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The Prospects and Challenges of BCI Technology in PTSD Treatment

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Abstract. This article focuses on the application of Brain-Computer Interface (BCI) technology in PTSD treatment, exploring its current status, challenges, and optimization directions. Through literature review and case analysis, summarize the principles of BCI technology and its medical application progress, and evaluate its efficacy and limitations based on domestic and foreign examples. At the same time, it points out the shortcomings of China's relevant policy support and proposes specific suggestions for improving regulations and incentivizing innovation. The study emphasizes the potential of BCI technology to improve PTSD rehabilitation rates, reveals issues such as limited data samples and fast technological iteration, and calls for strengthening interdisciplinary cooperation and technological upgrades.

Keywords: BCI, PTSD, policy recommendations, technological innovation, interdisciplinary collaboration.

1. Introduction

Brain-computer interface technology has gradually developed since the 1950s, moving from theoretical exploration to clinical applications. Early research focused on the connection between EEG signals and machine control, and in the 1970s, the feasibility of decoding neural signals was verified. In the 1990s, non-invasive BCI made breakthroughs in motion function reconstruction through advances in microelectronics and algorithms [1]. Since the 21st century, high-density electrode arrays combined with deep learning have improved signal resolution capabilities and expanded to interventions for mental illness. In 2024, the 65000-channel flexible chip developed by the Chinese team achieved a breakthrough in neural signal acquisition [2].

Noninvasive BCI uses EEG or fNIRS, while invasive BCI relies on implanted electrodes to obtain high-precision data. BCI can be applied in PTSD treatment, a psychogenic mental disorder characterized by repeated flashbacks, avoidance behavior, and excessive alertness [3]. Combining machine learning monitors brain activity to provide support for neurofeedback. At present, its application focus is on integrating neurofeedback and VR technology, and EEG training can optimize patients' regulation of fear memory. The FDA-approved closed-loop DBS system has undergone clinical trials, which detect abnormal electrical activity to trigger stimulation and block the consolidation of traumatic memory.

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This study focuses on integrating BCI technology into the field of PTSD treatment, to construct a comprehensive technical evaluation framework. The study delved into the application of neural decoding algorithms and neural feedback mechanisms in the consolidation of traumatic memory, revealing the technical limitations of existing intervention models in terms of symptom control accuracy and neural plasticity induction efficiency. The study focuses on the optimization of signal-to-noise ratio in non-invasive EEG signal acquisition systems and explores how cross-modal data fusion technology can assist in the development of personalized treatment strategies. The study demonstrated the potential of closed-loop neural regulation systems to reshape the function of the amygdala prefrontal neural circuit and discussed the algorithm iteration requirements of machine learning models in extracting trauma-related brain network features [1]. By establishing a technology maturity and clinical applicability evaluation system, this study provides theoretical support for optimizing BCI-driven precision intervention plans and promotes the formation of clinical translational pathways with evidence-based medicine value.

2. Theoretical basis of BCI-based PTSD treatment

2.1. Development of BCI technology

Brain-computer interface technology originated in the 1970s, relying on invasive electrodes to obtain signals in its early stages. In the 1990s, EEG technology promoted the development of non-invasive BCI, and paradigms such as P300 and SSVEP gradually matured. The core technology covers multi-channel EEG and fNIRS acquisition, time-frequency analysis, and deep learning classification, with a decoding accuracy of over 90% for motor imagery. In the medical field, BCI helps stroke patients reshape their motor function, regulates depression through neurofeedback, and combines machine learning to improve epilepsy localization accuracy [4].

2.2. Pathogenesis of PTSD

Post-traumatic stress disorder (PTSD) is caused by major trauma, and its core manifestations include repeated flashbacks, avoidance behavior, emotional numbness, and excessive alertness [5]. According to DSM-5, diagnosis requires confirmation of traumatic experience, symptoms lasting for more than one month, and affecting function [6]. ICD-11 distinguishes between common and complex PTSD. The evaluation combines interviews, observations, and physiological data, and children also need to refer to feedback from parents and teachers. The treatment mainly includes cognitive-behavioral therapy (CBT), exposure therapy (PE), and eye movement desensitization (EMDR), with SSRIs being the preferred drugs.

2.3. Treatment approaches of PTSD

Sattler Sebastian's research provides a reference for the acceptance of BCI technology, while Zabikova Martina et al.'s review reveals the potential of BCI in the field of mental health. Comprehensive analysis shows that BCI technology has certain effectiveness in the treatment of PTSD, but it also faces ethical and technical challenges [7].

In the clinical exploration of BCI technology for treating PTSD, a study targeting veterans employed a closed-loop neurofeedback system. The system uses 64-lead EEG to monitor neural oscillations in the frontal lobe and amygdala. Once abnormalities in the θ frequency band are detected, tACS is automatically activated for phase adjustment. After 12 weeks of treatment, the experimental group's CAPS-5 score decreased by 42.7%, which was better than the control group's

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23.1%. FMRI data also showed that the functional connectivity between the hippocampal gyrus and the default mode network was enhanced by 19.8%, indicating that BCI can effectively reshape the neural mechanism of traumatic memory.

Another multicenter study explored the use of a BCI-VR integrated system based on motor imagery for the treatment of PTSD in children. The system controls VR safety scenes by decoding SMR features and gradually introduces trauma-related stimuli [8].

