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Closed-Loop BCI-VR Integration: A Paradigm Shift in Precision Neuromodulation for Specific

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Abstract. Specific phobia is one of the most common anxiety disorders, with a global lifetime prevalence of approximately 7.4%. Existing treatments such as exposure therapy and cognitive-behavioral therapy are effective but often limited by high dropout rates, subjective evaluation, and constrained real-world applicability. This paper introduces a novel closed-loop brain–computer interface (BCI) and virtual reality (VR) integrated framework for precision neuromodulation in the treatment of specific phobias. The system utilizes real-time Electroencephalography (EEG) decoding to dynamically adjust immersive VR exposure scenarios based on individual physiological responses. Clinical evaluations involving patients with acrophobia and claustrophobia demonstrated significant reductions in subjective fear ratings and physiological arousal, with over 86% of participants showing improved adaptive responses. These results indicate that the BCI-VR closed-loop system enables quantifiable, personalized, and scalable intervention, offering a promising paradigm shift toward more accessible and effective phobia treatment. Further development may facilitate remote therapy applications and enhance treatment adherence through automated and adaptive neuromodulation.

Keywords: BCI, Virtual reality, Specific phobia, EEG

1. Introduction

Phobias are the most common mental disorders worldwide, characterized by excessive and unreasonable fear of specific objects or situations. According to the DSM-5 (Clinical Diagnostic Criteria), there are mainly three types of phobias, including specific phobia, social phobia, and agoraphobia. Specific phobia is the most common type of phobia, manifested as severe anxiety towards specific factors, including fear of animals such as spiders and snakes; certain occupations such as dentists or clowns; or certain situations such as heights or speed. Specific phobia results from the complex interaction of genetic susceptibility and environmental conditions [1]. Twin and family studies show that genetic factors play a certain role, and evolutionary theory suggests that innate fear of snakes, spiders, etc. is an adaptive survival mechanism. Genetic susceptibility, including high sensitivity to aversion and common pathways with social phobia, increases the risk of developing the disease, but genetic factors alone are not sufficient to cause the disease. Environmental trigger factors, especially classical conditioning, play a key role. In classical conditioning, neutral stimuli associated with trauma become conditioned fear stimuli. Implicit fear processing through the amygdala's "low road" may explain the occurrence of phobias without consciously recalling traumatic experiences, while social learning and direct traumatic experiences further influence fear responses [2]. Therefore, specific phobia reflects the interaction between genes and the environment, where genetic risk modulates an individual's sensitivity to environmental fear conditioning. A series of coordinated studies conducted by the World Health Organization in 22 countries in 2019 found that the global average lifetime prevalence rate is approximately 7.4%, while the average 12-month prevalence rate is about 5.5%. This means that approximately one in every 13 people worldwide may develop specific phobia in their lifetime, and in any given year, about one in every 20 people has an active phobia [3]. This indicates that specific phobia is a serious and non-negligible disease that affects humans, and with the sharp increase in modern social pressure, the current incidence rate may be even higher, which will have a significant negative impact on human mental health and cognitive development.

The main treatment methods for specific phobia include exposure therapy, cognitive behavioral therapy, and drug intervention, etc. Among them, exposure therapy is particularly effective, especially in real-life exposure therapy and virtual reality exposure therapy. Clinical trials show that its effectiveness rate can reach 70% to 90% [4]. Systematic desensitization therapy is usually implemented within the framework of cognitive behavioral therapy (CBT), achieving fear elimination by gradually facing fear stimuli, thereby significantly and persistently reducing symptoms. Notably, high-intensity "one-time" treatment plans can rapidly alleviate symptoms in 80% to 90% of cases, highlighting the responsiveness of this disorder to targeted intervention. However, there are still some limitations. Although it has a high success rate in controlled environments, its effectiveness in the real world is hindered by treatment accessibility, patient compliance, and the accuracy of implementation. Dropout rates remain high (20% to 45%), especially when the exposure therapy schedule is improperly arranged or there is insufficient psychological education, reflecting patients' fear of facing fear stimuli [5]. Drug intervention, such as benzodiazepines or D-cycloserine, has limited effects when used alone, and over-reliance on them may unintentionally reinforce avoidance behaviors. Although exposure therapy remains the standard treatment, certain subtypes of phobias face unique challenges due to ethical limitations of exposure therapy methods, thus requiring innovative adaptations. Additionally, comorbid conditions may complicate treatment outcomes, necessitating comprehensive and personalized treatment approaches [4]. Therefore, although specific phobia is one of the treatable mental disorders, optimizing practical application, reducing dropout rates, and enhancing treatment efficacy through personalized medicine remain crucial challenges for maximizing treatment effectiveness.

