Current Perspective of Brain-Computer Interface Technology on Mild Cognitive Impairment

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Abstract. This work find that the current literature review of brain-computer interface (BCI) in the treatment for the people suffering from mild cognitive impairment (MCI) is a relatively unexploited field compared to other application of BCI techniques. Through our literature retrieval strategy, starting from the theoretical basis of BCI in the treatment of MCI and the pathological basis of MCI, this paper explains the advantages and importance of introducing brain-computer interface into the treatment of MCI. Then, starting from the mode of obtaining brain-related information from BCI, the paper describes the detection methods and possible treatment methods of BCI in the field of treating MCI by applying multiple BCI-related methods such as BCI-based EEG method, BCI-based fMRI method, and BCI-based fNIRS method. This paper also discusses how these BCI-based methods can be combined and interact with each other to provide a better detection and treatment for MCI diagnosis and rehabilitation. Finally, the above several forms of BCI are used to describe the possible future development direction and the existing difficulties of these methods, and why these difficulties may prevent researchers from applying these methods to the actual clinical practices.

Keywords: Brain-Computer Interface, Mild Cognitive Impairment, EEG-BCI, fMRI-BCI, fNIRS-BCI.

1. Introduction

Between dementia and normal human aging, mild cognitive impairment is an extreme condition. Patients will have perceptible decline in memory, language and other cognitive functions, and clinical examination will also find a certain degree of damage, but not enough to affect the function of daily life. The pathogenic mechanism of MCI is multiple, and the risk of MCI increases with age. Stroke, diabetes, depression and other diseases may increase a person's risk of developing MCI [1,2]. Currently, there are no standard medications or guidelines for the treatment of MCI symptoms, so they can only make some auxiliary habits to keep their minds healthy. In addition to these mechanisms, some researches have shown that people with MCI are more likely to develop Alzheimer's symptoms. The most important symptom of MCI is memory loss, and BCI technology is known to restore and improve the memory ability of elderly patients; non-invasive BCI regulates brain activity through the use of electromagnetic stimulation and biofeedback as part of a rehabilitation program for memory recovery and improvement; Episodic memory in patients can be improved by BCI technology, and predictive memory may be encoded by oscillatory of the coupling mechanism of Alpha and Theta waves [1].

The pathogenic mechanism of MCI is diversified, which mainly depends on the main etiology. Aging is the most common and independent branch, with impaired attention and memory. Other significant causes of MCI include traumatic brain damage, neurodegenerative illnesses, and cerebrovascular diseases in addition to aging. Neurodegenerative diseases: this disease includes Alzheimer's type of dementia, Parkinson's disease, and Lewy body dementia. Cognitive decline occurs before other underlying symptoms. Cerebral vascular disease: patients diagnosed with cerebral infarction, multiple infarctions, chronic cerebral ischemia, and combined vascular brain injury by

MCI. Traumatic brain injury: mild cognitive impairment may be temporary or long-term persistence of traumatic injury [2].

Neuroplasticity is the ability of the brain to undergo reorganization in the linking of neurons, and it is the basis of all rehabilitative methods. BCI-based cognitive rehabilitation, like other rehabilitative methods, also needs to induce stimulation to the brain, therefore, triggering neuroplasticity. There are 4 mechanisms for stimulation of neuroplasticity: 1. Neurofeedback training, 2. Operant conditioning, 3. Reinforcing the neuron circuits 4. Hebbian learning. Neurofeedback provides patients with visual feedback of the brain activity from certain brain areas. Then patients would try to regulate this activity. The principle this method holds that regaining of brain activations that is more close to normal state would lead functional recovery. A neuronal circuit is strengthened via operant training by reinforcement by rewarding desired behavior and punishing undesirable behavior.For BCI, the reward is positive sensory feedback, such as the correct movement of a robotic arm, while the punishment is incorrect or no movement. It is believed that using this technique will result in the same neuroplastic changes as learning to interact with a new stimulus.Hebbian learning is mostly used in motor rehabilitation, where the relationship between movement-related brain activity and proprioceptive input is more tightly regulated, triggering Hebbian plasticity, which is hopefully enhancing the sensory-motor loop.

