Neurocognitive and Physiological Effects of Meditation

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Abstract. In recent years, brain-computer interface (BCI) technology has made significant progress in multiple interdisciplinary fields, especially with the combination of artificial intelligence, neuroscience and computing technology, which has achieved the decoding of human thinking and enabled patients who cannot speak to express their ideas again. This article mainly discusses the application of BCI in restoring language function, especially the research progress for patients with amyotrophic lateral sclerosis (ALS). First, this article introduces the lateralization of brain language function and analyzes the key brain areas involved in language generation and expression. These areas work together to complete the conception, organization and final muscle control of language. Secondly, this article focuses on the application of BCI in patients with language disorders, especially the case of ALS patients. The study obtains language-related brain signals by implanting microelectrode arrays and decodes them in combination with artificial intelligence algorithms, so that patients can display what they want to express on the screen. Finally, this article discusses the brain signal decoding technology based on EEG and phoneme analysis and summarizes the limitations of BCI technology in language restoration, such as the service life of implanted devices and brain atrophy of patients. Despite the challenges still faced, the continued development of BCI technology is expected to bring a higher quality of life to patients with aphasia and play a greater role in the field of neurorehabilitation in the future.

Keywords: Functional connectivity; pain modulation; short-term meditation; consciousness.

1. Introduction

In recent years, brain-computer interfaces are devoted to multiple interdisciplinary areas. One of its major focuses is combining artificial intelligence, brain-computer interfaces and neurological science to decode the actual thoughts of humans without them saying them aloud. One of its most significant applications that have been developed in the past several years is assisting patients who have disabilities in speech such as Amyotrophic Lateral Sclerosis (ALS), to regain the ability to communicate with the outside world. With the use of this specific technology, patients are able to transfer what they want to say into actual words on monitors, in certain cases, artificial intelligence is used to analyze the sound of patients' audio and speak again using their voice.

Over the past few decades, research in brain-computer interfaces (BCI) has made tremendous progress in enabling people to control external devices such as robotic arms, prosthetics, and even wheelchairs using only their brain signals. However, the conversion of thought patterns directly into language—specifically readable words or sentences—remains an elusive goal. The challenges in this endeavor are multifaceted, requiring a deep understanding of both the brain's neural coding and the development of sophisticated computational algorithms to decode those signals into intelligible outputs. Additionally, the hardware used to detect brain activity—whether through electroencephalography (EEG), functional magnetic resonance imaging (fMRI), or invasive neural implants—must be both precise and reliable, a challenge in itself [1].

In 2024, an experiment conducted at UC Davis successfully assisted a patient with ALS who is in the locked-in state to actually present what he is thinking on monitors which rebuilt his connection with the outside world [2]. With their breakthrough in this area, this technology can be further modified and advanced to be ready for the broader use of patients with similar symptoms.

Within this paper, the main focus will be explaining different parts of the brain that are devoted to the functionality of communication, specifically aiming at parts which express verbal signals. Furthermore, the collection of the verbal signals of the brain with the help of invasive electrodes of brain-computer interface. In the last part, it discusses the use of Artificial Intelligence and machine learning to find certain patterns in these verbal signals that were extracted from the brain and decode them into actual understandable language that could be shown on monitors. At the end, the paper will briefly cover the conveniences that this technology brought to real life and the problems that it can solve.

2. Lateralization of Brain Language Function and Generation of Language Signals

Before determinating the exact locations of the parts which reflect brain signals about verbal and communication ability of human, it must be decided which side of their brain is dominating communication and verbal abilities. This varies for different people, in the general case, most people have their left sided brain mainly focusing for their speech, communication and verbal abilities. Also it have a small dependency on which sided hand people ar e more used to, such as the hand they use more for writing, eating and etc. For about 90% of right-handed individuals, the left hemisphere of the brain is the dominant hemisphere for language processing, including speaking, understanding speech, and other verbal functions. But the left-handed people, however shows more variability. The majority of left-handed individuals still have their language centre located in their left hemisphere, but there is a significant portion of individuals 20%-30% have their language functions in the right hemisphere. In particular for some individuals they may have their language centre distributed across both hemispheres. This is more common for individuals who are ambidextrous (Able to use both hands equally), the brain's lateralization of language might be even more complex, they have the greater possibility to have their language centers split between both hemispheres of their brain compared to individuals that are either left handed or right handed. But this is not a perfect, predictable and traceable way to determine the language of individual, but it shows a weak trend that for most people they have their language centre located in their left-hemisphere of their brain. Therefore, before any operations to be carried out, individuals must undergoes certain examinations to determine which side of the brain consist of their language centre.

