilitate functions in diverse systems, including bioelectric signals associated with neurobehavior [22]-[23]. Such phenomena are characterized as stochastic resonance [24]-[25]. The information presented emphasizes the necessity of considering not only optimal noise levels but also the optimal parameter values when implementing stochastic resonance [26].

For the specific objectives of our closed-loop QEEG-NF system, we have devised auditory stimuli incorporating brainwave frequencies modulated with various carrier frequencies, encompassing white noise, pink noise, and brown noise. Additionally, visual stimulation will involve the use of RGB LED and/or a computer screen flickering at specific brainwave frequencies.

The proposed QEEG-NF system introduces an innovative approach by incorporating active auditory stimuli using the principle of stochastic resonance to enhance NF training efficiency. This novel methodology aims to improve the NF training time by stimulating the brain to produce increased brainwave activity within the selected training frequency. For instance, patients with an alpha-frequency deficiency can benefit from auditory stimuli designed to enhance alpha-frequency brainwaves. This targeted stimulation is expected to result in a measurable increase in the percentage of alpha frequency, thereby addressing the specific neurobehavioral deficit more effectively. By leveraging stochastic resonance, our system promises a more rapid and effective modulation of brainwave activity, leading to improved NF outcomes and shorter training durations.

2. Closed-Loop QEEG-NF Protocol Method

An effective design is essential for a comprehensive NF protocol system to attain favorable outcomes and efficiency [30]. Learning and adaptation play a vital role in this NF protocol, offering training subjects and self-regulatory mechanisms to govern neurobehavioral capabilities. The fundamental principle revolves around adhering to a behavioral model, where stimuli are applied to an organism, and in response, the organism generates a response, along with consequences that may loop back for self-regulation.

The QEEG-NF's engineered process control model, as depicted in Figure 1, involves two types of feedbacks. In this framework, the system possesses the capacity to utilize both internal and external functionalities to achieve the intended state. Internal functions refer to self-regulatory processes within the brain, whereas external stimuli act as inputs to the system, influencing the system's input without affecting the error measurement.

The EEG signals were recorded employing a 24-bit A-D converter board, specifically based on a single AD1299 chip, which possesses the capability to capture full-band EEG with an 8-point montage.

NF training was conducted utilizing internal software on a computer equipped with dual screens/monitors and RGB LEDs to provide visual feedback and stimulation. Furthermore, auditory stimulation was administered through earphones/headphones with the flattest frequency response available across the entire audio spectrum.

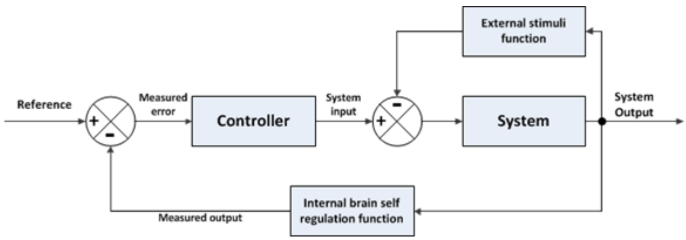

Figure 1. the engineered closed-loop control process model of QEEG-NF with active stimulation. Feedback signals are not directly relayed to the subject as controller input; instead, they are actively employed to adjust the system's parameters.

The EEG employed for recording and feedback was sampled at a frequency of 250 Hz, employing eight gold-coated scalp electrodes arranged in a multi-layered montage. These electrodes were strategically positioned at specified montage points using a standard EEG montage. For this QEEG-NF setup, the 8-channel electrodes were placed as follows: FP1, FP2, C3, C4, T5, T6, O1, and O2, depicting channel 1-8 respectfully. Their locations are adjustable based on the NF training protocol. Prior to application, the scalp area underwent meticulous preparation involving gentle abrasion with conductive gel, followed by the application of electrode paste.

