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Minimization of background brain activity to be recorded and interpreted by Brain-Computer Interfaces: Filtering relevant information for specific motorized functions.

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Abstract: In the contemporary world of modern science, the popularity of brain-computer interfaces (BCIs) is rising at an exhilarating rate. These interfaces come in the form of implanted devices, usually in the brain's cortical surface, and they can drastically help patients suffering from neurological impairments or diseases. However, BCI technology has not yet evolved completely and still experiences multiple limitations. One glaring issue brought to light in this paper is how the BCIs are not very well equipped to convert useful action potentials into desirable motor actions. Without an apt system, there would be interferences from background activity in the brain, disabling the BCI to interpret what exactly it is supposed to do. This will also happen due to the microelectrode arrays losing functionality over time due to the immune system's foreign body response. Some of the solutions that come forth are rudimentary and require finessing. This paper will investigate 2 case studies that have found certain solutions to filter out useful activity in the brain in their respective experiments and will try to come up with possible solutions for the future that may apply to other experiments, limiting this issue in the foreseeable future, using the best technology available.

I. Introduction

A Brain-computer interface (BCI) is a system that links the brain to a computer. The BCI can analyze and translate the electrical impulses, action potentials and spike trains (raw voltage) as brain signals and the machine learning program incorporated into the computer code can interpret the signals into desirable commands that are executed by an output system (for example, a prosthetic limb). The BCI linked to the computer usually guides a cursor, telling the computer exactly what the patient intends to do. It sometimes is also able to directly control the prosthetic limbs based on what the patient intends to do. The system usually includes a device in the form of microelectrode arrays (MEAs) that are implanted in the brain to read and record electrophysiological activity, which are later decoded by a computer. BCIs solely rely on signals from the central nervous system and are not dependent on any other activity that is not in the brain (in the location where it has been placed or implanted). The BCI is also a complete system that not only reads the signals but is also able to translate them into specific actions. If a machine is only able to read and interpret signals without sending those interpreted signals to an external device to act upon the intentions decoded, we cannot classify it as a BCI. The primary objective of BCIs is to help individuals or patients convert their intentions into actions (Shih, Krusienski, and Wolpaw 2012). The reason they are unable to do so, most of the time, is because they are suffering from some sort of neurological disorder. Brain-computer interfaces provide support for a myriad of conditions, such as paralysis, amputations, brain injuries, epilepsies and strokes, as well as multiple neurological diseases, including Parkinson's disease, ALS, Dementia, Huntington's disease, and Down's syndrome amongst several others. (Psychology Today 2024)

There are two broad categories that BCIs can classified into: invasive BCIs and non-invasive BCIs.

Non-invasive brain-computer interfaces

Non-invasive BCIs either measure neural activity (like invasive BCIs) and perform the desirable task or perform tasks and actions based on external stimuli. These BCIs are placed on the scalp rather than neurologically implanted into the cortex. Considering these interfaces are not connected to the neurons or not implanted into the cortex, unlike the invasive species, the readings obtained are less detailed but beneficial as it doesn't require surgery (Steyrl, Kobler, and Müller-Putz 2016). A few non-invasive BCIs include electroencephalography (EEGs), functional near-infrared spectroscopy (FNIRs) and functional magnetic resonance imaging. Due to the large distance between the scalp electrode and the target part of the brain, non-invasive BCIs are not as efficient and well-equipped to read and interpret electrical impulses in the brain. As a result, the signal-to-noise ratio is much lower compared to invasive BCIs, and the scope for background activity to get undesirably recorded is very high.

On the positive side, non-invasive BCIs are much less harmful than invasive BCIs. As there is no physical damage done to the brain, there is no foreign-body response by the immune system of the brain, making the non-invasive BCIs last longer. It is also much easier and more convenient to fix any hardware issues and does not cause significant damage in the long run. Additionally, FNIRs use near-infrared (NI) light emitter detector pairs that operate with two or more wavelengths. The NI light that diffuses through the scalp is scattered throughout the brain tissues in the form of photons. Since the coefficient of absorption is different for different wavelengths, some strategically placed sensors can detect the difference in concentration and decode the impulse using Beer Lambert's modified equation (Baker et al. 2014). This also means that FNIRs are not susceptible to electric noise as they use optical imaging modality (Naseer and Hong 2015).

