Applications of EEG-based BCI technology: A review

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Abstract - Brain-computer interfaces (BCIs) have proven to be useful in treating a variety of medical conditions, improving many patients' outlook on life. Implanted BCI technology, while effective, is expensive and difficult to implant. This makes it difficult for BCIs to have a large societal impact. As a solution, electroencephalography (EEG) waves have been proposed and implemented as a non-invasive alternative to traditional BCI technology. With this new proposal, EEG-based BCIs have been embraced across a wide variety of domains, including, but not limited to, cybersecurity, entertainment, and healthcare. Our review covers these domains and gives insight into the current breakthroughs in each respective area. Within the domain of cybersecurity, authentication, cryptography, and lie-detection are explored in depth. EEG-BCIs have also been studied in a video-game environment, proving that BCIs can be used for many different purposes. Finally, healthcare studies present novel applications like a continuous pursuit task and a better signal processing and classification method. With this technology being pursued in many different domains, there is no shortage of new, exciting breakthroughs powering the EEG-BCI revolution.

I. INTRODUCTION

Almost all biological animals, within themselves, in the natural world have some form of a system that serves as a conductor, orchestrating the different complex processes and interactions they have with the environment. This system, known as the nervous system, in mammals is usually composed of the peripheral and central nervous system, where the brain and spinal cord reside. The peripheral nervous system is home to interconnected nerves. The brain itself is a complex organ composed of billions of interconnected neuron cells which, according to Kenia A. Maldonado, Khalid Alsayouri in their book, *Physiology Brain*, serves to "command task-evoked responses, senses, movement, emotions, language, communication, thinking, and memory" [13]. These capabilities that the brain can achieve are an account of historical events and the evolution of life within the planet, that span for billions of years. For an individual to manipulate their environment, the brain must communicate with the peripheral nervous system to carry out an outgoing action, for instance moving a finger, hand, leg, jumping or picking object. With the advent of computers in recent decades, along with advancement in psychology and neuroscience in attempting to understand intelligence and the brain, it is now possible to translate and map brain activities to actions that can be carried out within an environment, without the intervention of the embedded peripheral nervous system.

A. *Signal Acquisition Interface*

The ability to translate and map brain activities to actions is accomplished through an interface. According to, Landau, O., Puzis, R., & Nissim, N, in their research paper *Mind your Mind*, a "brain monitoring device to record and analyze the brain's activity and translate it to the requested output" [12], together they formulate Brain Computer Interface, or BCI. There are two techniques or approaches, invasive or noninvasive, through

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which a brain monitoring device can record brain activity. The Invasive technique usually implies a surgical procedure in placing a monitoring or signal acquisition device with electrodes, to record brainwave signals from within the skull. Their counterpart, the non-invasive techniques, does not require any surgical procedures. Instead, a monitoring device with electrodes is placed onto the surface of the skull or head. Some of the invasive signal acquisition devices currently used are microelectrode, multielectrode, and Electrocorticography (ECoG). While some of the non-invasive acquisition devices are electroencephalography (EEG), magnetoencephalography (MEG), functional magnetic resonance imaging(fMRI) and functional Near Infrared (fNIR). Comparatively non-invasive signal acquisition techniques are cheaper than the invasive, however due to area of placement of the electrodes, there are differences in signal quality acquired. In a review study, *Brain computer interface control signal*, by Ramadan, R. A., & Vasilakos, A. V, the researchers noted that with invasive techniques, the signal produced would be of high quality than its non-invasive counterpart, however it will be “prone to scar tissue build-up over time and the signal might get lost” [15].

Given the complexity associated with signal acquisition techniques, non-invasive techniques are more widely adopted, especially with EEG, due to their cost and safety. EEG uses electrodes to record brain wave signals which are placed on specific regions of the skull. These regions adhere to the 10-20 international standard. The standard is used to establish uniformity among a diverse range of EEG meshed headsets worn by individuals. The EEG signals acquired will not be strong as a result of interference background noises, however through signal amplification and noise cancelling, filtering, better brainwave signals can be acquired from an EEG headset.

