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# Research Status and Application Scenarios Exploration of Brain Computer Interface Chip Technology

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**Abstract:**

Brain-computer interface is a rapidly developing emerging field in the 21st century, with important applications in multiple disciplines. This article mainly discusses the research status and application scenarios of brain-computer interface chip technology, and analyzes the related potential risks and countermeasures. Neuralink has made progress in the research and development of brain-computer interface chips, and at the same time, other researchers are also improving the signal processing algorithm. Brain-computer interface chips are widely used in the diagnosis and treatment of limb movement disorders, cognitive disorders, mental illnesses, sensory defects, epilepsy, and neurodevelopmental disorders. However, this technology has potential risks in terms of chip lifespan, stability, popularity, and ethics, which need to be addressed through countermeasures such as designing stable chips, conducting biocompatibility studies, improving cost-effectiveness, strengthening data protection, and formulating relevant laws and regulations. In conclusion, brain-computer interface technology has great development potential, but it needs to be fully studied in many aspects to ensure its healthy development.

**Keywords:** Brain computer interface; Current research status; Multiple application scenarios; Countermeasures.

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## 1. Introduction

Brain computer interface (BCI) refers to a technology that creates a connection pathway for information exchange and control between the brain of organic life forms and devices with processing or computing capabilities [1]. In 1969, implantable brain computer interface technology was first applied to primates, proving that the brain has good neural plasticity. On the basis of this success, in 1978, the first implantable brain computer interface device for vision recovery was successfully applied to the human body [1]. Regarding the brain computer interface of the "motor nerve prosthesis", significant progress was made in the late 20th century. In 1998, scientists first implanted an invasive brain computer interface in humans that could obtain high-quality neural signals to simulate movement, thus officially entering the 21st century. In 2005, a patient with quadriplegia achieved for the first time the use of an invasive brain computer interface to control a robotic arm and computer cursor control through motion intention. In 2012, a well-known magazine published the latest research results on brain computer interfaces. A female volunteer with high-level paralysis successfully controlled a robotic arm using only her thoughts, delivering a piece of chocolate to her mouth. In 2014, the research team further achieved 10 dimensional free control of external robotic arms, including shoulder, elbow, wrist, and finger movements, making it the most complex display of implantable brain machine interface controlled robotic arms to date. After a period of training, the patient is able to control the spatial three-dimensional movement of the external robotic arm, the three-dimensional rotational movement of the wrist, and the four dimensional free movement of the fingers through EEG. In 2020, a research team further achieved feedback decoding of grasping parts and strength, enabling paralyzed volunteers to effectively control their own grasping strength. With the increasing maturity of implantable brain computer interface chip technology, more and more functions are gradually being applied to various fields. In the current medical field, traditional medical techniques are no longer sufficient for the treatment and rehabilitation of patients with movement disorders and brain function, such as paralysis, Parkinson’s disease, ALS, and other diseases, as well as daily monitoring of health status in people’s lives, such as sleep quality monitoring, attention concentration monitoring, etc [2]. In order to address the limitations of traditional medical techniques in treating movement disorders and brain dysfunctions, the demand for brain computer interface chip technology with interactive functions has increased across various fields, with higher requirements for performance and functionality.

Therefore, the quality of chips, the functionality of chip technology research and development, the scope of application, and the accuracy and convenience of brain computer interface technology are constantly being improved.

# 2. Brain Computer Interface Chip Technology

## 2.1 Research Status of Brain Computer Interface Chips

Neuralink is currently a leader in the development of brain computer interfaces. The company focuses on manufacturing chips that can be implanted into the human brain through surgery, promoting direct connection between the human brains and computing devices [2]. In 2019, the first design product for implanted chips was launched; On April 9, 2021, Neuralink announced its latest research progress, which showed that a monkey successfully using an invasive brain computer interface could control its brain to play games and learn autonomously through mental control [3]. In 2024, the company conducted the first human transplant of brain computer interface chips.