Invasive brain-computer interfaces

Invasive BCIs are electrodes that are implanted into the motor cortex through neurosurgery. As a result, these electrodes can directly record spike trains, which are continuous action potentials, in close proximity to the firing neurons. The patient with the implanted electrodes can now just think of an action, and an output system, such as a prosthetic limb, has been coded accordingly and will respond as the patient thinks about what they are doing. As these BCIs have been directly implanted into the cortex, they have a much greater spatial and temporal resolution compared to non-invasive BCIs (Naresh Sardar Vallabhbhai Patel and Rk Naresh Sardar Vallabhbhai Patel, n.d.). This means that it is much easier for external systems to identify the part of the brain that needs to be operating, as well as clearly defined locations of spike train firing rates increasing or decreasing in specific parts of the brain (Naresh Sardar Vallabhbhai Patel and Rk Naresh Sardar Vallabhbhai Patel, n.d.). Invasive BCIs can also be implanted much closer to the targeted cortical areas using deep-brain stimulation BCI technology. A lot of the neurons in the brain that work together are within very close proximity to each other (as close as a few nanometers). The surgery can also enable the scientists to implant multiple electrodes to increase the range signals. Through this, the interpreted signals will be much more accurate. Additionally, invasive BCIs are very well-equipped to increase their signal-to-noise ratio. This helps directly with the objective of this paper. This means that invasive BCIs can maximize the useful signals that are required for a certain function while minimizing background activity. This is done by using filtering systems in the BCI and/or by implanting the BCI closer to the target location. But, invasive BCIs also come with a diverse range of disadvantages as well. Firstly, BCIs need a surgical implantation. This initiates the brain's foreign body response via microglia and astrocytes, along with the severing of blood vessels, and surrounding neurons which releases chemical messengers that initiate an immune signaling cascade (Kozai et al. 2015). The body's B and T-type white blood cells detect the BCI as an alien object, affecting the physical integrity of the electrode implanted. Additionally, the external wiring of these BCIs poses the risk of disease transmission ("Brain-Computer Interfaces," n.d.). Implantable BCIs, background disturbances, dependence on the patient and their preexisting conditions, and death of neurons around the BCI are a few drawbacks of implanting BCIs into the cortex (ROY A. E. BAKAY 2006).

Another disadvantage is that the BCI, once implanted, is not very accessible. If there is any hardware problem in the BCI, the neurosurgical procedure would have to be reversed. This can become extremely challenging, dangerous and expensive for patients who may face problems in the future (Zhao et al. 2023).

Differences in Implantable and Non-implantable BCIs

Invasive BCIs	Non-invasive BCIs
• Much more spatial and temporal clarity is achieved. (Naresh Sardar Vallabhbhai Patel and Rk Naresh Sardar Vallabhbhai Patel, n.d.)	• Signals are not as clear due to distance from the scalp and the targeted part of the brain. (Steyrl, Kobler, and Müller-Putz 2016)
• Requires a neurosurgical process to implant the electrodes into the cortex of the brain or any other part. ("Brain-Computer Interfaces," n.d.)	• No damage done to the patient as the electrodes are simply placed on the scalp to measure impulses. (Steyrl, Kobler, and Müller-Putz 2016)
• It can get extremely challenging to fix any sort of hardware malfunctions. (Zhao et al. 2023)	• Much easier to rectify hardware malfunctions and less strenuous procedure for the patient.
• Triggers a body immune system response from microglia and astrocytes. (Kozai et al. 2015)	• No retaliation from the body's end as there is no physical damage done to the brain.
• Can wear out much faster and are more expensive. (Zhao et al. 2023)	• Take lesser time to wear out and can be less expensive.
• Background activity can be minimized due to specifically located electrodes, close to the target	• Apart from FNIRs, non-invasive electrodes are highly susceptible to background brain activity,

location. (Naresh Sardar Vallabhbhai Patel and Rk Naresh Sardar Vallabhbhai Patel, n.d.)	leading to inaccurate interpretations of the impulses. (Steyrl, Kobler, and Müller-Putz 2016)

Table 1- Table of differences between invasive and non-invasive BCIs.