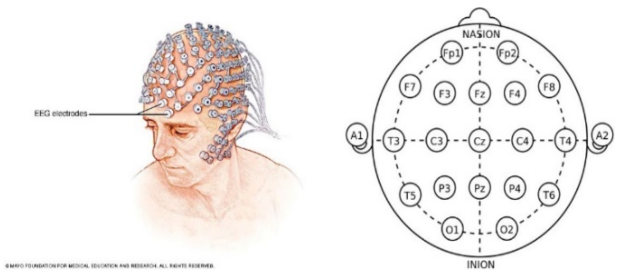

Figure 1. Left Image is an EEG headset borrowed from Mayo Clinic [5]. Right Image is the visual diagram on placement of the electrodes along the 10-20 standard, borrowed from Wikipedia [18].

B. *Signal Processing*

Signal procession is the second component of BCI. Within signal processing, there is feature extraction and feature translation. An important aspect of feature extraction is the classification of signal characteristics from extraneous content and their representation in a compact form, that can be used to translate into output commands. These features should be highly correlated with the user's intention. The feature translation algorithm then receives the generated signal features and transforms them into the necessary commands for the output device. The external device is operated by the commands from the feature translation algorithm, which performs tasks like letter selection, cursor control, robotic arm movement, and so forth. The user receives input from the device operation, closing the control loop.[2]

Figure 2. BCI Output devices [1][10][7]

C. *Analysis of Brainwaves*

In analysis of recorded brainwaves, Landau, O., Puzis, R., & Nissim noted there are some dominant brainwave signals, frequencies, observed regardless of their acquisition techniques, invasive and non-invasive [12]. These brainwaves form sinusoidal wave shapes which have been linked to “some typical patterns identified when the brain is active in the context of different tasks and behaviors performed by an individual” [12]. Therefore, the brainwaves are consistent, regardless of the recording technique and individual’s activity being conducted. For instance, “a person is relaxed with their eyes closed” [12]. Overall, these frequencies have been categorized into Delta, Theta, Beta and Alpha waves, a more detailed illustration is shown below in figure 3.

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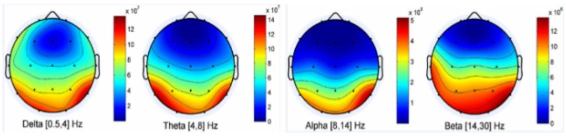

Fig. 4. Brain electrical activity by wave type [Delorme and Makeig 2004].

Table 3. A Summary of the Main Wave Types and Their Properties

Type		Frequency (Hz)	State in which it occurs	Associated with
Delta		1.5–4	Dreamless sleep	NREM sleep
Theta		4–8	Sleep or meditation	REM, memory processing
Alpha	Type 1	8–10.5	Relaxed wakefulness,	Learning, calmness
	Type 2	10.5–13	eyes closed	
Beta	Type 1	13–18.5	Waking consciousness	Physical activity, awareness of
	Type 2	18.5–21		the outside world, problem
	Type 3	21–30		solving
Gamma		30+	Excitement	–

Figure 3. Showcases the different types of brainwaves along with their temporal and spatial frequencies along with their activity's associations. Figure x is borrowed from Mind Your Mind [12].

Responses to certain events can be measured and analyzed through ERPs, Event Related Potentials, which are "electrical potentials generated by the brain that are related to specific internal or external events" [3] through with useful information on the brain's reactions to factors can be analyzed. ERP potentials are composed into modalities or components, which have letters and numbers to respectively indicate a positive or negative polarity and "the peak latency of the waveform" [3]. Some of the modalities identified are the SSVEP, P300, N100, N170 and the P200. The P300 is among the most widely used modalities and preeminent researched in applications research studies within this survey. The P300 is often "observed in the oddball paradigm, in which the stimuli that break from the preceding ones elicit a larger P300 amplitude than the standard stimuli" [3]. Therefore, through concentration or being attentive to a particular matter or object, a target stimulus shall evoke the P300 potential. For applications, the P300 importance lies in selecting commands which can be executed by a system, through having classifiers detect the command signals from the individual's brainwaves.

