Proceedings of the 5th International Conference on Modern Medicine and Global Health
DOI: 10.54254/2753-8818/2027.39199

Mechanisms and Applications of Neuroplasticity in Cognitive Enhancement Driven by Brain-Computer Interfaces

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Abstract. Brain computer interface (BCI) is changing from "reading brain" to "regulating brain". Cognitive enhancement has become an important development direction of BCI, and neural plasticity is the core mechanism connecting BCI intervention and cognitive function improvement. Focusing on the evidence chain of "BCI neural plasticity cognitive enhancement", this paper systematically combines the mechanism of closed-loop neural feedback inducing neural oscillation and synaptic plasticity, and reviews its application in the clinical rehabilitation of AD/MCI, the early intervention of healthy aging and MCI, and the emotional assistance of severe cognitive impairment. Existing studies have provided imaging, behavioral electrophysiology and mediating causal evidence respectively, but there is still a lack of research to verify the three at the same time in the same paradigm, and there are problems such as the timeliness of cognitive state decoding, feedback synchronization, individual differences, standardization of training protocols, long-term safety and cognitive transfer. Cognitive enhanced BCI may also cause social equity and ideological privacy risks. In the future, large sample randomized controlled trials should be carried out to promote the development of personalized, multimodal and family-based BCI systems, and long-term safety assessment, cost control and neural privacy legislation should be strengthened.

Keywords: Brain-computer interface (BCI), cognitive enhancement, neural plasticity, neurofeedback

1. Introduction

Brain computer interface (BCI) technology is undergoing a paradigm shift from reading brain signals to controlling external devices to optimizing brain function by actively regulating neural activities. In this context, cognitive enhancement has become one of the important application directions of BCI in the future, and neural plasticity is the core biological mechanism linking BCI intervention and improving cognitive ability.

Nierhaus et al. found that about 1 hour of pure psychological electroencephalography (EEG)-BCI training can induce T1-weighted signal of gray matter and resting state functional connectivity centrality changes corresponding to the training target space in BCI novices. In MI-BCI group, blood-oxygen-level-dependent activity changes in task state also occurred, and mu rhythm modulation is related to magnetic resonance imaging (MRI) changes in sensorimotor area; this study claims to be the first to show that BCI can rapidly affect brain structure and function through

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DOI: 10.54254/2753-8818/2027.39199

targeted neural feedback, providing supporting imaging evidence for BCI induced neural plasticity [1], but did not evaluate cognitive function.

The study of Gomez pilar et al. included 63 healthy elderly people, 31 of whom received five times of BCI neural feedback training based on motor imagery. The cognitive functions such as visual space, language, memory and intelligence were significantly improved in the training group (except attention control), but there was no significant change in the control group. The relative power of 18 Hz and 21 Hz frequency bands increased significantly in 11 neurofeedback training subjects who completed resting state EEG recording. This study provides behavioral and electrophysiological evidence for BCI neural feedback based on motor imagery to improve cognitive function in the elderly, and suggests that it may involve the mechanism of sensorimotor rhythm regulation and neural plasticity [2], but does not directly measure neural plasticity, and the mechanism explanation is suggestive.

Jacques et al. used the EEG neural feedback paradigm of double-blind and active placebo control, and found that the subjects who successfully increased the individual alpha frequency (IAF) had significantly shorter attention response time, higher efficiency, and shorter alpha event-related desynchronization (α-ERD) latency; Mediation analysis further showed that the improvement effect of neural feedback on attention was partly mediated by the change of IAF, and the effect of IAF on reaction time was mediated by α-ERD latency. This study provides direct causal evidence for BCI neural feedback to improve cognitive function through neural oscillatory plasticity (IAF trainability) [3].

To sum up, the existing evidence supports the imaging, behavioral electrophysiology and mediating causal links in the chain of BCI neural plasticity cognitive enhancement, but there is still a lack of systematic validation of the three in the same paradigm. In view of this, this study aims to comb the evidence chain of BCI, neural plasticity and cognitive enhancement from mechanism to application. A systematic review of this evidence chain will help to sort out the key mechanisms and existing evidence gaps of BCI regulating neural plasticity and enhancing cognitive function, and provide a theoretical basis for the development of individualized and targeted BCI cognitive intervention strategies. At the same time, it also has important scientific significance and application value to promote the transformation of BCI from a simple neural signal decoding tool to a cognitive function regulation and enhancement platform.