For real-time NF training purposes, the EEG signals were subjected to a 4th-order Butterworth band-pass filter (1 Hz to 50 Hz) using an Infinite Impulse Response (IIR) design, along with a 4th-order Butterworth notch filter (50 Hz). This processing aimed to attenuate EMG artifacts, mitigate environmental noise, and reject channel noise. Equation 5.1 to 5.4 presented below represent the digital IIR filters implemented in the program.

$$y(n) = \sum_{k=0}^{\infty} h(k)x(n-k) \tag{1}$$

Which gives a transfer function of:

$$y(n) = \sum_{k=0}^{N} b_k x(n-k) - \sum_{k=0}^{M} a_k y(n-k) \tag{2}$$

$$H(z) = \frac{b_0 + b_1 z^{-1} + \cdots + b_N z^{-N}}{1 + a_1 z^{-1} + \cdots + a_M z^{-M}} \tag{3}$$

$$H(z) = \frac{\Sigma_{k=0}^{N} b_k z^{-k}}{1 + \Sigma_{k=0}^{M} a_k z^{-k}} \tag{4}$$

The Fast Fourier Transform (FFT) is applied to raw data consisting of 256 points to calculate and export amplitudes (μV) for each frequency, excluding DC. Consequently, the amplitudes of individual brain wave frequency components (delta, theta, alpha, beta, and gamma) accumulate and increment with each occurrence. Each brain wave frequency component is normalized by dividing it by the total amplitude across all frequencies from delta to gamma, yielding the percentage contribution of each specific brain wave component. Equation 5.5 presented below represents the FFT algorithm implemented in the program.

$$X(k) = \sum_{n=0}^{N-1} x_n e^{\frac{-j2\pi nk}{N}}, k = 0, \cdots, N-1 \tag{5}$$

The principal outcome derived from our QEEG-NF computations is the quantification of brain wave composition, expressed as a percentage or fraction, observed within predefined intervals or treatment periods. For instance, during the observation of EEG signals at Ch1, the FFT computation block systematically collects its associated brain wave components within predetermined intervals. Using this methodology, the aggregate sum of each brain wave component across all channels must equate to 100% to represent each specific brain wave component as a fraction of the total EEG during each treatment period. The computational Equations employed in this algorithm are elucidated in Equations 5.6 to 5.10 presented below.

$$\delta(Ch(x)) = \sum_{t=0}^{T} \frac{\Sigma_{f=1}^{3} F(f)}{\Sigma_{f=1}^{50} F(f)}, x = 1, \cdots, 8 \tag{6}$$

$$\theta(Ch(x)) = \sum_{t=0}^{T} \frac{\Sigma_{f=4}^{7} F(f)}{\Sigma_{f=1}^{50} F(f)}, x = 1, \cdots, 8 \tag{7}$$

$$\alpha(Ch(x)) = \sum_{t=0}^{T} \frac{\Sigma_{f=8}^{12} F(f)}{\Sigma_{f=1}^{50} F(f)}, x = 1, \cdots, 8 \tag{8}$$

$$\beta(Ch(x)) = \sum_{t=0}^{T} \frac{\Sigma_{f=13}^{31} F(f)}{\Sigma_{f=1}^{50} F(f)}, x = 1, \cdots, 8 \tag{9}$$

$$\gamma(Ch(x)) = \sum_{t=0}^{T} \frac{\Sigma_{f=32}^{50} F(f)}{\Sigma_{f=1}^{50} F(f)}, x = 1, \cdots, 8 \tag{10}$$

In which T signifies the interval/treatment period, and F(f) represents the amplitude derived from the Fast Fourier Transform (FFT) for a given frequency f.

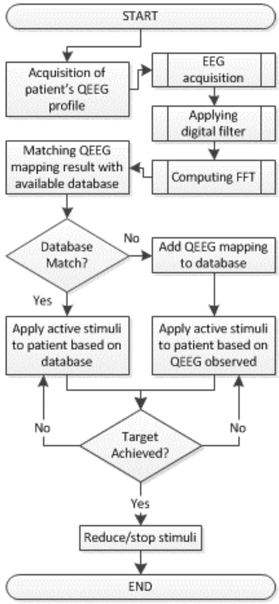

Figure 2. Flowchart of the closed-loop QEEG-NF protocol with active stimulation.

