# Brain Computer Interfaces

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## Abstract

Brain-Computer Interfaces are devices that create a direct communication route between the brain's electrical activity and an external output device. The sensors of a BCI read the electrophysiological signals transmitted within the brain and convert the information into bits readable by a computer. Brain-Computer Interfaces are modeled to analyze the brain's central nervous system. This means that whenever somebody makes a decision – or even thinks about making a decision – there are pulses sent throughout the brain that can be intercepted and read by the BCI. From there, the bits of information are sent through computer software, where they are processed (frequently by using machine learning algorithms) in order to interpret the information (Becher 2024). BCIs are currently being developed and tested in various professional sectors, but are predominantly used in the prosthetic/orthotic field. There are a few different types of BCIs, ranging from a non-invasive such as an EEG (Electroencephalogram) which is placed on the scalp, to an invasive ECoG (Electrocorticography) which is placed directly on the brain's surface. The closer to the center of the brain the hardware is attached to, the more clear the reading will be. Those developing BCIs are hopeful for the future as the technology is rapidly advancing. And while BCIs are becoming more powerful, the conversion on the risks grows in like manner.

## Introduction to Brain-Computer Interfaces (BCI)

The brain – perhaps one of the most complex things known to man. For thousands of years, the brain has puzzled mankind. The brain, afterall, named itself, and is now attempting to understand itself. It's a recursive problem that likely will never be fully solved. However, recent technological advances have brought about a greater understanding of the brain and how it operates. Ever since the invention of digital logic and modern computers, people have been especially intrigued by the similarities between the human brain and a computer CPU. With the invention of the electroencephalogram (EEG) in 1924 that would measure electrical activity in the brain, desire for the furtherment of neural science sparked. Later in the early 1970s, research began on a project with the aim of creating a device that was powerful enough and fast enough to interpret brain activity in real-time and perform actions. The goal of the device was ultimately to help assist those primarily with physical disabilities. The completed device is known as a Brain-Computer Interface (BCI).

Brain Computer Interfaces are devices that create a direct communication link from the brain's electrical activity and a computer. In essence, BCIs allow people to control devices with their thoughts (*Becher*, 2024). While BCI technology is still in its infancy, the possibilities for application are vast, causing a great excitement in the scientific community. The ultimate goal of BCIs is to replace or restore useful physical function to people disabled by neuromuscular disorders (*Mak & Wolpaw*, 2009). For those who are non-verbal, a BCI would interpret what the user is trying to say and would broadcast that using a computer-simulated voice. For those with paralysis, a BCI may be configured to allow them to utilize their limbs that they were not capable of operating. There are many current uses for BCI, with optimism for what the future may hold for BCIs. And while the primary usage currently of BCI technology is to help those with disabilities, it is also being utilized and developed for other purposes such as brain research, human-computer interactions, and even for military operations.

## Types of BCIs

There are two different types of Brain-Computer Interfaces: invasive and non-invasive. Invasive BCIs are planted directly to the patient's brain tissue and require surgical procedures. Since there are major risks associated with the necessary procedures for implanting an invasive BCI, they are typically only found in patients looking to recover from severe medical conditions such as paralysis and other neuromuscular disorders. On the other hand, non-invasive BCIs are wearable devices placed on the scalp that utilize electrical sensors to serve as a communication pathway between the patient's brain and the computer. This type is the more common route taken by patients due to the risks and cost associated with invasive BCIs. Since non-invasive BCIs are further from the brain than invasive BCIs, the signals are not as strong. This type of BCI is commonly used for patients needing to guide the action of a machine, such as a prosthetic device (*Becher,* 2024).

## How BCIs Work

Discovered in 1875 by Hans Berger, brain waves are electrical activity patterns in the brain that are produced by neurons firing together. This brain activity can be detected on the scalp, the cortical surface, or within the brain itself *(McFarland & Wolpaw*, 2011). BCIs are modeled after the electrophysiology of a brain's neural network, and operate on a patient's central nervous system. This leaves BCI hardware tasked with capturing these pulses and sending the information to the main computer to be translated. The BCI uses electrodes to acquire brain signals from the patient. Once the main computer receives the data, it pushes it through many complex algorithms in order to interpret the thoughts of the user. Since brain activity may look vastly different from user to user, machine learning plays an important role. On top of that, the algorithms must work hard to filter out all of the extra noise within the brain that was not meant to be processed. Over time, the software will become accustomed to the individual using the device and will become more accurate in its interpretation of their brain activity. This process of machine learning can take anywhere from a single session to multiple months. While the overall roadmap of how BCIs work is simple, the engineering behind BCIs require deep understanding of many neurological components, electrical engineering, and computer science.

## Historical Background

The science behind Brain-Computer Interfaces stretches back to the 1920s with the invention of the electroencephalogram (EEG) by German psychiatrist Hans Berger, which would record the electrical activity in the brain via electrodes attached to the patient's scalp. Hans speculated that eventually thoughts could be read using EEG traces. Hans' dream was merely science fiction at the time he proposed it, and it wasn't until the 1960s where his idea started to come to fruition. The goal behind the BCI was to develop a system that was powerful enough and fast enough to read the brain's electrical signals and provide feedback in real time. Research began at UCLA in the late 60's and 70's by experimenting with animals, such as monkeys, to develop new, direct communication paths between an external device and the brain. After enough successful experiments and system modifications, the first attempts on humans were performed in the 90's, and the first invasive BCI was implanted in 1998 (*Kawala-Sterniuk, Aleksandra, et al,* 2021). Researcher Jonathan Wolpaw provided the first full definition of the BCI in 2000. Since then, research and development of BCIs has grown dramatically. A deeper understanding of physiology, more powerful algorithms, and deeper learning in machines have all contributed to the growing success of BCI technology. The excitement around BCIs abounds due to its youth and its promising future usages.