3. Case analysis for PTSD treatment

3.1. PTSD treatment applications

In PTSD treatment based on brain-computer interface (BCI) technology, a Chinese team used a non-invasive EEG-BCI system to provide neurofeedback intervention to 10 patients with post-traumatic stress disorder [4]. By monitoring the activity of alpha and theta waves, patients were guided to regulate their EEG rhythm. After treatment, the PCL-5 scale score decreased by an average of 23.7%, and the frequency of invasive memory decreased by more than 50% in 5 patients. The effective rate was maintained at 68% during the 3-month follow-up. Two patients with high anxiety traits failed training due to their inability to concentrate. On a technical level, EEG signals are susceptible to interference from electromyographic artifacts, which can reduce classification accuracy. Ethically, there is a lack of data privacy protection mechanisms, and three patients are concerned about the security of data storage. In terms of clinical translation, high equipment costs and operational complexity limit grassroots popularization.

In the international practice of applying BCI technology to PTSD treatment, the closed-loop BCI system developed by the team from the University of California, San Francisco dynamically adjusts transcranial magnetic stimulation parameters by monitoring the neural oscillation characteristics of brain regions in real-time. Clinical trials in veterans have shown a 32% decrease in the amplitude of theta wave oscillations during traumatic memory arousal [5]. The Max Planck Institute in Germany adopts a multimodal BCI architecture, combined with functional near-infrared spectroscopy and electroencephalography, to construct a neural decoding model that incorporates edge system hemodynamic responses into closed-loop feedback, improving the accuracy of virtual reality exposure therapy scene switching to 89%. The National Psychiatric Research Center of Japan has developed a non-invasive BCI system based on steady-state visual evoked potentials, which induces gamma-band synchronization through light stimulation, trains patients to autonomously regulate network activity intensity, and significantly reduces CAPS scores in PTSD patients.

3.2. Comparative analysis

The paths of BCI technology in PTSD treatment vary internationally. The United States adopts non-invasive EEG combined with VR to construct a closed-loop neural regulation system; The EU focuses on invasive precision interventions, such as Germany's DBS technology. China is exploring EEG near-infrared fusion, but the decoding algorithm relies on imports. Policy support and technical standards affect development, DARPA in the United States heavily promotes military applications, EU ethical guidelines restrict invasive technologies, and China, although included in major projects, lags behind in funding and approval. Lack of standardization hinders cross-border research.

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4. Limitations and prospects

4.1. Limitation

The current research faces multiple challenges in exploring the application of BCI technology in PTSD treatment. The core issue is the insufficient sample size of the data, with clinical studies mostly based on small-scale cohorts and insufficient coverage of patient population heterogeneity, which limits the broad applicability of the results [9]. On a technical level, the signal acquisition of BCI systems is susceptible to individual differences in EEG characteristics and environmental noise, and the real-time stability of closed-loop feedback mechanisms need to be improved. The ethical review mechanism is not yet perfect, and there is a lack of systematic assessment of the risks of neural data privacy protection and long-term device implantation. In the future, research needs to build multi-center large sample databases and integrate machine learning algorithms to enhance pattern recognition. Develop wearable flexible electrodes and adaptive decoding models to enhance the universality of technology [10]. And an interdisciplinary ethics committee should be established to develop a standardized evaluation system for BCI medical applications to ensure the comprehensiveness and safety of the research.

There are significant limitations in the current BCI technology for treating PTSD. At the technical level, insufficient decoding accuracy of neural signals leads to high emotion recognition errors. The signal-to-noise ratio of non-invasive BCI devices limits the stability of therapeutic effects, while invasive devices have high resolution but pose risks of infection and implant tolerance issues. The neural feedback algorithm lacks universal parameters, and the development of personalized treatment plans is facing bottlenecks. The heterogeneity of research samples is insufficient, and clinical trials are mostly small-scale single center, lacking cross-cultural and cross course data. In terms of policy and ethics, China lacks special approval standards for BCI medical equipment and data privacy protection laws [11]. Lack of interdisciplinary collaboration hinders technological transformation. Short term capital investment and lack of basic research support [12]. The scarcity of professional talents and the shortage of composite talents affect the iteration and application promotion of technology.

4.2. Future research directions

The research on future BCI technology needs to focus on breakthroughs in core performance and in-depth exploration of multidimensional application scenarios. In terms of technological optimization, the key lies in improving the accuracy and real-time decoding of neural signals. Deep learning algorithms and high-density EEG acquisition technology should be integrated to develop specific EEG feature recognition models for PTSD patients. The research and development of biocompatible electrode materials needs to be accelerated, utilizing innovation in nanomaterials and flexible electronic technology to reduce the risk of invasive BCI infection and extend device lifespan [13]. For PTSD pathology, a brain computer interactive closed-loop feedback system should be constructed, integrating neural regulation and virtual reality exposure therapy to achieve personalized trauma memory consolidation intervention. Interdisciplinary collaboration requires the establishment of standardized research frameworks, the integration of neuroscience, psychiatry, and artificial intelligence theories, and the development of clinically applicable evaluation systems.

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5. Conclusion

This study found that BCI technology exhibits unique clinical value in the treatment of PTSD [14]. The current research mainly focuses on non-invasive EEG signal acquisition and neurofeedback training, guiding patients to engage in autonomous emotion regulation by decoding abnormal activation patterns in brain regions such as the amygdala and prefrontal cortex in real-time. Experimental data shows that the BCI system based on the motor imagery paradigm can effectively alleviate patients' symptoms of excessive alertness, with a relief rate of up to 63%, which is better than the 42% of traditional exposure therapy [15]. The closed-loop neural regulation mechanism of BCI technology can break through the limitations of traditional treatment, dynamically quantify the oscillation characteristics of θ and γ waves and construct personalized neural remodeling models [16]. The fNIRS BCI system with high spatiotemporal resolution can accurately locate abnormal blood flow signals in traumatic memory related brain regions and provide biomarkers for targeted interventions.

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