## 2.2 Exploration of the Application of Brain Computer Interface Chips in Multiple Scenarios

While Neuralink focuses on hardware development, other researchers are working on improving signal processing algorithms. At present, frequency spectrum analysis of signals mainly considers the trade-off between speed and accuracy, or ignores the non-stationary characteristics of signals. A significant advancement in this field is the development of an open-source algorithm for Fast Continuous Wavelet Transform (fCWT) [4]. The parallel environment of fCWT separates scale independent and scale dependent operations, while utilizing the optimized fast Fourier transform of downsampling wavelets. FCWT has been proven to have the accuracy of CWT, with a spectral resolution 100 times higher than algorithms with the same speed, and 122 times and 34 times faster than reference and state-of-the-art implementations. fCWT provides a better balance between speed and accuracy, enabling real-time, broadband, and high-quality time-frequency analysis of non-stationary noise signals. By reimplementing existing signal processing computing techniques, the technology has been successfully improved by 100 times [4]. Since the 21st century, the development of brain computer interfaces in China has been rapid. Brain-computer interface technology has transitioned from laboratories to practical applications, enabling disabled patients to control robotic arms and other devices using their brain’s electrical activity

### 2.2.1 Diagnosis and treatment of limb movement disorders

There are two primary methods that BCI technology is used for treating and diagnosing limb movement disorders. One is an auxiliary brain-computer interface (ABCI), which uses BCI devices to gather the patient’s intention for movement in order to control external equipment like exoskeletons or prosthetics. Theoretically, BCI systems can use a variety of sensors and other signal acquisition tools to track signals produced by brain activity. Through signal analysis and processing (feature extraction and pattern recognition in the following section), signals are categorized based on individual cognitive tasks, corresponding control commands are produced, and the objective of facilitating user-external device interaction is accomplished [5]. Typically, it is employed in web-based BCI platforms to enable users to visualize how their thoughts align with the control outcomes, as illustrated in Fig. 1.

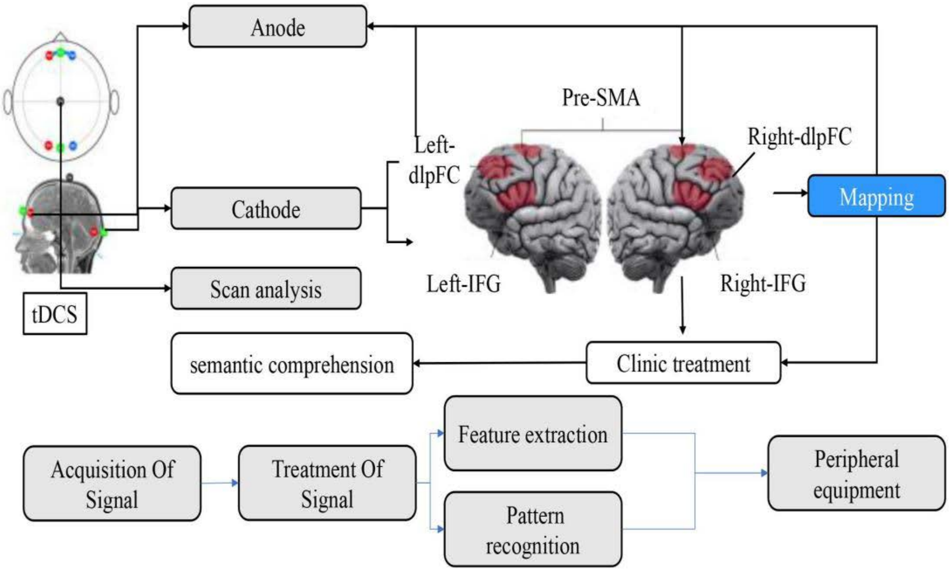

**Fig. 1 Schematic diagram of brain information processing [5]**

Another type is rehabilitation brain computer interface, it utilizes the plasticity of the central nervous system to directly apply repetitive feedback stimulation to the brain through BCI devices, thereby enhancing neuronal synaptic connections and achieving repair. The principle of using brain consciousness to control the operation of devices is demonstrated in Fig. 2.

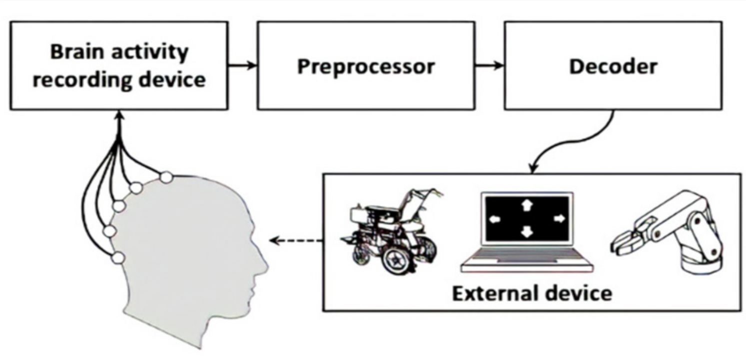

Fig. (1). Brain-Computer Interface (BCI) System.

