Implementations of Electroencephalography (EEG) Based Brain-Computer Interface (BCI) Devices

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What are the EEG-based BCI systems?

The concept to control prosthetics using brain signals was developed in 1971 and since then, research has transitioned into finding more accurate and convenient ways to interpret waveforms over external devices [1]. This is now "termed brain-computer interface (BCI)," and is used for two options: either "studying brain activity to investigate a feedforward pathway used to control the external devices without the aim of rehabilitation…[or through] closed-loop BCI systems during neurorehabilitation…[for] recovering the neural plasticity training or regulating brain activities" as suggested in [1, p. 2].

Obtaining a patient's brain signals can be carried out with one of two methods: either through invasive or non-invasive tactics. Invasive procedures require surgical operations to record 'single-neuron action potentials' [1] but due to close contact, it offers "high quality spatial and temporal characteristics" [1, para. 1.3]. This results in more accurate control over prosthetic devices [1], yet poses risks through surgical applications and "the gradual degradation of the recorded signals" [1, para. 1.3]. With non-invasive approaches, there is a larger range of spatial and temporal resolution results, yet electroencephalography (EEG) is widely used because it offers "direct measures of neural activity, inexpensiveness, and portability for clinical use," as demonstrated in [1, para. 1.4]. EEG records the brain activity by applying electrodes to the scalp through a head cap or by individually placing them with a binder to stick to the patients. This "measures electrical brain activity caused by the flow of electric currents during synaptic excitations or neuronal dendrites, especially in the cortex, but also in the deep brain structures" as evident in [1, p. 2]. Implementing EEG-based BCI systems needs a paradigm for the experiment to be carried out [1]. "First, the subject performs a particular task...in order to learn how to modulate their brain activity while EEG signals are recorded from the scalp" [1, para. 1.5]. The signals obtained from EEG are referred to as training data [1] to help the paradigm decode the specific neural activity. The task is repeated to ensure the paradigm picks up the correct signals for BCI control. The paradigms explored throughout the paper are as follows: slow cortical potential (SCP), sensorimotor rhythms (SMR), P300, and steady-state visual evoked potentials (SSVEP), with each having varying strengths and weaknesses based on the intended performance.

Slow Cortical Potential (SCP)

One of the commonly used signals for a non-invasive EEG-based BCI system is the slow cortical potential (SCP). The SCP provides the EEG with slow signal changes when the brain is attempting to prepare for a specific event [2]. The changes picked up by the SCP occur due to large cortical neuron assemblies which play an influential role in the cortical control of the lower brain [2].

An example of the application of the SCP was used in a training program conducted by the Clinic for Child and Adolescents Psychiatry, Psychosomatics, and psychotherapy, RWTH Aachen University in Aachen, Germany [2]. The purpose of the program was to improve the focus of 24 children with attention-deficit hyperactivity disorder (ADHD) using the SCP [2]. For the program, the patients were required to attend an "intensive" 20-session training five times a week for one hour for seven weeks [2, pg. 670]. The training was assisted by a neurofeedback coach to familiarize the participants with the SCP [2,]. The SCP produced signals from the Cz electrodeposition, which was referenced by the left mastoid [2,]. Although the initial process was strenuous, once the patients became more comfortable with the system, the program regulation of the SCP increased over time [2]. For the training program, the SCP was implemented for the participants to control an animated fish on a monitor using their emotions. A positive thought (such as getting a good grade) created a negative SCP signal prompting the monitor to move the fish above the water, while a negative thought (such as stepping in poop) created a positive signal prompting the fish to swim down [2]. The patients not only had to maintain the control of their thoughts but also had to sustain the created emotion for a "certain amount of time at a degree of 30% of the SCP regulated frequency ((24 μV)" [2, pg. 671]. Overall, the usage of the SCP had a positive influence on the attention performance of the ADHD participants; not only did the subject's attention span increase, but the ability to focus was sustained when the subjects came back for a 6-month follow-up [2].

Another application for SCP systems is the development of Neuroprosthetic Devices. Brain signals are recorded for detecting the time of movement intention rather than the movement itself to capture a readiness potential [3]. BCI technology with SCP learning systems is utilized to measure inputted brain signal waves to calculate the time it takes to identify the readiness potential. One study conducted by Upalasa University in Sweden took in a mix of healthy patients as a control group and stroke patients as the experimental group to participate in activities where they were tasked to move their dominant hand from the center of a screen towards a specified direction 2 seconds after they were told to move it to while maintaining eye contact with the center [3]. Signals were recorded through 34 channels over the frontal lobe selected to minimize the effect of artifacts and processed through an IR filter. What is shown through both types of patients is that movement intention can be detected around 500ms prior to actual movement and could be less if channels are successfully optimized. SCP signals, as a result, can show a high probability of movement among both types of patients after detecting the presence of a readiness potential can lead to new advancement in assistive technology and neuroprostheses as well as pave the way for utilizing the detection of readiness potential for motor recovery training protocols [3]. Results from both experiments, while preliminary, show promising ways in which patients can be subjected to neuroplasticity by going through SCP training protocols and various learning processes in order to improve both attention span and motor control.