The next section of the paper will take 2 case studies, one related to handwritten communication with the help of BCIs and the other about neuron conditioning, and analyse the limitations of their experiments due to background noise and how they, along with other people in the field, have tackled the issue of background activity.

II. Case studies analysis

Analysis of Case 1- Handwriting with Paralysis:

Research was done on a patient with a high-level spinal cord injury. Considering the patient suffered from paralysis from his neck to his lower body and suffered from micromotions and twitching, the experiments on the patient were performed to see if the complex motor skills were retained by the precentral gyrus of the brain and if dexterous tasks were replicable using and a brain-computer interface (BCI), illustrated in *figure 1*.

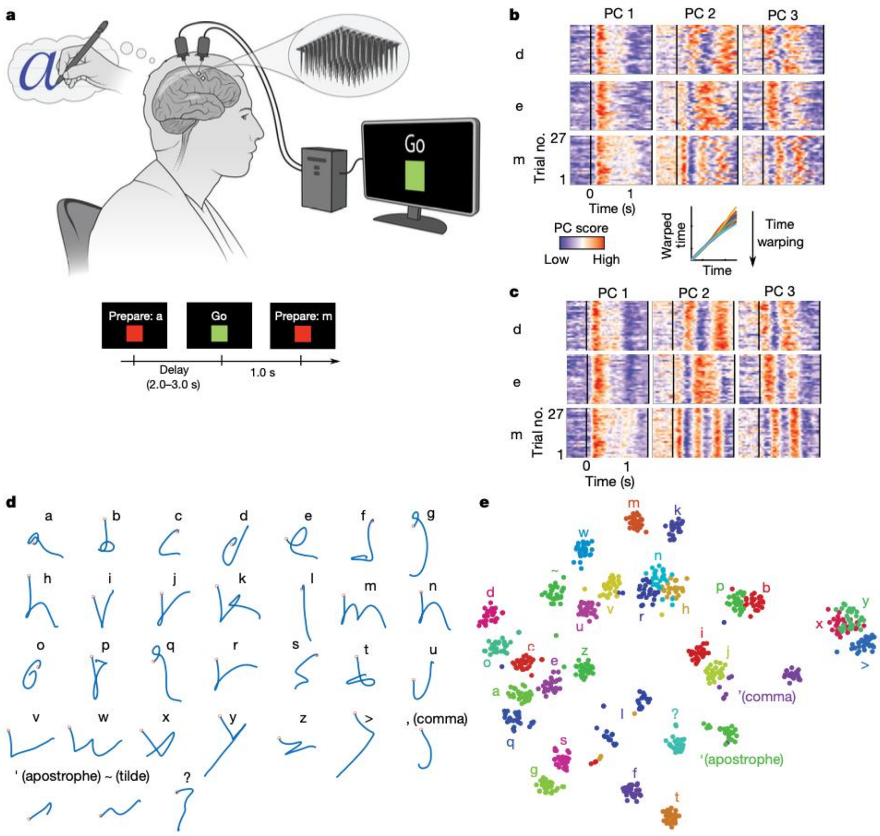

Figure.1- Image used from High-performance brain-to-text communication via handwriting article, showing a visual progression of the experimental procedure (Willett et al. 2021).

a. Shows the experiment set-up. Subject T5 (the subject) was made to imagine that he was writing the alphabet following the instructions given on the computer screen. Credit: The human silhouette drawing was created by E. Woodrum.

b. Represents the neural activity for the letters d, e, and m, respectively. These letter trials were repeated 27 times for each alphabet (to rid any anomalous results). The colour scaling was normalized within each panel separately for visualization.

c. Time warping the neural activity revealed consistency for each of the letters represented in part b.

d. The pen trajectories that were decoded are shown here. Using cross-validation ("Cross Validation in Machine Learning - GeeksforGeeks," n.d.) the intended 2-d pen velocity was linearly decoded. Orange circles denote the start of the trajectory.