**Fig. 2 BCI system [6]**

Regarding auxiliary brain computer interfaces, researchers have been studying the use to help paralyzed individuals regain control of their limbs, or to enable amputees to control prostheses and interact with computers using their thoughts. The devices implanted in patients record a large amount of neural activity, which is then transmitted to the brain through wires.

In terms of rehabilitation brain computer interfaces. Rehabilitation brain-computer interfaces employ functional electrical stimulation to activate muscles that have lost nerve control, potentially restoring or improving motor function. This stimulation induces muscle contractions, which can replace or correct lost motor function in organs and limbs. According to the principles of human neurophysiology, the nervous system has the ability to self-repair and reorganize. Leveraging this ability, electrical stimulation of nerves and muscles is used to stimulate incoming nerves and repeatedly train movement information. This stimulation and movement information is introduced into the central nervous system, forming neural traces in the cerebral cortex. This process plays a significant role in promoting the recovery of lost motor function. Functional electrical stimulation has been widely applied in the field of stroke rehabilitation and has attracted the attention of most rehabilitation workers. Appropriate FES can induce corresponding muscle contractions, thus compensating for lost limb movements. Simultaneously, the feedback from different users, including their satisfaction levels and sensory experiences, as shown in Fig. 3 is transmitted through the peripheral nervous system to the central nervous system. This feedback helps in mapping and promoting the reconstruction of limb movement function in the higher brain areas [5].

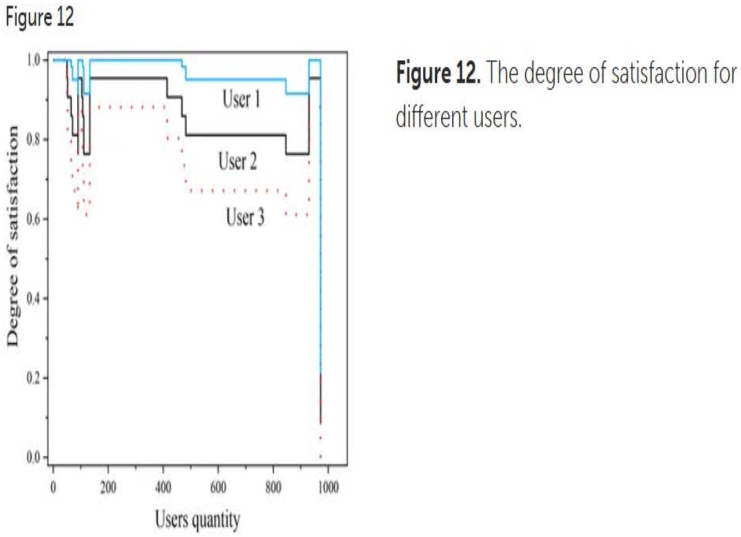

Fig. 3 The degree of satisfaction for different users [5]

### 2.2.2 Diagnosis and treatment of cognitive impairment

Early symptoms of Alzheimer's disease can be detected through the detection of patients' brainwaves, enabling early intervention treatment. Communication disorders are commonly present in Alzheimer's disease (AD). These disorders are often considered early indicators of neuropathology, as they can occur long before memory impairment. In the most advanced stage of Alzheimer's disease, short and repetitive high-frequency segments are mainly characteristic of the patient's speech. Patients may only be able to speak a few words, and may even regress to mutism. Despite these symptoms, even in the later stages of the disease, patients may seek social contact and attempt to respond to conversational stimuli through gestures, body language, and eye gaze [7].

The basis of brain computer interface is its reliance on directly recording and decoding brain activity, aimed at restoring, replacing, or enhancing damaged central nervous system (CNS) function. The uniqueness of this technology lies not only in providing an interface for interacting with external devices, but also in opening up new possibilities for neurological rehabilitation and therapeutic interventions [8].

The professor of MIT lab Li-Huei Tsai has demonstrated that stimulating the mouse brain with light and sound can produce positive brainwaves that enhance memory and cognition. Through brain waves, this non-invasive therapy offers hope for the treatment of Alzheimer's disease.

