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A Comprehensive Review of EEG-based Brain–computer Interfaces for Attention Training

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Abstract. Electroencephalography (EEG) has provided critical insights into brain activity by recording brain waves that reflect changes in neural potential across different regions. This review explores the evolution and applications of EEG-based brain-computer interfaces (BCIs), focusing on their role in attention training and treatment of attention deficit hyperactivity disorder (ADHD). BCIs, particularly non-invasive devices like Mindwave, have facilitated the development of serious games designed to enhance attention and cognitive functions through neurofeedback. The review examines various EEG-BCI-based interventions, such as *Harvest Challenge* and *BRAVO*, which have demonstrated efficacy in improving attention in children with ADHD. Additionally, advancements in EEG-BCI technology have shown promise in enhancing cognitive functions in healthy individuals, including the elderly. Despite these advancements, limitations such as small sample sizes and device accuracy issues remain. The review concludes with recommendations for developing more tailored algorithms and adapting training protocols to individual needs to enhance the efficacy of BCI-based attention training.

Keywords: EEG, BCI, attention, ADHD, Neurofeedback treatment.

1. Introduction

The brain's intricate structure facilitates the transmission of electrical signals between neurons through synapses when active. This signal transmission involves changes in electrical potential, forming the biological foundation for brain wave generation. Electroencephalography (EEG) allows for the recording of these brain waves as continuous curves, representing variations in neural potential across different brain regions. These brain waves encode a wealth of information, and by interpreting them, we can infer specific brain activities and even gain insights into the individual's thoughts at that moment. And this information can be further processed through specific algorithms, and translated into instructions to the computer [1]. The technology that enables this process called brain-computer interfaces (BCIs). Which establish novel communication pathways between humans and computers.

BCIs enable the control of external devices by directly interpreting brain signals, bypassing the need for physical movement. This technology is particularly beneficial in applications such as wearable mechanical devices that enhance the quality of life for individuals with physical impairments. Additionally, the fusion of BCI systems with computer multimedia technology has led to the development of serious games, which are recognized as effective tools for alleviating symptoms of mental illnesses [2]. By constructing feedback loops that deliver continuous stimulation and prompt feedback, these games can enhance participants' attention levels [3]. Due to neuroplasticity, serious

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games have also shown potential in treating mental disorders like ADHD. Clinically, it can be observed that some aspects of their daily life have been effectively improved [4]. For instance, training young patients with feedback on internal processes via various sensory channels, such as vision and hearing, during specific game-based stimuli has proven effective in mitigating symptoms of inattention, impulsivity, and hyperactivity [5,6]. Moreover, EEG-BCI training has demonstrated significant improvements in cognitive abilities in healthy individuals. In particular, older adults have shown enhanced memory and attention following specific BCI-based training [7].

This review begins by outlining the fundamental principles of EEG and BCI, followed by a brief overview of the primary devices utilizing EEG-BCI technology. We then focus on recent advancements in the application of EEG-based BCI for attention training, especially in treating ADHD, and discuss its potential use in cognitive enhancement for healthy individuals. Finally, we address the current limitations of this technology and offer suggestions for future improvements.

2. EEG-based Brain–computer Interface: Development and Devices

The first recordings of brain electrical signals were made from the cortical surface of animals in 1875. Electroencephalography (EEG) later emerged as the primary tool for visualizing these signals. The study of EEG led to the theoretical foundation of brain-computer interface (BCI) technology [8]. In 1973, Jacques Vidal developed a computer-based device that could collect electrical impulses from the scalp and convert them into commands [9]. This innovation enabled humans to control and operate external devices without relying on peripheral nerves and muscles [10]. BCI technology records voltage changes in specific brain regions, translating these into user brain activity data. BCIs can be categorized into three types based on the level of invasiveness: invasive, partially invasive, and non-invasive. Non-invasive devices, favored for their safety, ease of use, and low cost, have become the focus of most research in this field.

BCI systems, which are AI-based, recognize specific patterns in brain signals through five key stages: signal acquisition, signal enhancement or pre-processing, feature extraction, classification, and interface control. Various methods exist for signal acquisition in BCI, including EEG, magnetoencephalography (MEG), and functional magnetic resonance imaging (fMRI) [11]. Among these, EEG is often preferred in attention training applications using BCI due to its relative affordability, ease of operation, and broader accessibility.

Currently, the development of EEG-based BCI technology is focused on creating devices that are more portable and convenient for home use. Various devices are available for capturing EEG signals, including Enobio, Muse, and Mindwave. Mindwave, in particular, is a wireless Bluetooth EEG device designed as a lightweight, headband-style wearable that is easy to don and remove. Resembling common Bluetooth headphones, Mindwave has gained significant popularity in attention training applications due to its ease of use and user-friendly design [12].