e. Shows the clusters of individual characters' neural activity in the brain. Each singular circle is one of the 27 trials that were conducted. The technology used was t-SNE (Kemal Erdem, n.d.). (Willett et al. 2021)

Using a time alignment technology to prevent variance in temporal variability as well as a nonlinear dimensionality reduction method, the researchers were able to locate clusters of neural activity when certain characters were asked to be written (the patient had to imagine the characters as he/she was currently paralyzed). By achieving a 94.1% accuracy, the experimentalist concluded that BCIs can be used for decoding handwriting (Williams et al. 2020).

Convolutional neural networks, a machine learning algorithm, is used to decode the inputs, however, this presents constraints as the data set was too limited and the time taken for each word to be written is unknown. As a result, the experimentalists switched to speech recognition which provided promising results (Willett et al. 2021).

While this study achieved an accuracy of 0.89% with error rates of 3.4%-, this procedure required daily calibration due to constant changes in neuroplasticity and micromotions of the electrode array in the cortex. Due to the changes in the neural activity in the brain, there is a constant need to keep updating the reference data set as brain activity changes drastically after 7 days. This becomes inconvenient for the patient, making the process longer (Willett et al. 2021). Through the data they collected, they were able to conclude, that there is a high short-term stability for only 7 days.

Although not explicitly mentioned in the article, we can conclude two main reasons for instability. Firstly, neuroplasticity causes the shape and orientation of the neurons in the brain to constantly change. However, neuroplasticity is an essential process that helps the neurons develop and mature ("What Is Neuronal Plasticity and Why Is It Important?," n.d.). Another anticipated reason is due to the body's foreign response to the electrode implanted into the motor cortex, which initiates a signaling cascade that interrupts the communication between the neurons and the electrodes, over time.

The article concludes by stating the scope of BCIs in enhancing High-performance handwriting with adequate progress in the technology. By stabilizing the electrode implants in the brain, the experimentalists hypothesize that they might slowly reduce the need for daily decoder training, addressing the issue that was affecting the facile handwriting process for the patient with paralysis. With a more efficient implantation system, it is also possible to increase the longevity of a microelectrode array's life, which is estimated to be around 1000 days after implantation as of 2021 (Willett et al. 2021). This would not be viable for younger patients as they would require constant neurosurgery at around 3-year intervals after each implantation.

Another issue was the variability of performances between patients. They asserted that the experiment on subject T5 (a patient with a high-level spinal cord injury, paralysed from the neck down) was more promising than the previous attempts. While not giving a reason for this variability, we can assume that the accuracy was compromised due to the presence of a low signal-to-noise ratio due to continuous activity in other parts of the brain. This means that subject T5 had a higher signal-to-noise ratio, compared to the other subjects who yielded sub-optimal results. Another potential reason for the variability of performances is dependent upon the severity of the paralysis experienced by the patient. An experiment conducted at Rush University Medical Center (Chicago, Illinois) performed the same experiment on two different patients with a different degree and severity of quadriplegia. Through the results, they found a variance in the effectiveness of the BCI performances in both the patients and were able to conclude that patient's acceptance of the BCI is also dependent on their current physical condition. (ROY A. E. BAKAY 2006)

Analysis of case 2- Neuron conditioning to fire and suppress impulses in Monkeys:

An experiment was conducted on 2 Japanese Macaque Monkeys to test their control over neuron conditioning and neuron suppression. All the surgically implanted protocols followed the National Institutes of Health Guide for the Care and Use of Animals. (Kobayashi, Schultz, and Sakagami 2010)

For the experiment, both the monkeys were kept in controlled environments after having electrodes implanted into their lateral prefrontal cortex. The electrode implanted in the brain was inserted using a stainless-steel guide tube that penetrated the pachymeninx and was held above the cortex. The action potentials here were amplified and filtered.
They were also mildly fluid-deprived for this experiment to test their hypothesis accurately (Kobayashi, Schultz, and Sakagami 2010).