The University of Southern California team led by Professor Theodore Berger has figured out the brain's hippocampus's memory coding. It has been established through studies conducted on the brains of mice and monkeys that brain information may be duplicated for memory transplantation using electrical signals from silicon chips. Patients with Alzheimer's disease, stroke, and local brain damage may be able to regain their memories with the help of implanted chips. Comprehensive research on the possible use of brain-computer interfaces in Alzheimer's disease (AD) patients was carried out by Liberati et al. Their study focused particularly on patients in advanced stages who have lost their language communication abilities. They propose a shift from traditional brain-computer interfaces, which rely on tool learning and self-regulation, to models based on classical conditioning, potentially more suitable for AD patients. Traditional brain computer interfaces pose challenges to AD patients due to their cognitive impairments. Nonetheless, the author suggests a novel association technique that associates "yes" and "no" with both favorable and unfavorable emotional cues. A typical activation map for linear SVM classification, which is frequently used in brain signal processing, is shown in Fig. 4 to help explain this idea. This approach is based on the hypothesis of emotional brain computer

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interfaces, which reduces the requirement for patients to engage in active cognitive activities by using involuntary brain impulses, such as those associated with emotional emotions. Brain computer interfaces have the potential to open up a new communication channel for individuals with AD by leveraging these involuntary impulses, particularly those resulting from emotional stimuli. This could lead to an exciting new phase of advancements in AD rehabilitation and diagnostic techniques, as well as communication strategies [8].

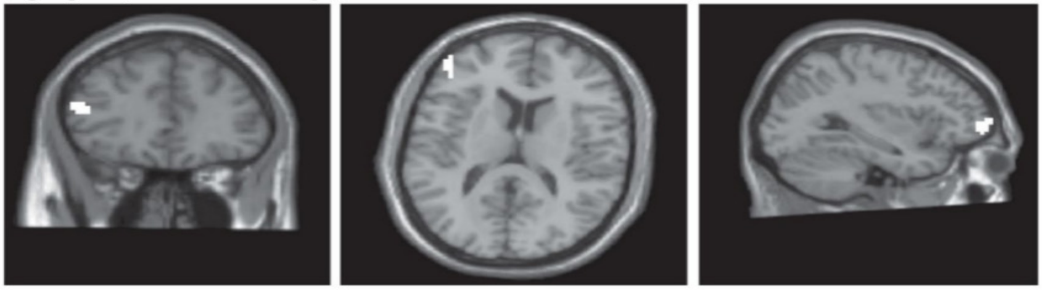

**Fig. 2.** Activation map from a healthy subject during the extinction phase of an fMRI classical conditioning paradigm ısing linear SVM. Acquisitions were done on a 3.0 Tesla body scanner with a standard 12-channels head coil (Siemens Magnetom Tim TRIO, Siemens, Erlangen, Germany) using an EPI sequence. The image showcases activation predominantly in the inferior frontal gyrus [6].

**Fig. 4 Linear SVM-based fMRI classical conditioning paradigm during the extinction phase of a healthy subject's motivation map [8]**

### 2.2.3 Diagnosis and treatment of mental illness

Emotion recognition research based on EEG signals can assist in the study and treatment of the pathogenesis of mental illnesses like depression and anxiety. The Amber project of Alphabet's experimental research and development laboratory, for instance, aims to obtain and analyze brain waves via brain-computer interface devices, develop objective measurement methods for depression and anxiety, and thus help healthcare professionals diagnose depression more easily and objectively. In the rehabilitation treatment of mental illnesses, neurofeedback training that is based on brain-computer interfaces can have a positive impact on the treatment of depression, anxiety disorders and other conditions.

Major Depressive Disorder (MDD) is a common mental health condition characterized by persistent despair, loss of interest, anxiety, and recurrent suicidal thoughts. At present, the main defense against MDD includes drug antidepressants. However, despite being the main drugs for depression, their efficacy is being questioned and the treatment effectiveness is not ideal. Therefore, there is a need for alternative therapies for patients with refractory depression, and attention should be directed towards neuroregulatory therapy.