Thus, this paper mainly investigates how the closed-loop BCI-VR integrated therapy avoids the problems existing in the above-mentioned therapies through precise neural regulation in the treatment of specific phobia. Meanwhile, based on virtual reality exposure therapy (VRET), the application of BCI is combined to provide personalized treatment plans for patients.

2. Working principle

2.1. Birth background of BCI-VR integrated therapy

2.1.1. Therapeutic potential of immersive interaction

VR technology has been widely applied in various fields in recent years. Among them, in the medical field, VR technology is completely transforming the methods of patient care and medical training, with its core being the realization of psychological adjustment through immersive exposure therapy [6]. Compared with traditional technologies, it effectively breaks through the limitations of time and location. Taking the treatment of acrophobia as an example, the traditional method requires the therapist and the patient to go to a specific place for on-site intervention, while with the help of VR technology, the entire treatment process can be completed in the clinic. Secondly, traditional methods rely on the acquisition of real objects and the use of actual scenes, while the virtual environment can directly skip this step and switch to different scenes according to the patient's needs, thus easily achieving cost-effective simulation training. Therefore, this technology significantly reduces treatment costs, especially for aviophobia, VRET can eliminate the purchase of aircraft in the traditional treatment methods [7]. Moreover, in terms of patient acceptance, compared with other therapies, the attrition rate of VRET for therapists is very low. Most research participants indicate that VRET is a treatment option that reduces fear and has a higher level of satisfaction, further confirming the overall acceptability. Finally, VR exposure therapy repeatedly builds the same virtual scenes, allowing the therapist to gradually test the patient's tolerance limit, providing personalized and quantitative treatment plans for each patient, and further ensuring medical quality [8]. However, a single VRET is not applicable in some cases: studies have shown that VR exposure therapy is effective in treating phobias, but if the patient also has other mental disorders, such as depression, then the effect of exposure therapy will be reduced. At the same time, as mentioned before, the treatment effect is often closely related to the patient's anxiety level, and this indicator has strong subjectivity and large individual differences, posing certain challenges to the evaluation of therapeutic efficacy [9]. To adapt to the needs of a wider range of patients, the participation of brain-computer interface technology has become an essential part.

2.1.2. The rise of brain-computer interfaces and breakthroughs in neural decoding technology

Brain-computer interfaces are an emerging technology that enables humans or animals to interact with the outside world without relying on normal neural pathways, converting detected brain signals into instructions that can control the operation of computer devices [10]. The four core elements of a typical brain-computer interface system are neural signal acquisition, experimental paradigm design, decoding algorithms, and user feedback mechanisms. Neural signal acquisition technology is the basic means for measuring brain activity, the experimental paradigm is designed through carefully crafted psychological tasks to regulate neural signals, and the decoding algorithm is responsible for converting the measured neural signals into operation instructions and transmitting feedback information to the user [11]. In recent years, medical enterprises such as Neuralink have recognized the significant value of brain-computer interfaces in physical medical applications and have achieved a few clinical application successes [12]. Then, the application cases of psychological medicine are still relatively few, but with the optimization of neural decoding algorithms, related research has shown a trend of increasing year by year. Neural decoding algorithms are mainly divided into four categories: decomposition algorithms, Riemannian geometry, deep learning, and transfer learning [11]. Among them, transfer learning can solve the problem of individual differences in BCI and can produce personalized treatment plans for complex comorbid conditions.

2.2. Dual-module collaborative framework

The closed-loop BCI-VR integrated therapy system is an independent real-time system. When abnormal brain waves during the onset of mental disorders are detected, it will provide treatment. EEG can detect biological markers of mental disorders in the brain, enabling VR to spontaneously adjust to the appropriate settings based on the patient's specific situation and severity [13].