2. Brain-computer interface development

2.1. From "reading brain" to "adjusting brain"

Brain computer interface (BCI) is an interactive technology that establishes a direct communication channel between the brain and external devices by collecting and decoding brain nerve signals. Its birth as an independent technology field is usually marked by the primate operant conditioned reflex experiment carried out by Fetz and other neuroscientists in the 1960s. They trained monkeys to control the rotation of analog instrument pointer by adjusting the discharge frequency of single motor cortex neuron [4]. After more than half a century of development, BCI has evolved from an early neurophysiological experimental tool to a comprehensive technology platform covering rehabilitation medicine, neuroscience, artificial intelligence, human-computer interaction and other fields.

Throughout the development of BCI, a clear transformation is taking place. BCI is changing from a tool for reading brain nerve signals, that is, reading brain signals to control external devices, to actively shaping and optimizing brain function through real-time regulation of nerve activities [5].

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The core goal of early BCI is to replace the damaged neuromuscular pathway and help patients control the mechanical arm, cursor, or wheelchair. With the improvement of neural decoding accuracy and the maturity of closed-loop feedback technology, the application boundary of BCI continues to expand. From controlling prosthetics, inducing rehabilitative neural plasticity to reconstructing paralyzed limb function, BCI has shown more potential than "substitution". In recent years, researchers have further proposed the concept of "neural co-processor". This concept refers to the integration of neural decoding and neural coding into the same device, and the use of artificial neural network and neural system to jointly optimize the objective function, so as to achieve a variety of functions from targeted neural rehabilitation to brain function enhancement [4]. This technological evolution marks that the functions of BCI are moving from "repair" to "enhancement", and from "defect repair" to "enhancement".

2.2. Cognitive enhancement

Cognitive enhancement refers to the process of surpassing the average cognitive level of individuals through technical means to improve their core cognitive functions such as attention and memory. Traditional cognitive enhancement mainly relies on pharmacological methods and behavior training, but these methods often have limitations such as inaccurate target, unsustainable effect, and large individual effect difference. BCI technology provides a new path for cognitive enhancement: by decoding the cognitive state of the brain in real time and providing accurate closed-loop neural feedback, BCI can realize the regulation of specific cognitive functions [6]. For example, Ta et al. developed a set of EEG-based BCI neural feedback games, requiring stroke and mild cognitive impairment patients to complete working memory tasks through their own attention levels. After three times of training, the EEG attention score of stroke patients increased by 4.29%-32.18%, and that of MCI patients increased by 4.32%-48.25%, indicating that closed-loop nerve feedback training can effectively enhance the attention and working memory skills of patients with neurological diseases [7].

2.3. Neural plasticity

Neural plasticity refers to the ability of the nervous system to adapt and repair through changes in synaptic strength and functional reorganization in response to changes in internal and external environments. Hebbian learning principle——nerves that fire together, wire together——provides a classic theoretical framework for activity dependent synaptic plasticity [8].

Closed loop neural feedback is the key mechanism to drive activity-dependent synaptic reinforcement, and its process is similar to reward learning: when BCI detects the target neural state and gives feedback immediately, the brain will associate this activity with positive feedback. The repetition of this process gradually strengthens the neural model of the target, and finally induces the lasting change of outstanding efficiency and functional network reorganization [9]. Based on this mechanism, BCI cognitive enhancement is not to instill information into the brain by external devices, but to guide brain self reorganization through closed-loop neural feedback. However, cognitive states (e.g., concentration) lack the time characteristics as clear as motor intention, which makes the closed-loop design of cognitive enhanced BCI face greater technical challenges in terms of feedback time synchronization.

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2.4. Application scenarios of cognitive enhanced BCI

2.4.1. Clinical rehabilitation of cognitive impairment in AD and MCI

The application of cognitive enhanced BCI in clinical rehabilitation of cognitive impairment focuses on solving the problems of limited drug efficacy and cognitive decline in patients with Alzheimer's disease (AD) and mild cognitive impairment (MCI). The key technology is EEG neural feedback as the core. EEG collects EEG in real time, extracts the characteristics of the target frequency band or brain region, and then through game or picture feedback, enables patients to learn to regulate brain activity autonomously.