Sensorimotor Rhythms (SMR)

Another type of signal used in EEG-based BCIs is a signal known as Sensorimotor Rhythms (SMR). These signals are usually detected in the motor cortex area of the brain anywhere between the frequencies 8-30 Hz. When a patient is connected to an EEG BCI system that utilizes SMR and they imagine the movement of a specific limb, there is a distinct disruption in the usual amplitude and frequency of the mu and beta waves being generated by the brain. With proper software and processing, it is possible to take the raw EEG data, distinguish which limb the patient is imagining moving, and use that to control a number of different systems and computer programs [4]. However, despite its seeming intuitive control scheme, unfortunately, it is not able to be fully utilized by all users [5]. However, this weakness appears to be able to be improved in some individuals with the addition of feedback [5] or training [4].

A study was performed by the Department of Neurotechnology at Technische Universitat Berlin to explore the variation in performances of users operating the SMR based BCI system. The study was done with 80 participants of varying ages and genders. Each participant did 10 EEG recordings using an EEG cap with 128 separate Ag/AgCl electrodes. Participants were prompted to imagine moving a distinct limb and patients had to then imagine moving the correct corresponding limb. Two trials were done, one calibration period where no feedback was provided, and one trial following the calibration period where feedback was provided on whether the user's input matched the requested limb. A more in-depth description of the exact setup is described in [5]. The results of this study divided the users into three separate categories. Users in category 1 (48 out of 80 participants), had calibrations and feedback performances that exceeded a 70% accuracy threshold. These users had strong modulation of their SMR signals that could be easily measured. Users in category II (14 out of 80 participants) had a calibration performance equal to or below a 70% accuracy threshold but above 70% accuracy in the feedback performance. Despite not performing well in the calibration trial, these users still exhibited at least somewhat strong SMR readings and therefore were able to be provided with accurate feedback which in turn improved their accuracy. Finally, users in category III (18 out of 80 participants) fell below the 70% threshold in the calibration test and could not be provided with feedback reliably as their SMR readings were weak and displayed close to no modulation after being prompted to move a limb.

The results in [5] support the idea that SMR based BCI systems cannot be used by all users in a reliable fashion at this current time. However, SMR based BCI systems, if made more accessible for all people, have very appealing potential applications. In a separate experiment done by the electrical engineering department of the Technical University of Denmark, one possible application of SMR BCI systems is shown. BCI controlled spelling interfaces can oftentimes be very slow and inefficient. As a result, the goal of this experiment was to create a more practical spelling interface utilizing SMR-BCI that would be more efficient. By creating a practical spelling interface, it could allow for severe ALS patients to realistically use the system as a way of communicating with others around them, even in the late stages of ALS. The new spelling system created was based on the 2-class BCI system known as Hex-O-Spell. Essentially, the user could navigate a wheel of letter groupings by imagining a specific limb movement and rotating the selection on the circle either clockwise or counterclockwise. Selection would occur when remaining on a letter grouping for a set amount of time. This is illustrated in the left half of [4, Fig.3]. To improve the efficiency of this system, the Hex-O-Spell system was modified to be a three-class system (three different possible inputs). The first two inputs worked like the original Hex-O-Spell system however, the addition of a third input allowed the user to switch to a wheel containing a list of words generated by predictive text based on letters that had already been inputted (Similar to predictive text in modern-day smartphones). This allowed the user to input a full word without having to spell out the entire thing manually. Users did however still have to undergo training of some sort to use this device. In this study, three different exercises were used to help subjects learn how to produce isolated imaginary kinematic movement. The result of this new spelling system resulted in the communication rate increasing on average by a staggering 147%. However, the success rate of detecting the correct signal decreased by 55% in comparison to the original 2 class Hex-O-Spell system. Ultimately, the three-class system was just as efficient as the two-class system [4]. But, it proves that using SMR BCIs to control spelling interfaces is very plausible and demonstrates its potential usefulness for broader applications.