3. Attention and Attention Deficit

Attention is defined as the ability to maintain focus on a specific action, thought, or object over time. EEG is one of the most widely used tools for studying attention, as it allows for the recording and analysis of brain wave activity across different frequency bands. Human brain waves are primarily categorized into three bands: α-waves (8-12 Hz), which are associated with relaxation and restful states and tend to increase when attention decreases; β-waves (13-30 Hz), which are linked to concentration and high mental activity, with their presence indicating focused attention; and θ-waves (4-7 Hz), which are related to memory and navigation, with fluctuations in θ waves representing changes in attention levels [13].

Attention deficit hyperactivity disorder (ADHD) is a neurodevelopmental disorder characterized by difficulties in sustaining attention, hyperactivity, and impulsive behavior. ADHD often manifests in childhood, typically emerging during early school years. Although the exact cause of ADHD remains unclear, it is generally believed to result from a combination of genetic and environmental factors.

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Individuals with ADHD face greater challenges in academic and occupational settings compared to those without the disorder, and their social interactions are often impacted as well.

The primary treatments for ADHD include cognitive-behavioral therapy (CBT) and pharmacotherapy. However, these treatments are not without side effects and risks [14]. Additionally, access to effective behavioral treatments is often limited by healthcare coverage constraints [15]. Therefore, there is a growing need for more accessible and efficient interventions, potentially suitable for home use, that can provide attention training for children with ADHD and help improve their attention levels.

4. Attention training using EEG based BCI system

Recently, the application of neurofeedback, which utilizes neurophysiological signals for biofeedback, has been effectively employed to train children with ADHD in physiological self-regulation skills [16]. Studies have shown that these children exhibit significant improvements in attention levels following neurofeedback training [3]. Moreover, many EEG-BCI-based neurofeedback video games have been increasingly utilized in the treatment of ADHD, offering an engaging and effective approach to managing the disorder [17].

4.1. Attention training for children with ADHD.

A group of academics in Colombia developed a 3D virtual reality video game called Harvest Challenge that utilizes an EEG-BCI system to train attention self-regulation. A pilot study conducted on children with ADHD found that participants who engaged with the game demonstrated an improved ability to sustain attention [15]. In another development, Valerio De Luca et al. created a serious game titled BRAVO (Beyond the tReatment of Attention deficit hyperactiVity disOrder) [18]. This project involved the development of several extended reality-based serious games aimed at enhancing patients' self-control, adherence to rules, attention, and concentration. Lim et al. designed an experiment using EEG-BCI technology to play Cogoland, a computerized 3D serious game [19,20]. Their findings revealed that an 8-week intervention significantly improved inattentive symptoms in children with ADHD. To enhance accessibility and reduce costs, Mercado et al. developed FarmerKeeper, a BCI video game, using a consumer-grade BCI headset. After training 26 children with ADHD, the study observed a slight improvement in attention compared to the control group, with participants showing less distractibility and better sustained attention [21]. Building on this, Mercado et al. conducted a comparative study between FarmerKeeper and BrainCats (another EEG-BCI serious game). The results indicated that FarmerKeeper was more effective for neurofeedback training, particularly in maintaining participants' focus for longer periods [22].

4.2. Attention training for healthy people

Analyzing data from EEG-based attention training in healthy individuals can contribute to the development of more effective EEG techniques and identify optimal approaches for ADHD treatment. Research indicates that EEG-BCI technology for sustained attention training is both effective and promising [23]. Wang et al. developed a closed-loop neurofeedback system for attention monitoring and training using EEG-BCI technology, demonstrating its reliability and effectiveness in young individuals [24]. Further advancements were made by Delisle-Rodriguez et al., who constructed a multi-channel EEG-based BCI system for attention training [25]. Their findings revealed that the system effectively enabled users to regulate θ/β wave ratios in specific brain regions, showcasing its potential for attention training. Additionally, EEG-BCI technology holds potential for mitigating cognitive decline in healthy older adults. Lee et al. found that BCI-based systems show promise in enhancing memory and attention in elderly users, and are noted for their safety, user-friendliness, and acceptability among senior participants [26].

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5. Challenges and Limitations

A primary limitation across the studies mentioned is the small sample size, typically ranging from 20 to 30 participants, due to constraints in time and funding. Additionally, signal collection from various brain regions may lack accuracy due to device limitations, and existing algorithms may not account for individual differences. To address these issues, it is crucial to develop more refined algorithms tailored to the specific needs of children with autism and to accommodate each patient's unique progress [19]. Furthermore, adapting training protocols to individual users based on human factors could enhance the efficacy of BCI learning [27].

6. Conclusions

In summary, EEG-based BCIs represent a significant advancement in the field of neurotechnology, offering novel approaches for attention training and cognitive enhancement. The integration of EEG with BCI technology has facilitated the development of engaging and effective interventions for treating ADHD, as demonstrated by various serious games and neurofeedback applications. Studies indicate that these technologies hold considerable promise for both therapeutic and cognitive enhancement purposes, extending to healthy individuals and the elderly. However, the effectiveness of these interventions is constrained by several factors, including small sample sizes and limitations in signal accuracy. To address these challenges, future research should focus on developing refined algorithms that cater to individual needs and improving the adaptability of training protocols. Such advancements are crucial for optimizing the potential of EEG-based BCIs in both clinical and everyday settings.

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