2.3. Key technology implementation

2.3.1. EEG neural decoding layer

In the collaborative treatment framework of VRET and BCI, EEG neural decoding is currently the optimal decoding solution. Its principle lies in real-time analysis of neurophysiological signals related to anxiety, fear, and cognitive regulation, and driving adaptive adjustments of the treatment environment based on this. The potential changes in the potential recorded by electrodes placed on the scalp from EEG signals are caused by ion current flows related to neural processes [14]. EEG signals can sensitively reflect the instantaneous brain state changes of the subject when performing specific cognitive tasks (such as responding to fear stimuli in the virtual environment). Thanks to its millisecond-level time resolution, EEG is particularly suitable for capturing the dynamic process of emotional responses and provides a key technical foundation for achieving closed-loop neural feedback.

The EEG decoding process begins with preprocessing of the original signals to suppress artifacts caused by body movement and environmental electrical noise - this is particularly important in highly interactive virtual reality. Then, through feature extraction and machine learning algorithms, neural markers related to psychological states are identified from EEG, such as brain frequency band power or event-related potentials (ERPs) that reflect alertness, anxiety intensity, or cognitive effort level. These decoded neural indicators constitute the input signals of the closed-loop system [15]. Based on the dynamically decoded neural states, the BCI system can dynamically adjust the parameters of the VR environment. For instance, when an anxiety level exceeds the threshold of high beta waves at 20-34Hz, or using the PhoVR anxiety algorithm which classifies anxiety into three levels (low level - within the range of [0, 3], medium level - within the range of [3, 7], high level - within the range of (7, 10]), when the value falls within the high level range, the system can automatically reduce the exposure intensity; if a successful emotional regulation signal is decoded, the challenge level can be maintained or moderately increased to promote habituation and extinction learning. This adaptive mechanism based on neural decoding overcomes the limitations of traditional VRET that relies on subjective reports, making the intervention more personalized and precise [16].

2.3.2. VR dynamic engine layer

The key to using VRET technology lies in whether the environment exposed to the patient is sufficiently realistic. Therefore, the construction of the VR platform and scene layout are of crucial importance. Developers use game engines to design virtual scenes, ensuring the authenticity and interactivity of the scenes. For example, the scenes developed by Unity Technologies using the product Unity 3D can simulate high-altitude environments and dynamically adjust the complexity and exposure level of the scene according to the patient's needs. Additionally, such game engines can be compatible with various computer operating system environments, such as Windows, iOS, Android, etc. The actual effect mainly depends on the patient's immersion in the virtual scene, which requires the scene to have good fidelity. When designing the virtual scene, some unstable factors can be added, such as setting it at a high position, enabling patients to quickly experience fear. After building the virtual scene, it is usually combined with virtual reality devices to use the VRET. The VR helmet (HMD) uses integrated screens, speakers, and gyroscopes to focus the patient's vision on the virtual scene, achieving visual isolation and dynamic perspective adjustment. Additionally, gesture capture devices use the "rubber hand illusion" technology to enhance the patient's tactile feedback, further enhancing the immersion. In the closed-loop BCI-VR integrated therapy, the VR dynamic engine layer can adjust the exposure level of the scene based on the patient's physiological signals in real time. For example, when the patient's heart rate increases or as mentioned earlier, the anxiety level exceeds the threshold, the system can automatically reduce the complexity of the scene or suspend the treatment to ensure the safety and effectiveness of the treatment [17].

3. Clinical application and analysis

3.1. Searching methodology

The research objective of this article is to include papers covering the cross-content of four main fields: Brain-computer interface, virtual reality exposure therapy, specific phobia, and EEG. Due to the broadness of the concept of specific phobia, in the search strategy, I need to focus on searching for acrophobia and claustrophobia. Similarly, this article also searches for the severity of mental disorders worldwide, the application principle of the BCI-VR collaborative mechanism therapy, and how to improve the stability of this therapy, and other related contents.

3.2. Reconfiguration of anxiety disorder treatment paradigm

3.2.1. Acrophobia

The conducted by researchers from Jiangxi University of Traditional Chinese Medicine employed VRET to intervene with 20 patients suffering from acrophobia, aiming to verify the feasibility and effectiveness of this therapy [17]. The experiment utilized Unity3D to construct three virtual scenarios, and adopted a three-stage design: the initial exposure stage recorded the baseline physiological data of the patients in scenario 1; the graded training stage conducted progressive exposure training every 3 days, each lasting 3 minutes, with a 5-minute interval; the effect evaluation stage analyzed the emotional regulation effect through heart rate peaks and brain wave frequency bands (α, β, γ). The results showed that 86.87% of the patients had a significant decrease in heart rate, and 90% of the patients experienced a reduction in fear levels, indicating that VRET has a significant therapeutic effect on acrophobia.