## Development

As research and development for BCIs continues at a brisk pace, excitement is building for the future of BCI advancement. The Brain-Computer Interface global market was $1.74 billion in 2022, and it is expected to escalate to $6.2 billion by 2030. That's an annual compounding growth rate of about 17.5% (*Alohaly,* 2024). This prediction makes sense considering the increase of excitement among researchers, developers, and the public eye. Scientists around the world look forward to the potential of BCIs being routinely used to replace or restore function for people disabled by neuromuscular disorders (*Krusienski, Shih, Wolpaw,* 2012). According to one of the leading BCI companies, there are fewer than 40 people in the world that currently have implanted BCIs. And from those people, all of them are experimental (*GAO,* 2022). One of the primary obstacles that BCI development faces is that each person's brain generates unique signals. Configuring a device that can universally learn to read unique brain signals and produce accurate results is a challenging feat to overcome. In order to bring about the exciting future that BCIs promise, there are three primary areas that researchers and developers need to engage heavily in and improve: signal-acquisition hardware, BCI validation and dissemination, and reliability (*Krusienski, Shih, Wolpaw,* 2012).

**Signal-Acquisition Hardware:** All BCI systems depend heavily on the sensors and other hardware associated with acquiring the signals from the brain. The faster and more accurate the sensors and electrodes are, the better the results will be. Invasive BCIs, while they produce the fastest and most accurate signaling, scare away lots of people who may benefit from it. The idea of having a surgery in order to implant a device into the brain is simply not appealing to many. In order for BCIs to be readily accessible by the public, BCIs ideally need to be small and fully portable. They also need to be comfortable for the user without requiring an extensive amount of time to set up. For invasive BCIs, the hardware needs to be safe, fully implantable, durable, and function for decades (*Krusienski, Shih, Wolpaw,* 2012). As invasive

BCIs continue to be developed, their research primarily relies on animal studies before human trials can be conducted, drawing out the development process.

**Validation and Dissemination:** Development of BCIs for disabled persons requires a look into the patient's real-life value in terms of efficacy, practicality, cost-effectiveness, and overall impact on quality of life. In other words, are BCIs worth it? This is a complex question because the answer varies from person to person. In order to come up with some sort of formula that could be applied to the general public, lengthy studies must be conducted on many willing groups. While there are studies that are currently being conducted, they have just started and results won't be available for some time. Another obstacle for furthered development for BCIs is that those who would likely benefit from BCIs are primarily those who have severe neuromuscular disabilities. This user population is relatively small, meaning the current sample size is miniscule and not sufficient to formulate conclusions. On top of this, while the initial setup cost of an non-invasive BCI system is 'relatively modest', with a range of $5,000-$10,000, the required ongoing technical support can easily drive up the total investment (*Krusienski, Shih, Wolpaw,* 2012).

**Reliability:** Although the future livelihood of BCI technology relies on hardware improvements and clear and concise validation studies, there still remains what would appear to be the biggest issue: reliability. Regardless of the improvements to hardware, software, and other important components in these systems, BCI reliability has still remained poor. In order for BCIs to be used regularly for real-life applications, it must be reliable. Because the brain is not as easily measurable and containable as a computer, it is under question if reliability can ever truly be achieved. While BCIs today can be successfully used to perform simple, rudimentary communication operations for those with the most extreme disabilities, they struggle to be consistent when handling anything even a little more complicated (*Krusienski, Shih, Wolpaw,* 2012).

## Security Concerns

Just as with any digital device, there are security concerns that must be addressed. Software and security engineers are in an on-going battle against attackers trying to undermine the integrity of information systems. It's an arms race with no end in sight. Having one's device compromised can be devastating, even if it's just a laptop or a mobile phone. Now imagine just how horrific a compromise to a device implanted in one's brain can be. When a device is reading messages directly from somebody's brain, the stakes have gotten exponentially more extreme. A malicious exploitation of a BCI, or any neurological device, can mean complete loss of privacy as the attacker could quite literally read the user's thoughts. To make matters even worse, an attacker could block off the input into the interface that usually comes from the brain signals, allowing them to take control of input and manipulate whatever the device was outputting information to, such as a prosthetic device. This vulnerability means a complete compromise of one's physical safety and of those around them. While these vulnerabilities are mainly hypothetical because, as mentioned previously, there aren't many cases of people with invasive BCIs, the security concerns must be properly addressed and secured before BCIs could become a commonly used device.

## Conclusion

Despite all of the concerns regarding system components, reliability, and security, the rage of enthusiasm for BCIs amongst the researcher community is at an all time high, and there are many who are committed to seeing the development of BCIs succeed. With enough time and interest, BCIs have the potential to become mainstream devices that have seamless integration, high-end security, and effective translation. These devices could bring about an incredibly positive impact on the quality of life for those with neurological disabilities.

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