BCI technology has begun to have a lot of research and breakthroughs in neurotherapy, but in the field of MCI, the application and research of BCI is relatively few. This essay aims to conduct a review of all recent research on the use of bci in the area of mci. The basic tenets of BCI are presented first in this essay, classifies the EEG collection methods of BCI, and explains the detection and therapeutic role of BCI in the field of MCI in multi-mode and single-mode. Finally, the corresponding advantages and disadvantages and prospects are summarized.

2. Related works

Decoding brain signals in the BCI research area has specific approaches to process the brain data, they can be utilized to control model, automatic robot, cognitive analysis, and some analysis in cognitive disease. Some neuroimaging modalities have common acquired methods, data preprocessing, feature extraction, and some analysis tools. Specifically, those processes are indicated as follow: i) Acquired brain signals; ii) Signals preprocessing; iii) Signal feature extraction; iv) Features analysis and classification. From the perspective of this work, some neuroimaging modalities are summarized in the MCI diagnosis as the following content.

2.1. Different Types of BCI for MCI Diagnosis

Several types of BCI methods, in terms of EEG, fMRI, fNIRS, are currently applied in MCI diagnosis and treatment. All these three are relatively mature methods that have been studied and improved for several decades. They are widely recognized as effective, cost-efficient non-invasive techniques for brain functional detection and imaging. Based on this, they could also detect abnormal functions or activities of brain on pathological changes. Thus, once available biomarkers of MCI are determined, EEG, fMRI, and fNIRS could be used for early non-invasive detection and assessment of MCI, which is rather vital in the entire MCI treatment, especially at the early phase. In addition to detection and assessment, fMRI and fNIRS have also shown potentials in curing or suppression MCI via combination with neurofeedback training. With neurofeedback training method, MCI patients can manage to inhibit or enhance one particular kind of brain activity, regaining a brain functional pattern that is more similar to normal state. Further, this is believed to show benefits in the curing of MCI. In this part, the writers will discuss the above contents in depth, and also introduce their classifications, mechanisms, how they work, their effectiveness, while illustrated by state-of-the-art cases of research.

2.2. EEG-based BCI

The electroencephalogram (EEG) is a method introduced in neuroscience research and creating BCI to detect and measure the brain activity and does not require implantation of any artificial materials directly onto the human brain. EEG brain signal detection is widely used as a biomarker during the diagnostics of symptoms of cognitive impairment at the early stage of the disease. In general, neuro-degenerative diseases can be difficult to be recognized and distinguished from common consequences of aging, therefore, a unique EEG signal of MCI patients can be a useful biomarker to indicate the existence of the disease, even before the symptoms have been observed. A study by Yu-Tsung Hsiao and his team used an EEG-based classification system to separate MCI patients from healthy controls. Interestingly, the Higuchi's fractal dimension (HFD) was not used in this experiment; instead, the Katz's fractal dimension (KFD) was [3].

EEG is usually combined with other BCI-related method to improve cognitive performance for the MCI patients. In 2019, Jirayucharoensak and his team introduce a novel method, which receives brain signal information of the candidates from EEG detecting devices, to enhance the cognitive performance for the amnestic mild cognitive impairment patients based on game. The results of this experiment revealed that the new system which combines the game and neurofeedback training greatly improved the ability of processing visual information, decision making and spatial memory for the patients [4].

2.3. fMRI-based BCI

fMRI-bci is a noninvasive method used to image the brain. FMRI can track the changes of blood flow. The principle is that when the corresponding region of the brain becomes more active, it consumes more energy and needs more oxygen, so more blood flows to that area, providing it with the oxygen it needs. fMRI uses the BOLD principle, the ratio of oxygenated hemoglobin to deoxyhemoglobin in the blood, to present an image of the brain. In the form of voxels. The basic steps of FMRI-BCI system and BCI are the same, including signal acquisition, signal analysis (feature extraction) and instruction conversion. fMRI-BCI generally takes exercise imagination as the paradigm and can reflect the changes of cerebral blood oxygen metabolism in the process of exercise imagination. For example, when subjects perform motor imagination tasks, analyze their significantly activated voxels and determine a coefficient that converts data from these voxels into BCI output, which is used to feedback to the subjects to produce the effect of neural feedback. The FMRI-BCI model is divided into two models: screening and treatment in the field of cognitive impairment. In the Sitaram team's research, positive and negative emotional states (for example, happiness and disgust) can be distinguished by using support vector machine classifiers. In addition, by taking bold signals from multiple brain regions and classifying them online, researchers have created an FMRI-BCI to provide users with feedback about their emotional state, which may be used to treat emotional problems such as impulses caused by MCI [5]. Owen and his team can detect online "neurobehavioral" through a fMRI-BCI, so it can be used as an important diagnostic tool for assessing disease progression in consciousness disorder [6]. Kazuhisa and his team used online feedback to decode FMRI signals to evoke a pattern occurring in the visual cortex. In the absence of awareness of what to stimulate participants to learn, only the induced activity mode is sufficient to induce visual perceptual learning. It can be seen that decoding fMRI can lead to the plasticity of nerve cells and has the potential to improve MCI [7]. Similarly, according to Rana and his team, this approach may also help slow motor function and cognitive ability decline due to aging [8].