From the perspective of paradigm transformation, in this experiment, the VRET therapy possesses the following three elements: Quantifiable: Through heart rate and brain wave data, the objective assessment of fear levels can be achieved, providing a standardized basis for treatment effectiveness; Adjustable: Dynamic scene adjustments based on physiological signals (such as reducing exposure intensity) ensure the safety and targeted nature of the treatment; Accessible: Combined with remote medical care and automation technology (such as virtual coaches), it reduces treatment costs and enhances the scalability.

In summary, due to the use of heart rate peaks as a quantitative indicator of fear levels in this experiment, the decrease (86.87%) directly reflects the enhancement of patients' adaptability to high-altitude stimuli. High-frequency brain waves (α, β, γ) are highly correlated with emotional regulation, further confirming that VRET improves fear responses through neural plasticity. 18 patients (90%) had a significant reduction in fear levels, verifying the universality of VRET; while 2 patients did not show significant improvement, possibly due to individual differences or insufficient scene adaptability, suggesting that future optimization of personalized treatment plans should be combined with AI technology. Additionally, the study points out that the authenticity of the virtual scenarios still has limitations, especially in terms of tactile and auditory feedback. Therefore, enhancing the immersion of patients to achieve better treatment effects is an inevitable improvement direction in the future [17].

3.2.2. Claustrophobia

The study conducted by researchers from National Institute of Mental Health Topolova explored the application effect and neural mechanism of the closed-loop BCI-VR integrated therapy in the treatment of claustrophobia [18]. The research team developed a VR exposure therapy system, simulating closed scenarios such as elevators, underground parking lots, and subways through HTC Vive Pro devices, and recruited 18 subjects (10 patients with claustrophobia and 8 healthy controls) for experimental verification. The study employed the Subjective Distress Scale (SUDS), State-Trait Anxiety Inventory (STAI-XI), and Spatial Presence Questionnaire (IPQ) as the main assessment indicators, while combining electroencephalogram (EEG) to monitor changes in neural activity.

The experimental results showed that patients with claustrophobia exhibited the highest anxiety levels in the elevator scenario (average SUDS = 6.1), significantly higher than the control group ($p < 0.05$). Additionally, the spatial presence score (IPQ) of the patients was significantly positively correlated with SUDS ($r = 0.71$, $p = 0.021$), indicating that the immersive nature of the VR environment directly affects the anxiety-inducing effect. Notably, all participants did not show obvious motion sickness or other adverse reactions (SSQ score showed no significant difference), verifying the safety of this therapy.

From the perspective of paradigm transformation, in this experiment, this therapy possesses the following core characteristics: Quantifiable: Through SUDS and EEG data, the anxiety level can be objectively evaluated, providing a scientific basis for efficacy monitoring. Adjustable: The difficulty and interactivity of the VR scene can be dynamically adjusted according to the patient's response, such as extending the elevator blockage time or increasing the density of virtual characters, to achieve personalized intervention. Accessible: VR equipment is portable and cost-effective, making it suitable for promotion in clinical settings.

Specific case analysis revealed that a 35-year-old female patient (S02) had a peak SUDS score of 8 in the elevator scenario, but after multiple VR exposure training sessions, her anxiety level significantly decreased (FMA score increased by 7 points). Another 28-year-old male patient (S04) had a lower SUDS score (4 points) in the subway scenario, but a higher IPQ score (15 points), suggesting that the scene design needs to be further optimized to enhance the therapeutic effect.

In conclusion, the closed-loop BCI-VR integrated therapy provides an innovative solution for the treatment of claustrophobia through quantifiable, adjustable, and accessible technical paths. The study also points out that future research should expand the sample size and optimize the VR scene design to further verify its clinical applicability and long-term efficacy [18].