Neuroregulation utilizes external devices to directly or indirectly affect various aspects of brain function. These include neuronal transmission, firing patterns, neural plasticity, neurogenesis, brain metabolism, and the occurrence of epileptic seizures. Neuroregulation methods can be categorized into invasive and non-invasive approaches. Invasive methods, which require surgical intervention, include deep brain stimulation (DBS) and electroconvulsive therapy (ECT). Non-invasive methods, on the other hand, include various forms of transcranial stimulation such as repetitive transcranial magnetic stimulation (rTMS) , accelerated transcranial magnetic stimulation (aTMS), intermittent theta burst stimulation (iTBS), and transcranial electrical stimulation (CES). Among them, ECT has long been recognized for its therapeutic effects. However, its side effects, such as memory loss and cognitive impairment, have prompted the search for more refined interventions.

Due to these demands, a targeted innovation for ECT called focal electric epilepsy therapy (FEAST) has been developed. New developments in real-time brain imaging and electroencephalogram (EEG) feedback in brain computer interface (BCI) technology offer a revolutionary platform for optimizing neural regulatory methods. With its distinct benefits, brain-computer interface (BCI) can help overcome certain obstacles in neural regulation by enabling more individualized care and precise control. Through real-time brain activity analysis, brain-computer interface (BCI) systems are able to tailor therapies according to each person's distinct neural patterns, which may enhance responsiveness and minimize adverse effects. Furthermore, more substantial therapeutic benefits might be possible through the combination of BCI with currently used neural regulatory techniques like rTMS, aTMS, MST, and iTBS, particularly in situations when patients have become resistant to conventional therapies. BCI offers opportunities for FEAST invention and improvement, but it also makes other neural regulatory techniques more optimized, leading to more specialized and adaptable treatment modalities. Focal electroconvulsive therapy (FEAST) represents an innovative treatment method in the field of neural regulation. Compared to traditional ECT, FEAST offers more precise targeting and potentially fewer side effects.

This progress witnesses a shift from broad brain targeting to more precise and localized methods, particularly targeting the right prefrontal cortex (rPFC), an area that has long been associated with depression. The key to FEAST's innovation lies in its unidirectional and asymmetric placement of the anode and cathode in the frontal lobe region of the right hemisphere. This unique location makes local transcranial direct current stimulation possible. In clinical practice, FEAST is gaining recognition as a superior alternative to traditional ECT. This transformation is supported by research, which shows significant improvement in patients with refractory depression and minimal side effects. In summary, FEAST provides a promising treatment approach for refractory depression, avoiding serious side effects such as cognitive impairment or amnesia traditionally associated with ECT. Repetitive transcranial magnetic stimulation (rTMS) is a leading, non-invasive, long-term (tested for weeks to months) brain stimulation therapy primarily used for patients resistant to traditional depression treatment. By utilizing a strong magnetic field with a strength of 1-2 Tesla, rTMS generates electrical currents in neurons, thereby altering their firing patterns and internal ion flow. The integration of electroencephalogram system enhances the effectiveness of rTMS. This enables the detection of transcranial magnetic stimulation induced cortical potentials (TEPs), thereby improving the accuracy of surgery. The non-invasive nature of rTMS makes it a favorable treatment for MDD. Accelerated transcranial magnetic stimulation (aTMS) represents an innovative improvement over traditional rTMS therapy, specifically designed for refractory cases of depression. By utilizing stimulation settings similar to rTMS, targeting the DLPFC region with an intensity of 1.5-2T and a frequency of 10-50 Hz, aTMS stands out with its accelerated treatment regimen. The mechanism behind this acceleration method lies in the concentrated and intense application of magnetic stimulation, which may induce more direct neural plasticity changes in the target areas of the brain. Unlike traditional rTMS clinical trials that typically take 4-8 weeks, aTMS completes its treatment cycle within five consecutive days. During this period, patients may receive up to six sessions per day. The concise duration of treatment and rapid therapeutic effects make ATM an attractive option. In addition, clinical studies have found that ATM is relatively well tolerated, with transient headaches being the most common side effect. Magnetic epilepsy therapy (MST) is a non-invasive treatment method that uses ultra-high magnetic fields to induce controlled epileptic seizures in the brain, typically lasting no more than 10 seconds. MST draws inspiration from the epilepsy induction therapy of electroconvulsive therapy (ECT) and integrates the unique neural regulation techniques of transcranial magnetic stimulation (TMS) to target refractory.

