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Innovative Non-Invasive Brain-Computer Interfaces for Addressing Cognitive Decline in the Elderly

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Abstract. The problem of cognitive decline in the elderly is becoming increasingly crucial as the population ages. It is normal to experience some degree of cognitive decline as one ages. However, severe cognitive decline can lead to some elderly individuals being unable to engage in independent daily life. Thus, it is important to research strategies for enhancing cognitive capacities or preventing cognitive decline, particularly those related to Brain-Computer Interface (BCI) technology. Functional Near Infrared Spectroscopy Imaging (fNIRS)-BCI, for instance, is real-time, portable, non-invasive, and appropriate for mobile environments. However, its spatial resolution is low, limited by its light penetration ability, making it difficult to monitor deep brain activity. On the other hand, sophisticated brain-computer interfaces and complicated brain function studies can benefit from functional Magnetic Resonance Imaging (fMRI)-BCI due to its high spatial resolution and wide coverage. However, the equipment is expensive, bulky, and requires a static environment with poor real-time performance. Transcranial Doppler (TCD)-BCI is appropriate for risk assessment and cerebral blood flow monitoring as it is portable, non-invasive, and able to track changes in blood flow in real time. However, monitoring only blood flow velocity indirectly monitors brain activity, limiting its application scope. This article will introduce the research and application of three different types of non-invasive BCI in improving cognitive decline in the elderly, as well as their respective advantages and disadvantages.

Keywords: Brain-computer interface, cognitive decline, non-invasive BCI.

1. Introduction

Elderly cognitive decline refers to the phenomenon where cognitive functions gradually decline with age. This decline includes a decrease in memory, attention, executive function, and other aspects. With the intensification of the global aging trend, cognitive decline in the elderly has become a common and important public health issue. Its impact is not limited to individual quality of life but also involves pressure on social medical resources. Therefore, researching and developing effective detection, prevention, and intervention methods is of significant social importance. A brain-computer interface method called functional near-infrared spectroscopy imaging (fNIRS) brain-computer interface (BCI) uses near-infrared light signals to detect changes in surface blood oxygen content, which is then used to interpret user brain activity [1]. This method is non-invasive because it uses near-infrared light to penetrate the scalp and gather data on variations in cerebral blood oxygen levels without requiring implanted instruments. Because of its portability and low weight, the device may be used in a variety of settings, such as homes, clinics, and mobile situations [2]. Moreover, compared to other brain imaging

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techniques, fNIRS equipment is less costly. It is appropriate for monitoring brain functions like cognitive state, attention, and effort despite having a reduced spatial resolution since it has strong temporal resolution and can swiftly reflect changes in brain activity [3,4]. It is widely used in rehabilitation therapy and educational research. Blood oxygen level-dependent (BOLD) signals in the brain are detected by Functional Magnetic Resonance Imaging (fMRI) BCI, a magnetic resonance imaging-based technology that interprets human brain activity [5,6]. It monitors deep brain activity and covers the entire brain with great spatial resolution and accuracy in locating brain activity zones.

Its high resolution enables fMRI BCI to be used for precise brain function research and is commonly used in cutting-edge research in the fields of mental illness, neurological rehabilitation, and emotion recognition [7]. Transcranial Doppler (TCD) BCI is a method that measures variations in the direction and velocity of blood flow in the cerebral blood vessels, interprets brain activity, and manages the interface using ultrasound technology [8]. TCD is a mature clinical tool with portability and real-time capability, mainly used for monitoring cerebral blood flow and evaluating cerebrovascular health status [9]. Its application primarily focuses on blood flow monitoring rather than the direct interpretation of brain neural activity.

2. fNIRS-based BCI

Near-infrared light signals form the basis of the non-invasive brain functional imaging method known as fNIRS. fNIRS-BCI interprets these signals to determine user intent and employs fNIRS to measure changes in brain oxygen concentration. This allows the gadget to communicate with external devices. fNIRS first uses near-infrared light sources and detectors to monitor changes in blood oxygen levels in brain tissue through the scalp. The obtained optical signals are then preprocessed because there are many kinds of noise in the near-infrared spectral signals. Before converting the original data, experimental errors and instrument noise must be eliminated because they are independent of brain activity. After data preprocessing, different brain activities are classified based on certain features. Classification techniques are used to identify different brain signals generated by users and predict their intentions. Lastly, translate the recognition outcomes into commands to operate external devices.

Subcortical brain impulses are very efficiently captured by fNIRS. It is inexpensive, lightweight, and portable. Its temporal resolution is likewise good [10]. Consequently, there is a great deal of promise for the application of near-infrared spectroscopy in neurofeedback research. Mihara illustrated how users might be given the freedom to modify their hemodynamic responses through the use of fNIRS-based neurofeedback [11]. They discovered that fNIRS-based brain feedback improved the hemodynamics linked to motor imagery. Kober discovered that fNIRS-based neurofeedback may be utilized for prolonged training, and that this type of recurrent neurofeedback can cause focused and targeted brain activation [12]. Communicating with patients who have mobility impairments is one of the primary uses of brain computer interfaces. For binary communication, Naito and Naseer created a fNIRS-BCI system based on prefrontal brain activation [13,14]. Answers of "yes" or "no" were contingent upon the individuals completing a predetermined task, such as mental arithmetic or musical imagination, to maintain relaxation or increase cognitive load. Based on fNIRS-BCI, Sitaram presented an online word speller [15]. Their method entails moving the cursor on a two-dimensional image with the right and left hands' motion imagery in order to choose letters. Restoring motor function in individuals with movement problems is a significant use of fNIRS-BCI. To enable users to move freely while using wheelchairs or prosthetics, use the control commands that the BCI system generates. These applications also need to be quick enough to offer real-time control and cannot tolerate large error rates. A few fNIRS-BCI experiments aim to increase the rate of information transmission and classification accuracy [16]. For brain functional imaging, fNIRS-BCI offers a non-invasive, portable, and reasonably priced option that is appropriate for broad application in clinical and research settings. However, its use in some fine brain function research is limited because of its relatively poor resolution and the limited absorption of light signals by the skull and scalp.