2.4. fNIRS-based BCI

fNIRS is also a non-invasive method that measures the changing of Hemoglobin concentrations evoked by neural activities [9]. When a brain area is active, the rate at which oxyhemoglobin is consumed would increase. This leads to increased perfusion of oxygen-rich blood to this area, and such increa14se could be significantly detected by infrared electromagnetic wave, which has a wavelength of 700-900 nm, because biological tissues are highly transparent to light at such wavelength [10], with only hemoglobin (Hb), myoglobin (Mb), as well as cytochrome oxidase (CytOx) absorbing electromagnetic waves [11]. Among these, Mb is not present in normal mammalian brains, while CytOx only changes its oxidation state under severely hypoxic situations, thus is not interesting in functional imaging perspective [11]. fNIRS can be subdivided into three categories, that include continuous-wave fNIRS, frequency-domain fNIRS and time-resolved fNIRS. Continuous-wave fNIRS continuously emit electromagnetic waves at a fixed frequency. Hence, this method could only measure relative change in oxy-Hb and deoxy-Hb concentration, thus is usually used in task studies to investigate the relative change of activity. Frequency-domain fNIRS uses a continuous beam of electromagnetic wave which has sinusoidal amplitude; time-resolved fNIRS uses near-infrared pulses which lasts for picoseconds. The latter two methods can measure absolute changes in Hb, hence is applied in rest-state studies to measure the absolute level of cerebral oxygen. fNIRS is widely used for detection and evaluation of brain pathological changes caused by MCI. Yang et al. in 2019 evaluated 15 digital biomarkers for diagnosing MCI by performing various tasks with fNIRS [12]. Researchers also apply fNIRS to assess the effectiveness of MCI treatment. Ghafoor et al. detected and compared fNIRs signals of working memory from MCI patents, MCI patients treated with acupuncture, and healthy controls and patients treated with acupuncture had significantly improved fNIRS signals proving the effectiveness of acupuncture in treating MCI [13]. In another aspect, neurofeedback method based on fNIRS has shown its potential in MCI treatment owing to its capability to change and enhance some specific activations in prefrontal brain. A study from Hudak et al. demonstrates that fNIRS-neurofeedback training aimed at prefrontal cortex could improve inhibitory control of highly impulsive adults [14]. Children and adults with ADHD are also trained by fNIRS-neurofeedback protocol in many studies. Research based on Go-noGo task by Marx et al. in 2015 reveals that fNIRS-neurofeedback training might improve inhibitory control in ADHD children. Further, Blume et al. showed that adult participants trained by 12 rounds of fNIRS-neurofeedback gained better inhibitory control and reduced ADHD symptoms [15]. Nevertheless, control groups trained by EEG and EMG-neurofeedback has minimal improvement in inhibitory control, demonstrating that fNIRS-neurofeedback can improve inhibitory control, leading to decreased ADHD symptoms, with advantages over EEG and EMG-neurofeedback in ADHD-related cognitive therapy. On the other hand, Li et al. discovered that fNIRS-neurofeedback training could be used to modulate the activation the orbitofrontal cortex (OFC), which indicates its potential application in cognitive flexibility and reward processing [16].