D. Introduction Conclusion

A Brain computer interface, or BCI, is the direct communication path between the brain and an external device. It aims to translate human brainwave patterns using an interface for controlling an external device. Using a BCI, users can detect and quantify the features of their brain signals that indicate their intentions and translate these features into real-time commands for devices. To achieve this, a BCI system consists of three sequential components: signal acquisition, signal processing, and the output device. An operating protocol controls these three components, including onset and timing of operation, signal processing details, command nature, and performance monitoring. An effective operating protocol allows a BCI system to be flexible and effective. [2]

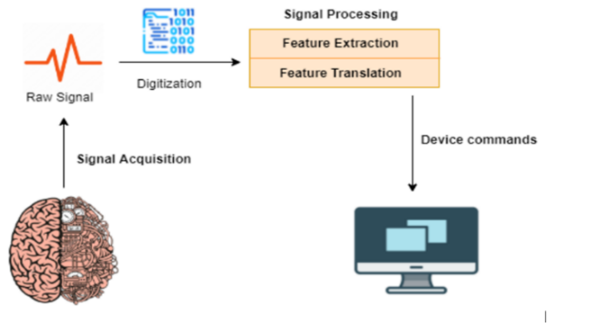

Figure 4: BCI components borrowed from Brain Computer Interface Technology By: A. Sethi, K. Yadav, Konstantinos Psannis [2].

II. APPLICATIONS, METHODS AND EXPERIMENTS

With the ability to capture an individual's intent or thought, numerous experimental applications have been conducted to harness these capabilities offered from BCIs systems. These applications stem from diverse domains in health, security and entertainment. Each of these domains have their own overarching distinctive goal, nevertheless all are consistently aiming to utilize BCI's potential in improving individuals' quality of life. Figure 5 is a taxonomy of the domains and their applications surveyed.

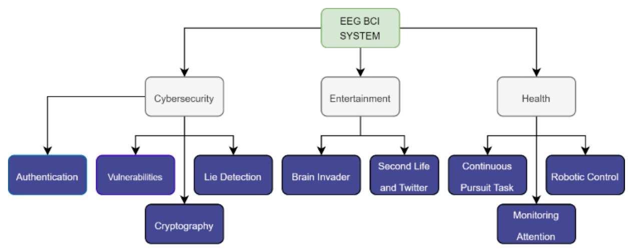

Figure 5. A taxonomy of the different domains and applications surveyed within this paper.

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A. *Cybersecurity*

Security is a form of safety from harm and threats. In the BCI security context, it has been observed that brainwaves “have unique patterns that can represent an individual’s characteristics, and thus they can be used for many cyber security challenges” [12]. Some of these challenges as noted in the research paper, Mind Your Mind, are in authentication, cryptography, and lie detection [12].

a. *Authentication*

With authentication, brainwaves are utilized as a biometric. Biometrics according to the Meriam-Webster dictionary refers to, “the measurement and analysis of unique physical or behavioral characteristics” [14]. Physical abstractions could be fingerprints, eye retina or facial structures, while behavioral characteristics are habits such as an individual’s unique posture when walking, running, or resting. Biometrics hold advantages in ensuring security over the traditional technique of memorizing passwords or pins, as they are distinctively embedded into the individual, making them difficult to replicate. The authentication of an individual is accomplished when the “individual’s brain pattern [is] recorded when he/she is thinking a specific thought” [12] in conjunction with a captcha. The reasons for the captcha stems from distinctive reactions to events and you “cannot accurately reproduce the brainwaves of another person’s brain without direct access to the person” [12]. Limitations to BCI authentications are brain activity changes over time due to aging and factors such as trauma, diseases, and stress [12].

b. *Cryptography*

Cryptography principles encompass the transformation of information from a plain-text to cipher-text format and vice versa. The methodology to accomplish the above-mentioned transformations is through symmetric and asymmetric encryption. In symmetric both the sender and receiver share a single public key, while in asymmetric encryption both sender and receiver individually maintain a public and private key. The main goal of both the sender and receiver is to achieve confidentiality, data integrity and authentication. When it comes to integrating BCI with cryptography, the brainwaves are used to generate random numbers in a crypto-biometric system. In cryptographic research mentioned in, Mind Your Mind, conducted by Ravi and Eswaran, “an EEG scan performed with 61 electrodes to generate a 61-bit key to randomize a Huffman tree, which was then used to encrypt the data” [11].