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3. fMRI-based BCI

The BOLD effect is the foundation of fMRI, a non-invasive brain imaging method. FMRI-BCI collects high-resolution brain activity data using MRI technologies. Preprocessing fMRI pictures is necessary to enhance their quality before moving further with additional analysis. Next, identify the brain regions that are actively active in real time and perform either univariate or multivariate analysis. Interpret user intentions through analysis. Finally, convert the inference results into control signals to achieve interaction with external devices.

Neurofeedback, which is the intentional self-regulation of activity in a particular region of the brain by feedback on activation levels in that region, can be implemented using FMRI-BCI. Because fMRI has a high spatial resolution and can photograph the entire brain, activation levels at certain anatomical areas (ROIs) can be extracted using fMRI-BCI and used as feedback. In a pain research, DeCharms employed flame-like feedback, where the flame's intensity rose in proportion to the signal strength [17]. Red and blue are employed in thermometer feedback, which Sitaram investigated, to show whether the signal is above or below baseline [18]. Weiskopf employs the feedback intensity difference curve, wherein activity enhancement is shown by rising arrows [19]. Decoding brain states, which entails examining the subject's MRI data to ascertain their purpose and then using that information to communicate with external equipment, is another usage for fMRI-BCI. Yoo divided brain signals into four states using pattern matching to allow computers to travel in space using BCI [20]. Sorger created the first fMRI-BCI based spelling system in history by using pattern matching to identify 27 different brain states [21]. Three BOLD signal characteristics can be separately changed by individuals in this method, producing 27 distinct brain responses that correlate to 27 characters. Because of its extensive brain activity coverage and excellent spatial resolution, fMRI-BCI is an effective tool for researching complex brain disorders and functions. However, its application is limited by high equipment costs, complex operations, and high environmental requirements, and is mainly used in laboratories and hospitals.

4. TCD-based BCI

TCD-BCI is a system that measures cerebral blood flow velocity (CBFV) in the brain's major basal arteries using ultrasound technology, interprets the data, and uses the data to operate the interface [22]. TCD measures blood flow velocity by first passing high-frequency ultrasonography through the skull and then measuring the ultrasound's reflection in the cerebral blood vessels. Subsequently, TCD analyzes variations in blood flow velocity to indirectly infer the condition of brain activity. Ultimately, the blood flow signals that have been detected are analyzed and transformed into control signals that can be utilized to operate external equipment or check on the health of the brain through the brain computer interface. Eshtiak used TCD to investigate how the human brain's activation and relaxation states are decoded [23]. Two ultrasonic TCD probes at the participants' temporal window were used to collect signal data; these probes could not be positioned in opposite directions. In the end, the features that were chosen were classified using a naïve Bayes classifier and linear discriminant analysis (LOA), which effectively distinguished between psychological activities that were relaxed and those that were activated. Thus, proving the feasibility of decoding the psychological state of the human brain.

TCD-BCI is a mature clinical tool with wide applications in cerebral blood flow monitoring. Its advantages lie in portability and real-time monitoring capabilities, but due to only monitoring blood flow changes, it cannot directly interpret complex neural activity signals, and its application scope is relatively limited [9].

5. Conclusion

FNIRS-BCI is portable and real-time, suitable for use in various environments, especially clinical and mobile environments. And it is non-invasive, without the need to penetrate the skin or skull, providing a comfortable user experience. But its spatial resolution is low, and it can only monitor surface activity of the cerebral cortex, unable to penetrate deep into brain structures. Moreover, optical signals are easily affected by scalp, skull, and hair, and data may be affected by noise interference, affecting accuracy.

Therefore, fNIRS has significant advantages in mobile or outdoor applications, especially in the fields of rehabilitation and emotional monitoring, with good application prospects. Compared to fNIRS BCI, fMRI BCI has higher spatial resolution, allowing for clear brain imaging that covers the entire brain and delves deep into deep brain structures. But its equipment is expensive and bulky, and requires a specialized shielding environment. Due to the need for subjects to remain still, fMRI is not suitable for application in dynamic environments, limiting its application scope. FMRI has low temporal resolution and poor real-time performance. Appropriate for the investigation of intricate brain processes, analysis of high-level cognitive abilities, and identification and management of neurological conditions. The TCD-BCI device is relatively portable and suitable for bedside monitoring and daily clinical applications. Can quickly provide blood flow data with real-time capability. However, it has a single function and mainly measures cerebral blood flow velocity, which cannot directly monitor neural activity or provide detailed brain imaging. Therefore, the application scope is limited. Commonly used in stroke risk assessment, cerebral blood flow monitoring, and other situations that require dynamic blood flow data. The application range of TCD is limited, the real-time performance of fMRI is inadequate, and the spatial resolution of fNIRS is restricted. These restrictions have affected their popularity and promotion in a wider range of application scenarios. Future development paths include developing more sophisticated signal processing methods, decreasing costs, increasing portability, and boosting spatial and temporal resolution. And technology integration, combining the advantages of different technologies to develop more powerful and comprehensive brain computer interface systems.

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