3. Discussion

However, for the EEG-based BCI, there are also some challenges that EEG-based techniques need to face. Firstly, since the EEG brain signal sensing devices are commonly non-invasive, they can be easily interfered with by other noise sources, leading to blurred results which are difficult for the researchers to interpret. To solve this low signal-to-noise ratio, better signal processing technology advances might be the solution. Moreover, the machine learning method may also contribute to the solution to this challenge. With the machine learning method, the BCI devices are able to spontaneously upgrade and 'evolve' themselves to yield more clear and accurate results for the researchers to interpret and help researchers understand the experimental results. Secondly, the neural pathway is possible to be rewired after brain injury, therefore, it could be difficult to locate the source where the EEG signal comes from. Thirdly, the brain signal can have different characteristics in different individuals which may negatively impact on the interpretation of experimental results. Creating a subject-specific model could be helpful to overcome this issue.

The main drawback of fMRI-BCI is the resolution; the images generated by its scans do have a resolution i.e., voxels. As technology improves and the voxels of fMRI become smaller, the higher the spatial resolution of fMRI becomes, with high resolution fMRI scans being able to divide the brain into about a million regions. The problem, however, is that one million regions is still too large compared to the neuronal perspective meaning that fMRI is far from being able to show all of the neurons. While the resolution of fMRI-BCI relative to neurons still needs to be supported by technological developments.Current research suggests that ultra-high magnetic field fMRI at 7T intensity can observe a finer view of brain structure and can explore finer patterns of overlapping activation within brain regions [17]. A more serious problem lies in the temporal resolution, the delay between brain activity and the fMRI response seen by BOLD imaging is a significant drawback of fMRI-BCI, restricting the temporal resolution, which may affect the degree of MCI detection, as well as neurofeedback therapy for BCI, according to recent study, by performing BCI only with EEG data after doing simultaneous EEG/fMRI sessions to establish the mapping from EEG to fMRI. A new function for translating fMRI to EEG has been proposed, bringing fMRI closer to EEG, so that in the future sampling methods combining several different techniques may be able to solve the problem of temporal resolution [18]. The main goal of current fMRI-BCI based techniques for brain rehabilitation lies in the development of RtfMRI combined with neurofeedback mechanisms. RtfMRI signal feedback is not only used in clinical imaging of brain nerves, but also used in the treatment of related diseases.In the process of clinical application of RtfMRI, it is found that time delay is a fatal shortcoming of this method. The reason is that the neurofeedback principle of FMRI-BCI requires timely feedback for signal analysis. However RtfMRI is still difficult to achieve this, so the time delay in signal acquisition and imaging analysis warrants more future research [19].

fNIRS has several advantages over EEG and fMRI. First, temporal resolution of NIRS is inferior to EEG, but is still acceptable. Nevertheless, the spatial resolution of EEG is quite poor, while NIRS have a good spatial resolution. The temporal resolution of NIRS is nearly equal to fMRI yet the crucial advantage lies in the portability [9, 11]. fNIRS systems are well-miniaturized and wireless, enabling unconstrained measurements. An fNIRS device only include one or several pairs of diodes, which is commonly placed over the patient’s head using the 10-20 system. Another strength is that fMRI can be readily integrated with other neurocognitive techniques. Many studies have combined fNIRS with fMRI to complement each other, allowing a more versatile application. Attempts are also made to combing fNIRS with EEG. In addition, fNIRS is immune to ordinary electrical or magnetic devices including pacemakers, hearing aids, etc., which is a limitation to fMRI. Nevertheless, many obstacles still exist in front of fNIRS [11]. One issue is that, fNIRS is susceptible to motion artifacts which result from undesired moving of patients during image acquisition. Second, fNIRS can only acquire information from certain parts of brain, mainly frontal regions, with a depth of few centimeters, which is one of the key limitations of fNIRS [9]. Third, signals derived from fNIRS are often interfered by noises coming from physiology factors. A series of methods and algorisms are developed to counteract noises coming from motion artifacts and physiology interferences, however, further improvements are still needed is this field. Moreover, fNIRS does not present anatomical information, so MRI or 10-20 system is needed to aid such information.

4. Conclusion

BCI as a burgeoning field of research has shown promising applications in multiple directions. In MCI, one of the most important issues is identifying the biomarkers of MCI, which can be used for early detection, classification, and assessment of MCI. BCI methodologies, including EEG, fMRI, and fNIRS are widely used for aiding this issue and have shown capabilities and their respective advantages in this field. On the other hand, these BCI techniques are appreciable in MCI treatments. Existing studies indicate that BCI-based MCI treatment is an underestimated area that more attention and deeper research.

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