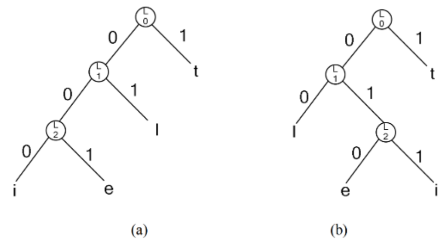

Figure. 1. (a) Original Huffman tree for the word ‘title’ (b) Shuffled Huffman tree (with leaf nodes L1 and L2 shuffled)

Figure 6. Image borrowed from Ravi and Eawaran research paper, “Data encryption using event-related brain signals” [11], demonstrating a shuffled Huffman tree.

To decrypt the data, another EEG scan was performed to generate a key to decrypt the data. The cognitive task used to generate and record an individual brain wave signal, had the individual simply looking at picture containing black and white stripes. The researchers conducted the cryptographic experiment “with 10 subjects, and 40 EEG scans were extracted at various times” [12]. The major takeaway from the research was the length of the key can be increased through adding more electrodes, thereby improving the overall encryption of the data.

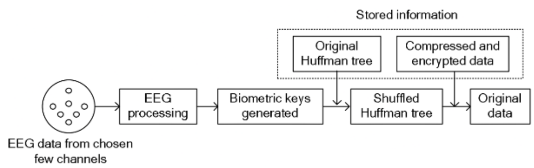

Figure 4. Decryption steps

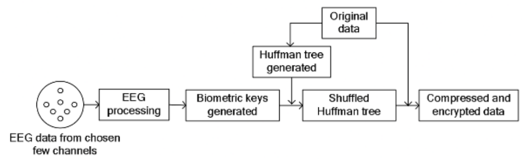

Figure 3. Encryption steps

Figure 7. Images borrowed from Ravi and Eawaran research paper, “Data encryption using event-related brain signals” [11]. Demonstrates a high-level pipeline

of the EEG decryption, up image and EEG encryption, down image.

c. *Lie Detection*

Currently, polygraph tests are widely used in organizations such as the CIA, or FBI, to analyze physiological data from an individual to deduce if they are telling the truth or lying. The analysis of the data itself is often conducted by a specialist; however, the individual being assessed through adequate training of body responses to questions can deceive the polygraph tests. With ERPs, it was noted that responses to external events or stimulus can be recorded with a brain signal acquisition device, which can be interpreted through analysis feedback. Likewise, when it comes to lie-detection, brainwaves can be utilized to analyze reactions from individuals, with P300 being the modality of interest. This is intuitively described in *Mind Your Mind*, when an individual "lies, then he/she is likely to feel some guilt, stress, or other emotions that will affect the emotion-related ERPs visible on an EEG scan" [12]. An interesting experiment mentioned in Mind Your Mind was the study conducted by S. Anwar, T. Batool, and M. Majid, who developed a BCI Event Related Potential lie detector. The experiment involved 30 individuals who knew each other. Everyone wrote comments on other individuals within the group but themselves. After writing the comments, everyone was given a box of comments and was left individually themselves within a room. The instruction was not to read the comments in the box. After some time, everyone was called back from their individual rooms and brought back to be with the group [16]. The researchers were able to identify the lying "subjects those who had already seen their comments, and therefore would recognize them when they appeared on screen, unlike the subjects who were seeing them for the first time" [16]. The results remained consistent, even after the experiment was conducted once again with a new group of individuals and fewer electrodes.