In a study of 10 patients with AD, the researchers used nerve feedback training twice a week, a total of 30 times. The results showed that the total score of Cambridge Cognitive Examination (CAMCOG) was improved by an average of 2%, and the memory and learning subdomains were significantly improved. Its advantages are non-drug, non-invasive and repeatable. However, due to the small sample size, lack of long-term follow-up and strict control, the clinical significance and long-term safety still need to be verified [10].

In a randomized controlled trial of 27 patients with MCI, the researchers used EEG nerve feedback training. With the goal of individualized alpha band (PAF to PAF+2Hz), they collected signals from PZ electrodes, trained patients to autonomously regulate brain activity through three-dimensional games and sound feedback, and conducted 10 times of training (30 minutes each time). The results showed that the comprehensive score of memory in the experimental group was significantly improved (from 89.76 ± 14.49 to 101.25 ± 11.59, P=0.003), and remained improved after 30 days of follow-up. There was no significant change in the pseudo feedback group. This study suggests that EEG neural feedback has the potential to intervene memory decline in patients with MCI, and it is a non-drug and non-invasive method. However, the sample size is small, there are differences in baseline memory scores between groups, and EEG power has not changed significantly, which still needs to be verified by larger samples [11].

In addition, sun et al. also proposed a personalized EEG neural feedback scheme to customize the training frequency band and target by comparing the EEG differences between patients and healthy people, so as to solve the problem of training inefficiency caused by individual differences. This scheme is expected to improve the intervention efficiency, but it still needs to be verified by randomized controlled trials [10].

2.4.2. Healthy aging and early intervention of MCI

The application goal of cognitive enhanced BCI in the healthy elderly, subjective cognitive decline and early MCI population is to delay cognitive aging and improve cognitive reserve. The key technologies are usually multi-band EEG neural feedback, working memory or attention training, and BCI devices that are easier to home.

Houmani et al. performed double-blind EEG nerve feedback training on 37 healthy elderly with subjective memory complaints, targeting gamma band synchronization. The study used unsupervised machine learning to analyze individual neural dynamics. It was found that only part of the subjects in the real feedback group successfully enhanced gamma synchronization and extended to the full frequency band, while the sham group had no such effect. This study reveals the key influence of individual differences on the effect of neural feedback, and provides the basis for personalized BCI intervention in healthy aging. However, the sample size is small, there is no long-

DOI: 10.54254/2753-8818/2027.39199

term follow-up, and the cognitive improvement is not apparent, which still needs to be verified by larger-scale randomized controlled trial (RCT) [12].

Jirayucharoensak et al. used game EEG nerve feedback training for 65 aMCI and 54 healthy elderly women, extracted beta/alpha power ratio with consumer Emotiv headgear to assess attention level, and trained 20 times. The results showed that spatial working memory strategy and continuous attention were significantly improved, but pattern recognition memory did not change. This scheme is low-cost and can be family-oriented, but it is limited to female samples and lacks sham control. The long-term efficacy needs to be verified [13].

2.4.3. Low threshold assisted interaction for severe cognitive impairment: exploratory direction

Application of cognitive enhanced BCI in assisting people with severe cognitive impairment patients with moderate to severe AD who are difficult to learn complex neural feedback paradigms. The key technology is to use high contrast emotional cues, such as laughter and crying, instead of traditional feedback signals, so that patients can participate in training without complex learning. However, at present, this direction is still in the early exploration stage, and there are few BCI studies directly targeting moderate and severe AD. The existing evidence is mostly from healthy subjects or people with mild disorders, and the clinical transformation is limited.

Sun et al. mentioned that emotional brain computer interface can be used for such patients. Its advantage is to lower the threshold of training and improve participation. However, the specificity of EEG characteristics, individual differences, ethical issues and long-term efficacy induced by emotional stimulation still need to be verified [10].