Within the language centre, there are many different parts that will be responsible for particular function matching language, communication and verbal abilities. The one most prominent part for extracting brain signals and decoding it into electrical signals and display on screens will be the left pre-central gyrus, it is a important cortical area responsible for the co-ordination motor activities related to speech. There are also other very important parts such as the Broca's area, located in the frontal lobe. The Broca's area is crucial for speech production and language expression. It helps with forming grammatically correct sentences and producing speech. Motor cortex is another worth mentioning part which is located in the frontal lobe, specifically in the pre-central gyrus. The motor cortex is responsible for controlling voluntary muscle movements, including those involved in speech. It works with Broca's area to help with the physical act of speaking.

The process by which the brain generates signals for what a person wants to say and how those signals are transferred to the body for speech production is a complex sequence that involves co-operation with multiple regions of the brain. The process begins with the prefrontal cortex, which is responsible for higher cognitive functions like planing, decision-making, and conceptualizing speech. When a person decides to speak, the brain must first formulate the idea or concepts you want to express. The prefrontal cortex is involved in selecting what to say, while the temporal lobes (Wernicke's area) are responsible for associating words and concepts with meaning. Once decided on what to say, the brain needs to translate those concepts into language. This is where regions like Wernicke's Area come into play. Wernicke's area processes the meaning of words, sentences and ideas. It assist the person to select the correct words and organize these words into grammatically and logically correct sentences. Once the words are selected and arranged the brain will plan how to physically produce the sound of speech. This is where the Broca's area and the motor cortex became involved and working together. Broca's area first planned out the articulation of words by coordinating the muscles and form grammatically correct speech patterns. The motor cortex will continue sending the signals to the muscles such as mouth, tongue and lips controlling the physical aspect of speech.

3. Application for BCI in Patients with Language Disorders

For people with paralysis such as ALS, their muscles are not able to coordinate and produce the sounds that they intended to produce, so they cannot normally communicate with others. In order to restore their ability to communicate with the outside world, they must choose an alternative path to output their intended brain signals which represent what they want to express. With the current developing progress of technologies and science this problem can be overcome by using BCI. The brain signals that are generated will be extracted through an invasive BCI device, but they cannot be carry out by their muscle due to paralysis. This does not affect the generation of communicative brain signals, it just require a different place to output the speech signals. According to a recent experiment conducted, patients of ALS are able to express himself again with the use of BCI technologies.

In order to focus on extracting the signals generated, invasive electrodes must be implanted into certain areas that reflect the signals of speech. Referring to the previous studies and experiments conducted, four micro-electrodes array were implanted into the left pre-central gyrus. Each micro-electrodes array have 64 electrodes arranged in an 8 by 8 grid inserted 1.5 mm into the cortex with the use of specialized high-speed pneumatic inverter. The array were implanted through a 5cm by 5cm craniotomy on the left side under general anesthesia.

The arrays are connected to one percutaneous connector(pedestal) designed to transmit the neural recording to external computers. The two pedestal provide 256 different sites. The pedestals are connected by detachable connectors that us HDMI cables to transmit data to computers. These computers sit on a wheeled cart and are connected to standard electrical wall outlets [3].

After the implantation of recording devices in the patient’s pre-central gyrus. There must be a period of recovery for the patient’s health, preventing any potential infection due to the operation of implantation and any negative side effects that may occur after the operation.