d. *Potential Vulnerabilities and Attacks*

As with any other system, vulnerabilities exist and given enough time, an attacker will find and exploit them. BCI systems are no different from conventional systems, with preventive measures ensuring the robustness of them. However, BCI differs from other systems, given the interface serving as the link between the brain to conventional computing system. It is the most vulnerable part. Some of these vulnerabilities mentioned in Mind Your Mind were noise addition attacks, misleading or altered stimuli, data leakage and privacy violation [12]. With noise addition, data sent from the signal acquisition device can be corrupt or disrupted. A misleading or altered stimuli attack involves the manipulation of outgoing stimulus and feedback with their own. In data leakage, an individual's private own brainwaves can be used by an attacker for malicious purposes. In terms of privacy violation, an individuals' brain waves can be used for other intended purposes without their intention or consent. For instance, the EEG headset manufacturer can sell an individual's brainwave signal to medical or insurance companies, who can analyze signs of neuro-diseases.

e. *Cyber Security Conclusion*

So far, we have investigated some of the security applications of BCI systems. The applications themselves are intriguing in their abilities of expanding the capabilities of the brain when it comes to lie-detection, cryptography, and authentication. At the same time, we have seen BCI systems are not immune to vulnerabilities or attacks, but employing existing security measures, these vulnerabilities can be mitigated or reduced to some degree. Some of the deductions mentioned related to security involved better regulations and standards of neurotechnological sciences to address security loopholes.

B. *Entertainment*

a. *Brain Invaders*

Brain Invaders is a simple arcade shooter game, where players can destroy aliens displayed on a 6x6 grid by concentrating on the intended target. According to researchers Congedo & Jutten, the application makes use of the P300 modality that "enables the user to successively select symbols among an available set, without relying on any motor command" [6]. This selection of a symbol or target will exploit the odd-ball paradigm from which the classifiers and learners integrated into the game will analyze for a modality potential. In their results, they found that "89% of trials required at most three repetitions to destroy the target" [6].

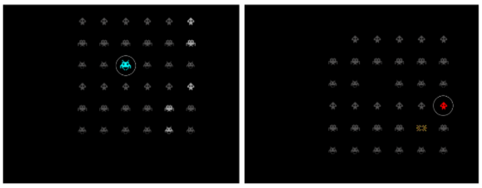

Figure 8. Image from Congedo & Jutten, "Brain Invader a prototype of an open-source P300-based video game working with the OpenViBE platform" [6]. Demonstrates a blue alien being the target and destroyed in subsequent progression.

b. *Second Life and Twitter*

Second life is a free 3D online virtual environment where people engage in conversations with each other, twitter is the counterpart with similar functionalities to second life, however socialization occurs within a 2D environment of text and video [9]. Both applications are used worldwide, and their integration with BCI is possible when using the P300 as a control modality in both applications [3]. As with Brain Invader, there is grid, 6 by 6, showing the control commands available for the individual to focus onto. Below is a snapshot of both BCI applications

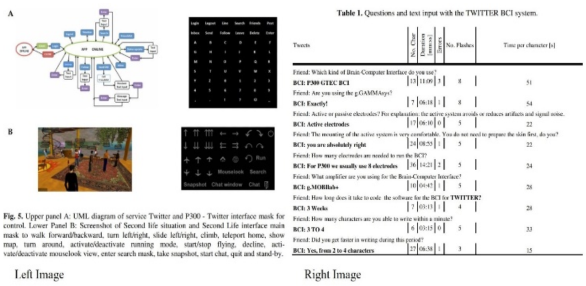

Figure 9. Images borrowed from Gunter Edlinger and Christoph Guger, "Social Environments, Mixed Communication and Goal Oriented Control Application Using a Brain-Computer Interface" [9]. In the Left image bottom left, showcases second life video game, along with the commands in the grid to control the player. The right image demonstrates two individuals on different interfaces, one of them will be utilizing a BCI system to communicate with the other on a keyboard interface.

c. *Entertainment Conclusion*

In this section, we looked at some of the video game applications that have utilized BCI as an interface. This expands the possibilities involved in improving accessibility and video game mechanics for a wide range of individuals. At the same time video games offer a unique platform in experimentation and research in exploring possible breakthroughs in EEG-based BCI technology.