An advancement over conventional TMS is intermittent theta burst stimulation (iTBS), a sophisticated non-invasive neuromodulation method. Through the integration of cutting-edge algorithms and BCI feedback, along with the concept of θ burst activity, iTBS has emerged as a promising treatment option for depression. It is a useful tool in contemporary mental health care and has the potential to alter the course of depression treatment due to its efficiency, patient comfort, and efficaciousness of treatment [9].

#### 2.2.4 Diagnosis and treatment of sensory defects

Brain computer interface technology can enable patients' own sensory information, potentially enabling sensory recovery. An advancement over conventional TMS is intermittent theta burst stimulation (iTBS), a sophisticated non-invasive neuromodulation method. Through the integration of cutting-edge algorithms and BCI feedback, along with the concept of θ burst activity, iTBS has emerged as a promising treatment option for depression. It is a useful tool in contemporary mental health care and has the potential to alter the course of depression treatment due to its efficiency, patient comfort, and efficaciousness of treatment [9].

#### 2.2.5 Diagnosis and treatment of epilepsy and neurodevelopmental disorders

In the diagnosis of epilepsy, electroencephalography has always been an important reference for clinical diagnosis. With the breakthrough of collection devices and methods, research on brain function and diseases has become increasingly in-depth, and brain computer interfaces have many relatively mature applications in the field of epilepsy. For example, in the diagnosis and treatment of epilepsy, the brain's function and disease signals can be determined through EEG output, and "instructions" can be generated by electrical stimulation of intracranial electrodes to induce the response of patients' functional areas. Alternatively, techniques such as surgical resection, thermocoagulation, and laser damage can be used to alter and treat the brain's epilepsy network.

Besides epilepsy, brain computer interface technology is also applied in other neurodevelopmental disorders, such as ADHD, autism, sleep disorders, and language disorders [7].

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### 2.3 Potential Risks and Countermeasures

The first crucial consideration is the lifespan of the chip itself. If the chip cannot maintain stability or gradually fails in the brain, it may have an impact on brain function. Therefore scientists need to design chips that can work stably for a long time, while considering ways to replace or repair the chips. The next consideration is the stability of the chip in the brain [10]. This involves examining whether the chip can be securely fixed and whether this fixation will affect surrounding neural tissue, which requires detailed biocompatibility studies and long-term tracking research. Chip design must consider compatibility with brain tissue to avoid damage or interference to nerves. Finally, the popularity of chips also needs to be considered [10]. The popularization of technology involves factors such as cost, technological maturity, and social acceptance. Chips need to have high cost-effectiveness and undergo extensive verification in order to be widely popularized. Chips also involve the collection and transmission of personal privacy data, so strong data protection measures are currently needed to prevent data leakage and abuse. The final consideration is the ethical issues involved in implanting chips, including respect for individual wishes, the use and misuse of chips, and so on. Society needs to formulate and improve laws and regulations related to brain computer interface technology, and regulate relevant ethical issues.

## 3. Conclusion

Currently, brain computer interface technology is an emerging field of significant international interest, attracting attention from numerous universities and high-tech enterprises. This technology has great research space and many cutting-edge research directions. It can play a crucial role in scientific research, medical care, and consumption fields, helping people improve their convenience of life and health levels. In the near future, scientists may combine invasive and non-invasive BCIs to give full play to their respective advantages, which will bring a great breakthrough at the technical level. For example, in terms of signal acquisition, a hybrid signal acquisition system that combines the two may appear in the future. For instance, non-invasive electrodes are used on the scalp to obtain relatively comprehensive electroencephalogram signals. At the same time, tiny invasive electrodes are implanted in specific areas of the intracranial cavity to obtain accurate signals from key brain regions, comprehensively improving the signal quality and the accuracy of interpretation. In terms of electrode technology, new types of electrodes that combine the advantages of invasive and non-invasive electrodes may be developed someday. For example, a wearable microelectrode array that can partially penetrate the scalp and enter the shallow layer of the intracranial cavity not only ensures a certain degree of safety and non-invasiveness but also can obtain high-quality brain signals. In terms of signal processing algorithms, more intelligent and efficient signal processing algorithms will be developed for brain signals with different characteristics collected by invasive and non-invasive methods. With the continuous development and improvement of technology, BCI chips are also likely to have more mature technology and lower costs, and the application of this technology to multiple fields such as education and entertainment will further improve ethical standards. Overall, the development of BCI technology will bring enormous opportunities, but it also requires sufficient research and discussion in terms of technology, safety, ethics, and other aspects to ensure its healthy development.

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