P300

Another one of the most commonly used signals for BCI systems is the P300 signal, a constituent of the event-related potential (ERP) that was reported by Sutton [6]. ERPs are electrophysiological responses to internal or external stimuli that demonstrate fluctuations in EEGs that are controlled by a motor, sensory, or cognitive event. P300 is most often detected during oddball paradigms, which are experiments where sequences of stimuli are measured and categorized into two types, target (T) and standard (S). In other words, with P300, sequences of events are categorized into either unsurprising events or surprising events, where the subject finds something unexpected and goes through memory modification/learning. What made P300 more popular over the last decade was how fast, effective, straightforward, and easy it was for a variety of subjects to use, even for the disabled subjects. Among the most important features is its lack of needing actual training. However, drawbacks have been brought to light with the traditional experiments that have been practiced ever since 1988 [6].

The traditional BCI approach was called the "P300 matrix speller", which was made by Farwell and Donchin [7]. In Brunner's study [8], the BCI's dependence on eye gaze was investigated using 17 healthy subjects. Subjects sat 60 cm in front of a screen and were shown a 6x6 matrix of letters and numbers centered on the screen. An eye tracker was used to measure the subjects' eye gaze at 60 times per second. The first session consisted of Condition 1, where the subjects had to spell out words by directly looking at the target letter. The second session and condition were that subjects stare at a cross centered on the matrix while paying attention to their target letter. There were pauses between each run to allow subjects to properly shift their attention to the new word to spell. The results showed that the subjects performed more successfully with Condition 1. Condition 1 yielded 80-100% accuracy while Condition 2's accuracy ranged from 2.8-90%. Other factors were taken note of to test for possible improvements in both conditions. As the distance increased between the subject and the screen, accuracy would fall and become less effective for Condition 2. Adding more electrodes, or channels also proved to show more accurate results as the group of subjects that tested with the 64-channel montage tested better than the ones with the 8 channel montage. This even allowed tests with Condition 2 to improve, suggesting that more channels are more appropriate for when there are eye gazing issues. In conclusion, eye gaze plays an important role in using P300 signals for BCI based systems. As a result, subjects with vision impairments (such as ALS) could be limited by using this type of BCI system.

To lessen limitations for those with vision impairments, a study was conducted to compare space independent P300-BCI spellers to those that are space-dependent like the P300 matrix speller [9]. There were eleven right-handed participants with normal vision and no neurological disorders. For the tested Rapid Serial Visual Representation (RSVP) mode, subjects were given the task to spell 5-letter words by counting the amount of times their target letters would flash on a 20" LCD screen with a refresh rate of 60 Hz, placed 60 cm from the participant. A quick practice session of spelling out "HI" took place before spelling any word, which was not included in the analysis. There were five blocks per word (one block for each target letter), where different letters flashed at random. If the subjects were able to correctly account for how many times their target letters flashed, the letter was accounted for. There were 7 scalp electrodes placed where there was the best P300 b classification performance. For each letter block, the average was taken between the absolute difference between the time's subjects counted their letter and the number of times their letter was seen. RSVP mode had an average of 86.02% while the matrix mode showed 88.58%. Despite the Matrix P300-based BCI speller being more efficient and having *slightly* better accuracy, RSVP mode was still on par with its effectiveness. This would mean that for users that are more visually impaired, RSVP mode with its spatial independence and potential key improvements could be more effective since it performs with nearly the same success as the traditional matrix mode.

Steady-State Visual Evoked Potentials (SSVEP)

The human brain is capable of things that humanity is yet to discover, our brains are trained to do multiple tasks unconsciously and efficiently. Research shows that since our brain is compatible with multitasking, we are better able to do more actions and functions when we are in the middle of some sort of white distraction [10]. While the technology of the brain-computer interface is still expanding, many researchers are trying to utilize our cognitive ability and how much we could overload it for it to be functional. One of the most common signals used in BCI studies is the steady-state visual evoked potentials (SSVEPs). SSVEPs are steady-state visually evoked potential signals and they are usually used to record natural responses through mostly visual stimulation and set frequencies given different types of shapes and colors [10].

A study was conducted where different perturbations were given to the patients to test the SSVEP and see if the performance was impacted positively or negatively by the quality of the EEG signals or due to the increase in cognitive load [11]. The way the study was organized was that there were four circles and subjects had to give feedback to one of the circles using 60 channels. However, the circles weren't placed in a particular order rather in different locations with different flickering frequencies and led lights [11]. Also, there was a 28inch monitor that was 90cm away from the subjects so that their eyes aren't tired when looking at the screen to close for 9 minutes straight [11]. The goal of the subject was that four circles were presented and after focusing on the circle for three seconds a red circle would appear and then the subject had to click either yes or no to answer if the circle was in that position. Throughout the process, there would be four types of perturbations and one would be no distractions and the others consisted of counting out loud or mentally. There was one perturbation where a sampling rate of 22kHz was pre-recorded which the patient's voice repeated while the patient was taking the test to see how well they coped with it. The participants consisted of 24 subjects which included about 8 males. What was extracted from this data is not how long the person took but rather if the person was able to focus on the location of the circle they chose after distractions being thrown at them. Also when selecting yes or no the participants didn't have a time limit but distractions were still there but given in a random order so that the patients aren't able to determine a pattern [11].