Van der Heiden et al. used functional magnetic resonance imaging (fMRI) semantic classical conditioned reflex paradigm to pair consistent/inconsistent word pairs with infant laughter and scream, trying to decode "yes/no" thinking. The key technology is to use emotional sounds to induce conditioned brain responses, and to distinguish the two types of responses by the activation of the left insula and the trigone of the inferior frontal gyrus. In the late acquisition stage, the emotional stimulation can still be distinguished, which suggests that the training threshold for patients with cognitive impairment can be reduced. However, the samples are small, only healthy people, rely on fMRI and fade quickly, and the clinical transformation is limited [14].

At present, there is insufficient direct evidence for the direction of cognitive enhanced BCI to provide low threshold assisted interaction for people with severe cognitive impairment. Most existing studies come from healthy people or people with mild cognitive impairment. Although van der Heiden et al. proved that emotional conditioned brain response can be used for decoding, fMRI and healthy subjects cannot be directly extrapolated to EEG-BCI of moderate and severe AD. Therefore, the scene is still an exploratory direction.

3. Deficiencies and prospects

Cognitive enhanced BCI faces technical challenges such as poor timeliness of cognitive state decoding and difficult synchronization of feedback, large individual differences and inconsistent training protocols, unclear effects of cognitive transfer and long-term maintenance, lack of assessment of long-term safety, and small existing research samples and insufficient control.

In addition, the purpose of cognitive enhanced BCI is to improve people beyond the normal level, rather than restore the function lost. Therefore, if this kind of BCI enters the market, its high technology cost may lead to the further expansion of "cognitive difference". The economically

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advantageous groups improve their academic ability and professional competitiveness by using cognitive enhanced BCI, and exclude the economically disadvantaged groups. This kind of problem may aggravate the gap between the rich and the poor and form more serious social differentiation.

Moreover, BCI directly reads and regulates brain activity, which means that the privacy of personal thoughts will be under unprecedented threat. Once the cognitive enhancement BCI system is frequently used in the work or learning scene, it will produce a large number of data about individual emotional tendencies and potential ideological tendencies. Once these data are obtained by commercial institutions, it may lead to the risk of "neural monitoring" and "thought manipulation". The power of individuals to control their state of consciousness and thoughts will be threatened and challenged with the application of BCI.

In the future, we should develop high-time resolution decoding and adaptive closed-loop feedback, construct individualized programs and unified training protocols, carry out large sample randomized controlled trials and long-term follow-up, establish a long-term safety evaluation system, and promote multimodal and familial BCI systems to improve intervention accessibility and ecological validity. At the same time, technology costs need to be reduced to ensure that economically disadvantaged groups can also use it, so as to reduce the aggravation of the gap between the rich and the poor caused by cognitive enhancement differences, and promote the government to design relevant laws to protect personal ideological privacy and avoid ideological data leakage.

4. Conclusion

This paper reviews the mechanism and application status of BCI driving cognitive enhancement through neural plasticity. BCI technology can induce neural oscillation and synaptic plasticity by means of closed-loop neural feedback, realize the regulation of cognitive functions such as attention and memory, and promote the paradigm shift of BCI from "reading brain" to "regulating brain". In the three application scenarios of clinical rehabilitation of AD and MCI, early intervention of healthy aging and MCI, and emotional assistance for severe cognitive impairment, BCI-driven neurofeedback training has shown preliminary efficacy, in which there is relatively more evidence of clinical rehabilitation, while emotional assistance for severe cognitive impairment is still an exploratory direction. However, problems such as the timeliness of cognitive state decoding, feedback synchronization, individual differences, standardization of training protocols, long-term safety and cognitive transfer effect still need to be solved. At the same time, the application of cognitive enhanced BCI is bound to cause social equity problems, and may disclose the user's ideological privacy, which will bring the risk of neural monitoring and thought manipulation. Future research should focus on the long-term safety assessment of cognitive enhanced BCI, reduce technology costs to ensure that economically disadvantaged groups can also use it, so as to reduce the problem of increasing the gap between the rich and the poor caused by cognitive enhancement differences. At the same time, relevant government agencies need to design laws to protect personal ideological privacy and avoid ideological data leakage. On this basis, its application scope is further expanded, not only limited to clinical treatment and rehabilitation.

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