C. Healthcare

Healthcare has long been the center of focus with BCI technology. Even as research in other domains becomes more popular, many studies have a clinical element to them. In this section, we review some domains that have been combined with healthcare and made great strides in improving many peoples' lives.

a. *Robotic Control*

BCI's have been shown to improve the lives of people who suffer from neurological disorders or missing limbs. Combining robotics and healthcare with EEG-based BCI technology provides an interesting opportunity for prosthetic technology. In a recent study out of the University of Minnesota and Carnagie Mellon University, it was shown that EEG-based BCI training and signal processing for robotic movement could be improved upon using an improved training task, as well as an improved signal processing technique [8].

b. *Continuous Pursuit Task*

BCI training paradigms have historically used discrete trial (DT) tasks. These tasks often lead to increased BCI training time and user frustration. To improve upon the training environment and outcome, a new continuous pursuit (CP) task was proposed. The purpose for this new task was to increase realism in training, leading to better real-time performance. The problem with DT tasks is that they have a specific goal/end. While a user could become proficient in doing a specific task, real-life hand and arm movement needs to be much more fluid and complex. The CP task eliminated this by forcing users to control a cursor via an EEG-BCI and follow a dot on the screen as best they could. Because the dot was moving randomly and over a set amount of time, the user was challenged to sustain concentration and facilitate random movement. Using this task, BCI learning was improved by 60% for traditional tasks (DT) and over 500% for the CP task [8].

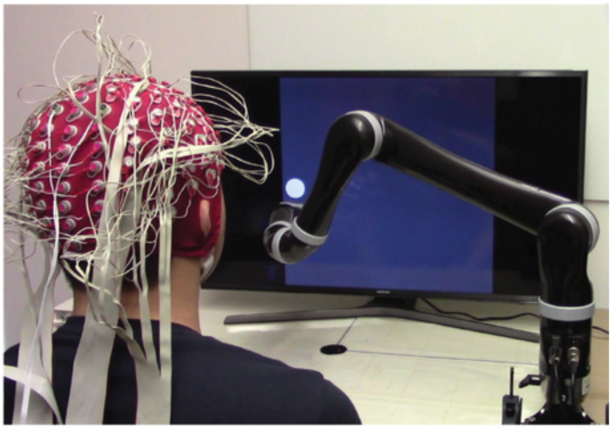

Figure 10. A snapshot of a user performing a CP task using a robotic arm [8].

c. *Electrical Source Imaging*

Transitioning to EEG waves as the signal for BCI presents some challenges. EEG waves are weak and prone to giving noisy data. Historically, spatial filtering has been used to de-noise non-invasive BCI signals with decent success. However, a different approach, Electrical Source Imaging (ESI) has been shown to provide vast improvement over traditional techniques. Prior to this study, ESI had only been tested in offline environments. Researchers developed a "real-time ESI platform to evaluate neural decoding" while avoiding extra processing steps that accompany other spatial filtering techniques [8]. ESI implementation resulted in a 10% increase in CP BCI control.

d. *Monitoring Attention*

In the USA today, it is estimated that 6-16% of children ages 3-17 years have been diagnosed with Attention-Deficit/Hyperactivity Disorder ADHD [4]. This presents a challenging issue for researchers striving to keep that number from increasing. Some major issues in diagnosing ADHD are that there is no single test to diagnose a child, and it is often time-consuming and difficult for a parent to get their child through the process. Additionally, researchers are looking for ways to prevent the worsening of symptoms of children with ADHD. To do this, it is important to identify and treat early warning behaviors of the disorder. A study out of the University of Sevilla aimed to improve the ease and accuracy of ADHD screening in children by getting them to play a video game while measuring their levels of attention.

Often, it can be difficult to get a child to sit still. This difficulty is increased when a child has ADHD or a general attentional deficiency. This can provide challenges when conducting behavioral tests as the child may struggle to be as engaged as they should be. To solve this, children were given a video game to play. The game could be played on a tablet and had multiple levels, each with increasing difficulty. To progress, the child had to maintain a certain threshold of attention. Attention was measured using a commercial, single-channel EEG headset [17].

52 control-group children and 23 ADHD diagnosed children participated in the study. During the study, researchers found they could in fact record attention using a very simple EEG device. Even more importantly, researchers found that the attentional biomarker could also identify children who exhibited reduced attentional ability. The study proves the viability of EEG in a clinical setting as a screening tool for early detection of attentional traits in order to prevent their development [17].