The impact and the importance of giving distractions were to figure out that if performance was affected at all. There wasn't a clear distinction if subjects' performance was impacted by either thinking mentally and counting the numbers or was it listening to the numbers [11]. Some patients did have a drop in performance but that was because their attention span was divided. However many participants had increased their performance when there were distractions. The benefits from SSVEPs signal and this test were that it was a strong indicator that for most people being surrounded by white distractions showed that our cognitive workload is capable and so prone to multitasking that for some people rather than dividing their attention it makes them more goal and focus oriented. When the cognitive brain is not pressured it tends to be more attentive to its surroundings. This makes that when using BCI's and integrating SSVEPs signals, subjects could efficiently achieve more tasks if they are given multiple tasks at once so that way subjects are more likely to focus rather than being distracted [10]. This type of device will be appropriate for people who are young adults, mostly the ones who are exposed to technology and also have lived in a city type of environment. This device will help people in those categories thrive because multitasking for them is second nature.

Discussion

Within each study, the results from each paradigm stemmed from patients interacting with a stimulus. How the stimulus was presented varied based on what EEG-BCI system was used, hence specific tasks were associated with each study to get the correct stimulated brain waves. As a result, training protocols were developed which, while easy for a patient to learn, required a large amount of time and sessions to improve their performance in the experiments. For example, SMR had the most non-intuitive user interface that required subjects to go through pre-trial training. The pre-trial training was issued in a form of mini-games that allowed each patient to get accustomed to the system so that in the actual trial, the hex-o-spell exercise, the correct signals based on the detection of a readiness potential were detected. These signals indicated a patient's intention to perform a particular motor function and were recorded through upper and frontal cortical areas. Conversely, P300's interface required little to no training before the trials because of its dependence on memory and visual tactics that relied primarily on eye movement recorded over the parietal lobe, unlike SMR's physical movement. This means that P300's interface was more user-friendly because it depended on analyzing the natural responses from patients whereas SMR required a preset response. For both SCP and SSVEP, each interface lies between P300 and SMR however are more closely related to SMR due to patients still needing training but on a simpler scale.

The target audience varied based on the specific application for each system. The SCP and SMR systems were best suited for subject groups focused on intention rather than execution, while the P300 and SSVEP centered on movement. Although both SMR and P300 focused on ALS patients, the SMR obtained muscle intention signals whereas the P300 collected eye-movement. The SCP assisted ADHD and stroke patients by collecting imaginative signals such as emotion and muscle intention. Lastly, the SSVEP used a group of healthy patients to observe eye movements and focus.

Equipment based studies are heavily dependent on the setup and subjects need to understand the nature of the setup. For cognitive-based studies, the general subjects were healthy and required minimum training so the setup was similar because the experiments required measuring visual retention rather than doing an action that would output signals. The studies that required more visual signals like P300 or SSVEP had more channels, LED lights, and monitors implemented in the setup so that required multiple tasks could be accomplished because the monitoring of visual actions was vital. Compared to signals that include SMR and SCP, several channels weren't defined because studying the action that generated the signal itself was a more important area of study, therefore various numbers of channels and monitors were included in this setup.

In all the discussed studies, there was not much mention of a minimum or a maximum number of electrodes that would help optimize signal detection. However, the placement of the electrodes varied between all the different signals. SCP-based BCIs for instance targeted the Frontal Cortical areas of the brain while the electrode placement for SMR based BCIs targeted the Motor Cortex. In some cases, multiple areas were targeted. The BCI system using P300 had electrodes targeting the Occipital lobe, Parietal lobe, and Frontal lobe. SSVEP BCIs are similar in the sense that electrode placement targets multiple areas of the brain including the Central, Temporal, and Parietal lobes.

Conclusion

Overall, it was found that SCP, SMR, P300, and SSVEP have different disadvantages and advantages when taking on the challenge of being user friendly to potential users with disabilities. With constant improvements being made to these EEG-based BCIs, accessibility is growing for those with visual, neurological, or motor impairments, such as ALS, ADHD, and stroke patients.

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