Both the monkeys were made to stare at a screen showing a white fixation spot for a 0.5-second time interval known as the fixation period. Following this, there was a fractal image generated on the screen around the fixation spot for a 1-second cue. If the monkey's gaze diverted from the fixation spot, a green bar would enlarge from the starting point and not change colour. Consequently, the Monkey would not receive any reward. If, however, the Monkey's gaze remained focused on the fixation spot, the monkey would be rewarded with a drop of juice and the green enlarging bar would become red. This all happened in a 0.7-second delay period.

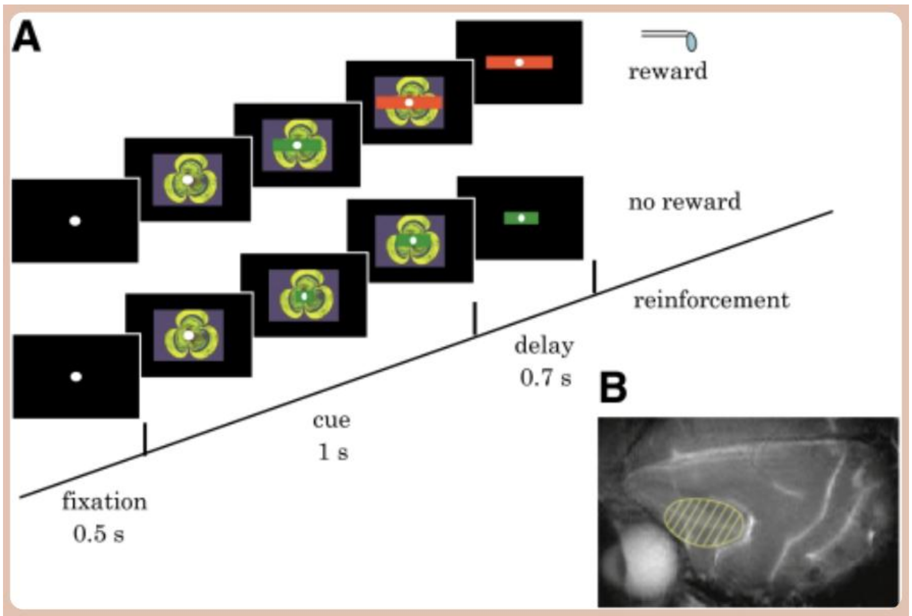

Figure.2- Image obtained from an article titled 'Operant Conditioning of Primate Prefrontal Neurons' (Kobayashi, Schultz, and Sakagami 2010)

After seeing these results following 30-40 trials, the researchers understood that the Monkeys had become acclimatized to the procedure, as they noticed spikes in the monkey's brain activity through a computer that was linked to the BCI implanted in the lateral prefrontal cortex.

Then the researchers randomized the reward system, regardless of whether the monkeys followed the required procedure. Over 2 weeks, the researchers discovered that the monkeys were able to not only identify the guaranteed reward when the experiment was not randomized, but they were able to control their brain activity by choosing when to spike and suppress their neuron activity based on the nature of the experiment.

The researchers were able to monitor the monkey's intentions through the computer rather than through visible responses. This proved that the monkeys were able to condition and suppress their neuronal activity rate by identifying the reward they received (Wyler et al. 1980).

III. Conclusion

BCI technology has certainly revolutionized the world however, there are some limitations. If these issues are addressed, it will make the utilization of BCIs a lot more convenient, effective and safe for the foreseeable future. Here are a few solutions that could improve BCI technology:

Neuron conditioning and suppressing- The experiments conducted by Fetz Baker and Kobayashi, respectively, were confirmed by Wyler to apply not only to primates but also to humans (Wyler et al. 1980). This means that theoretically and practically, humans could control which neurons should spike their activity and which ones should suppress their activity. This helps them to perform highly specialized tasks. It also may prevent background disturbances in the neuron activity. For example, suppose a desirable motor skill is lifting a glass of water. In that case, the neuron suppression can disable(?) the BCI to pick up any additional voluntary signals as the subject will suppress them. They could potentially also control the functioning and firing of the neurons at a single neuronal level. This could be beneficial for the future of BCIs as it could possibly minimize background activity, leading to negligible disturbances in the interpreted impulses.