When the patient’s physical condition are stable enough after observation. The next stage is the collection of data and decoding that are to be carried out. According to the actual case that were carried out by Nicholas S Card they started collecting data after 25 days of the implantation, they carry out 84 sessions to collect data from the patient’s brain activities. In order to train the decoding system, their team carry out two different methods to let the system to study the pattern. The first method is instructed-Delay task, the method is basically words are shown on screens for the patient, and the patient attempt to say the words shown on the screen, the brain signals for the patient to attempt saying these words will be recorded by the device and learning how the signals is corresponding to the actual words. The second method is patient-paced conversation mode. This mode allow the patient to speak whatever they wanted, during the conversation decoding happened in real time, the cortical activities at the micro-electrodes arrays was recorded and decoded. As the system decode the real time conversation for the patient, the decoded words will be shown on screens. The patient will be able to see the words on screen, and the patient can use an eye tracking device to reflect whether the decoded sentences and words are correct, partially correct or incorrect. By conducting these two different learning methods for the system, the system will be able to conclude and adapt how the signals extracted correspond to the words attempted to pronounce. After all series of testing sessions the system will be able to accurately translate what the patient attempted to say with high accuracy.

4. Brain Signal Decoding Technology and Language Recognition

By going further into mechanism of how cortical signals is decoded, the concept of EEG and phoneme. EEG follows a structured processed involving signal acquisition, feature extraction, machine learning-based classification and output generation. EEG capture electrical activities from the brain, without any physical contact within the inside of the brain. To decode brain impulses by EEG, the EEG device detect the electrical activities of the patient's brain. During the process of decoding with EEG, electrode that are like small metal disks with thin wires will be pasted onto the patient's scalp. They are able to detect tiny electrical charges(brain signals) that is coming from different brain areas and carry out information about thoughts, movements, or speech [4-6]. The strength and type of signals depend on whether the patient is imaging words, trying to move, or just simply thinking. EEG can capture brain signals when people image speaking specific words [4] and can help paralyzed patients to actually communicate in real time with the outside world by detecting signals when they try to spell the words [5]. The second stage of decoding of EEG is cleaning and filtering the signals extracted, mainly to remove static noise from the signals extracted. The raw EEG signals contain a lot of noises such as background static. These noises need to be filtered out, all these different kind of useless signals like muscle movements, the filter process will only remain the useful brain activity signals. One specific methods that can be used is bandpass filtering to isolate key brain wave frequencies [4.] After the filtering process, patterns in the signals need to be identified. EEG signals are analyzed to find patterns linked to words, movements or thoughts. These patterns are turned into features that computer can understand. For example, finding the EEG patterns linked to imagining different words [4]. Also the system need to recognize when a paralyzed patient tries to communicated based on their activeness of their brain signals [5].

At last, the system will convert brains signals into action such as words shown on screens. Machine learning models learn what each brain signals means and match it to words, movement or commands. The system predict what the user wants to do or say based on the alternation of brain signals and output an interpretable message to an external device such as computers [7].

The second way of decoding brain signals is by interpreting phonemes. According to the case conducted by Nicholas S Card and his team, they record the cortical activity every 80 millisecond to predict the most likely English phonemes being attempted. Phonemes are the smallest units of sound in a language that distinguish one word from another. The system developed by Nicholas S Card and his team input the collected phoneme sequences that could be arranged to form actual words into artificial intelligence language models to learn, adapt and translate the sequence of words that had initially been predicted from the neural activity into the most likely English sentence. In order to obtain high translation accuracy, the team collect a lot of data, they combine the data and continuously calibrate the decoder to achieve higher accuracy [8].

5. Limitation of BCI

For patients that use BCI due to lose of speech ability such as ALS, they need to consider the longevity of BCI implant, especially referencing the status of the patient. According to a case study, a patient with severe ALS was implanted with BCI for the convenience it can brought to communication with the outside world and caregiver alert over the original eye-gazing device that became less effective due to the progressive neurodegeneration. The implanted BCI was used continuously for over 6 years for communication. By the 6th year neural signal amplitude declined, leading to reduced performance. The BCI was discontinued in the 7th year due to the progressive loss of brain function, not due to the hardware failure. Patients with significant brain atrophy will have a very obvious progressive shrinkage of the motor cortex, increasing the distance between electrodes and brain tissue, which will eventually lead to the disability of implanted BCI [9,10].

6. Conclusion

With the discovery of this combined interdisciplinary BCI technology, patients with speech paralysis regain the ability to communicate. As this technology being more advanced and completed, more patients with speech paralysis such as ALS will gain better experience in communicating with others. This would significantly increase the quality of life for patients that can not express themselves verbally. In the future it is very likely that BCI could be used to cure certain paralysis regarding to the brain. This is only the beginning of the discovery of this new area. In the future BCI will play a prominent role in multiple interdisciplinary areas.

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