Figure 11. A snapshot of the game used to study attention in children [17].

III. DISCUSSION

Brain-computer interfaces have been shown to improve the lives of people who suffer from neurological disorders or missing limbs. Currently, the best implementation of a BCI is through a procedure in which a device is implanted in the brain for the purposes of signal acquisition [8]. While this procedure has proven effective, it excludes a large portion of the population due to the cost and difficulty of implanting a device in the brain. As a result, researchers have turned to non-invasive EEG-based BCI's to broaden the accessibility of BCI devices. BCI technology touches on a vast range of domains. In this article, we reviewed a few of the domains in which there have been interesting breakthroughs.

Using EEG waves presents a few issues that challenge researchers. EEG waves are weak and need to pass through the skull to be collected. Additionally, signal classification proposes a major challenge as it can be difficult to filter the often-noisy EEG signals. However, through various applications of EEG-based BCI technology, new techniques have been developed to improve signal acquisition and processing. It is important that EEG-based BCI technology be researched within many different domains. With each domain-group bringing unique ideas to the forefront of their research, a vast range of potential solutions can be tested and compared.

Techniques coming from the domain of cybersecurity require an extremely high level of accuracy. If an EEG is going to be used to authenticate or encrypt, it is paramount that the signal is repeatable whenever it is needed. This accuracy is so important that many electrodes are needed to capture the EEG. One such study used 61 electrodes to capture a signal [12].

Sometimes accuracy is not as critical, however. When doing real-time processing, speed is an important factor. For real-time processing events in the domain of video games and robotic control, it is critical to reduce the time it takes to initiate an action from a mental command. Time saved relies upon how quickly the signal can be processed and returned. Electrical source imaging has been shown to be an effective way to process signals quickly and accurately for real time applications such as robotic movement [8].

Video games provide another way to do fast, live processing. By looking at a specific symbol, a certain brainwave frequency could be induced and measured using the P300 modality [3]. While it may seem like video games don't provide much value in terms of research, they have been used in many medical applications, and can provide further accessibility to the domain for people who cannot operate a video game controller.

In ADHD research, complex electrodes were not even required. A single-channel commercial device was sufficient to capture a readable EEG-signal for attention monitoring [17]. ADHD research has proven that a high-end EEG device is not required for every application. This has shown the potential of EEG-based BCI technology in small, everyday tasks. This study also highlights the importance of the "hardware" aspect of EEG-based BCI technology. The devices being used to collect EEG signals should be comfortable, not bulky, and should not hinder the user in any way. In studies looking at children with attention deficits, it is especially important that any distraction be minimized,

While EEG-based technology has come a long way, and is gaining popularity in many new domains, there remain challenges of signal acquisition and classification. The P300 modality, for example, requires some external stimulus to be present. While this has been exploited successfully in many cases, it places a limit on what the user can do. New techniques such as electrical source imaging aim to improve signal classification while avoiding the need for an external stimulus. By utilizing MRI data, ESI has been shown as a better solution for live, complex processing compared to the P300 modality [8].

As researchers aim to tackle the challenges of EEG-based BCI technology, we suggest a few improvements for the technology. The first improvement would be to focus on novel training techniques like the continuous pursuit task. Improving this area can lead to better signal acquisition and user outcomes for basic use of EEG-based BCIs. Another area for improvement is of course signal acquisition. Since EEG waves are so weak and prone to noise, it might be useful to design a hybrid system that incorporates multiple biofeedback channels. For example, combining heartrate and EEG waves to measure anxiety levels in people with varying anxiety levels, potentially leading to better diagnoses and treatment of anxiety-related disorders.

IV. CONCLUSION

This review highlighted the various applications of EEG-BCI technology. EEG-based BCI technology has already proven to researchers that it can be useful in many different applications. As more domains embrace EEG-based BCI technology, new techniques for signal acquisition and processing will be developed, current techniques will be improved, and physical EEG acquisition devices will become better suited for long-term, everyday use.

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