4. Challenges and solutions

4.1. Multi-modal fusion of fnirs-eeg resolves the challenge of signal fidelity

Although the spatial resolution of EEG is limited, its advantages in terms of non-invasiveness, relatively low cost, and high temporal resolution make it the preferred choice for VR-BCI closed-loop therapy. Although functional near-infrared spectroscopy (fNIRS) has an advantage in spatial resolution, its temporal resolution is lower than that of EEG because it measures hemodynamic responses, which change more slowly than brain electrical activity, and is therefore more suitable for applications that do not require immediate feedback. However, EEG is more sensitive to electrical noise and disturbances caused by body movements. This is a challenge in the virtual reality (VR) environment, as users often interact and move. To further achieve the goal of simultaneously obtaining high temporal resolution and high spatial resolution of neural information, existing research has explored the effective application of the fusion of EEG and fNIRS, which has weakened the interference of movement trajectories by 40% in terms of signal-to-noise ratio [19]. This enables researchers to precisely locate brain activity regions while also obtaining instantaneous closed-loop feedback. Therefore, EEG neural decoding in VRET-BCI collaborative therapy essentially builds a quantitative and adaptive communication channel, providing a novel neural engineering paradigm for the treatment of specific phobias.

4.2. Future technology optimization for immersive experience

In the future, through big data technology, physiological data and behavioral data of patients can be collected and analyzed to build personalized treatment models. For example, as mentioned earlier, PhoVR uses machine learning algorithms to classify patients' fear levels (low, medium, high) and dynamically adjust the treatment plan [16]. AI algorithms can make diagnosis more efficient and accurate [20]. Combined with BCI technology, the system can monitor patients' brain wave signals in real time and predict their fear state through AI algorithms. This closed-loop feedback mechanism makes the treatment process more precise and efficient. Moreover, it is worth noting that as AI drawing skills gradually improve, artificial intelligence technology can be used to optimize the design of virtual scenes. For example, through deep learning models to analyze patients' feedback data, a more challenging or safer scene can be automatically generated to meet the treatment needs of different patients [21].

4.3. Remote treatment addresses equipment and cost issues

As mentioned earlier, the two most common implementation methods of VRET currently are head-mounted display devices (HMD) and immersive virtual rooms. The latter usually consists of wall or floor projections, 3D stereoscopic glasses, motion capture systems, and operation equipment. Due to the high requirements for hardware equipment, physical space, and computer technology support of immersive rooms, their promotion is limited, and they are less used in clinical applications. In response to this, the application program developed by Oxford Virtual Reality Company (such as virtual coaches) has achieved automated treatment without the intervention of therapists, further reducing the cost of VRET through online treatment [17]. In the future, combined with cloud computing and 5G technology, closed-loop BCI-VR integrated therapy can be further promoted to the remote medical field, reducing treatment costs and improving accessibility.

4.4. Suggestions for breakthroughs in clinical application bottlenecks

For various phobias, current research has initially identified several intervention measures and described and distinguished their therapeutic effects. However, for specific types of phobias, the sample size for clinical applications is scarce, making it difficult to fully verify the direct effects of intervention measures or distinguish their influence from accidental factors and other uncontrolled variables in the study [22]. Therefore, only by scaling up clinical application cases and standardizing experimental procedures can a clear basis be established for the effectiveness of a specific treatment method in alleviating issues related to phobias, thereby encouraging more patients to accept the closed-loop BCI-VR integrated therapy.

5. Conclusion

This study demonstrates that closed-loop BCI-VR integrated therapy offers a innovative and effective approach for treating specific phobias through precise, real-time neuromodulation. By leveraging EEG-based neural decoding and dynamically adaptive VR environments, the system enables objective assessment and personalized exposure, addressing key limitations of traditional therapies such as subjective evaluation and high dropout rates. Clinical applications in acrophobia and claustrophobia confirm significant improvements in both physiological and subjective metrics, supporting the feasibility of this integrated model. Despite these promising results, challenges remain in signal fidelity, immersive experience optimization, and clinical scalability. Future work should focus on multimodal neural signal fusion, AI-enhanced scene generation, and large-scale randomized trials to further validate efficacy and promote translation into routine practice. With continued technical refinement and clinical validation, closed-loop BCI-VR therapy holds strong potential to expand access to precision mental health care and reshape treatment paradigms for anxiety disorders.

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