Low-pass filters- For involuntary activity, such as the functioning of the heart, the BCIs should have low-pass filters below which they do not capture and translate those impulses. generalize the effectiveness of the filters, but to help make them specialized. A few examples of low-pass filters include the Chebyshev, Butterworth, Savitzky-Golay and elliptical low-pass filters. Based on the cutoffs, each low pass filter will be able to ignore any activity that is below a certain decibel level, making the obtained activity as pure as possible.

All BCIs do currently have some low-pass filters incorporated into them. However, it is essential to make these low-pass filters a lot more effective. For example, it would be a good idea to introduce customized low-pass filters for certain BCIs to record specific action potentials. Depending on their location in the brain, the low-pass filters can have different cut-off points beyond which readings are recorded. This diversity in low-pass filters will make it easier to not

Minimize background noise- Another efficient way of minimizing the background noise generated in the brain is by identifying the sources of noise in the brain and trying to reduce it to the greatest extent possible. The first potential source of noise could come from the rise in temperature.

$$v = \sqrt{4}kTR\Delta f$$

Through this equation of voltage, we can see that the voltage in a system is dependent on Boltzmann's constant (k), the resistance (R), the change in frequency (Δf) and the Temperature (T). To reduce thermal noise, we should aim to reduce the temperature rise and resistance, and the change in frequency. To reduce the change in frequency, we can also increase the response time ($\Delta f = 1 \div 3\Delta t$). To reduce the temperature in the system, we could add a cooling device (it should be noted that for the microelectrode array to perform well, there shouldn't be a drastic difference between body temperature and the temperature of the microelectrode array). Apart from thermal noise, a system is susceptible to flicker noise, shot noise and environmental noise. As a future research goal, it is essential to reduce all unwanted noise to the greatest extent possible (Harvey, n.d.).

Shielding- Another possible method is to increase the signal-to-noise ratio. To do this, one suggestion is to add a Faraday cage around the instrument and the target site (this is applicable only for invasive BCIs). While not done so far, faraday cages can be made to enclose the instrument, inhibiting unwanted electromagnetic radiation from reaching the microelectrode array. This is because it is not practical to have people sitting in faraday cages. Firstly, it makes the BCI remain intact for a longer period and is less likely to degrade or wear out over time. If the cage is too big, it can only cover the sensitive parts of the BCI, and the wanted activity in the form of electromagnetic radiation can get absorbed by the Faraday cage's conductive material. Additionally, using a differential amplifier and a modulator will also aid in increasing the signal of interest.

Neurotrophic electrodes- For invasive species, incisions should be minimal and should have a protective layer to prevent any damage. They should also try to incorporate neurotrophic electrodes (Bartels et al. 2008). These electrodes last longer, and neurites grow inside this electrode's glass tip. Inside are gold wires that measure these signals. The glass tip keeps the activity isolated from other neural activity, making the readings as clear as possible without disturbances. Additionally, the growth of neurites can help replicate the natural environment of the brain, to minimize foreign body response.

fNIR technology in a deep brain stimulation electrode- If neural engineers can incorporate the fNIR technology into invasive BCIs, it may become beneficial for the patient. Firstly, a deep brain stimulation will, anyway, have a milder foreign body response than an implantation in the motor cortex. This is because there is a smaller astroglial population in deeper parts of the brain than. Additionally, with the incorporation of FNIR technology, the range of a BCI increases by a lot. This means that a single electrode in the brain will be able to access multiple parts of the brain despite being far from the multiple target sites. This prevents the number of incisions that need to be made in the brain to implant electrodes, as the infrared penetration range is vast. Through this incorporation, microelectrode arrays will be able to record activity, and the moderators will be able to stimulate activity, making the extent of BCI usage extensive.

By making a few alterations to the preexisting BCI technology, modern-day science will see paramount benefits in the fields of neural and biomedical engineering. It will also become a much more reliable technology that is available to different patients. Yes, some limitations, such as the patient's injury severity, may continue to persist. However, with significant breakthroughs, even those obstacles will be handled as we get to see greater advancements in the field.

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