2.0.1 Preliminary Data

As a preliminary study, 12 high school students aged 15–18 years were selected to participate in QEEG-NF sessions. The inclusion criteria for these participants were: being within the high school age range of 15–18 years, having a deficit in alpha-frequency brainwaves as determined by pre-recording QEEG signals compared to a normative database, and exhibiting clinical conditions associated with alpha-frequency deficiency, such as a lack of concentration ability.

3. Result and Discussion

This paper discusses the important role of QEEG and NF in the context of neurology. The use of active stimuli with stochastic resonance for auditory and visual stimulation is described as an important aspect of therapy. The potential benefits of NF in improving attention, language, memory, visuospatial function, and executive function are discussed in detail, providing a comprehensive overview of the potential of this therapy in addressing neurobehavioral deficits. The use of normative databases is essential to handle potential complex combinations of QEEG data. If a patient's QEEG data is not in the database, collaboration with the clinician is necessary. QEEG mapping results can assist doctors in diagnosing the required active stimulation. For instance, if a patient's brain waves are too low, the use of specific noise-modulated brain waves may be considered as an appropriate form of active stimulation.

The QEEG-NF system is designed as a closed loop involving both auditory and visual stimuli. A comprehensive NF protocol was developed for learning and adaptation, using high-resolution (24-bit) EEG signal recordings. The main output of the QEEG-NF calculation is the percentage of brain wave composition observed during a predetermined interval or treatment period. To evaluate the effectiveness of the QEEG-NF treatment, pre- and post-treatment scores of 14 high school students aged 15-18 were analyzed. The scores represent the percentage of alpha brain wave frequencies, a critical target for enhancement in this study. Below are the summarized results:

Table 1. QEEG result of the QEEG-NF Training Session

Alias Name	Pre-QEEG-NF Treatment	Post-QEEG-NF Treatment
KFY	16.8%	17.5%
KBP	18.7%	20.1%
NDA	16.8%	17.5%
AKA	14.8%	15.2%
NRN	11.6%	18.5%
AHA	15.2%	16.5%
ALT	14.8%	15.6%
AKP	11.6%	17.5%
ATA	19.0%	19.9%
B	8.30%	11.3%
GAW	17.7%	18.4%
HH	15.6%	17.2%

The efficacy of the QEEG-NF treatment was assessed using a paired t-test to compare the mean alpha brain wave percentages before and after treatment across the 12 participants. The results indicated a statistically significant ($p < 0.05$) increase in alpha brain wave percentages post-treatment with an exact p-value of 0.018. This suggests that the QEEG-NF system, utilizing auditory and visual stimuli with stochastic resonance, effectively enhanced alpha brain wave production in the targeted participants. The study results confirm that the use of QEEG and NF has great potential in diagnosing and treating neurobehavioral deficits. A closed-loop approach with active stimulation has been shown to be effective in improving therapy outcomes, while additional benefits have been seen in improving cognitive aspects and brain function. This study provides a strong foundation for understanding the integral role of NF in establishing a holistic and personalized approach to neurobehavioral treatment.

4. Conclusion

The study provides compelling evidence that the QEEG-NF system, employing active auditory and visual stimuli with stochastic resonance, is effective in enhancing alpha brain wave activity in adolescents with deficits in this frequency band. The significant increase in alpha brain wave percentages post-treatment supports the hypothesis that targeted neurofeedback interventions can successfully modulate brain wave patterns associated with neurobehavioral deficits. This research underscores the potential of QEEG-NF as a personalized and effective approach to improving cognitive functions and addressing neurobehavioral disorders. Further research with larger sample sizes and longitudinal studies are recommended to corroborate these findings and explore additional applications of QEEG-NF in clinical settings.

The full range of QEEG-NF units will undergo protocol refinements and normative database expansions over time to ensure the units will meet changing requirements based on subject conditions that may not previously exist in the data. The use of active stimuli with stochastic resonance for auditory and visual stimulation is described as an important aspect of therapy. The potential benefits of NF in improving attention, language, memory, visuospatial function, and executive function are discussed in detail, providing a comprehensive overview of the potential of this therapy in addressing neurobehavioral deficits.

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