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UNIVERSITEIT
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BRAIN CONTROLLED WHAT?

A computer scientist's guide to
brain-computer interfaces and a
comparison study of multiple
state-of-the-art motor imagery EEG
classification approaches

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2021 - 2022

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Proefschrift ingediend met het oog op het behalen van de graad van Master of Science in de Ingenieurswetenschappen: Computerwetenschappen

HERSENGESTUURDE WAT?

Een computerwetenschappelijke handleiding tot hersen-computerkoppelingen en een vergelijkende studie van enkele van de beste EEG-classificatiemethoden voor ingebeelde motorische handelingen

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Abstract

Brain-computer interfaces (BCIs) are fascinating systems that aim to translate brain signals into actions. A recent rise in scientific and commercial interest in these systems has helped in popularizing them outside highly specialized labs. With seemingly thousands of use cases for these systems, many researchers and students have shown interest in contributing to the field of BCIs. However, the highly interdisciplinary nature of BCI research among other factors cause a steep learning curve which deters many individuals who wish to work with these kinds of systems. Those who do commit to overcoming the steep learning curve are faced with complex and sometimes contradictory research.

This master thesis aims to facilitate this entry into the fascinating field of BCIs for computer scientists. Part I aims to provide all foundational knowledge required to work in the BCI field as a computer scientist. An exhaustive literature review in the introductory chapter aims to provide an intuitive introduction to the field by addressing the reasons for a growing scientific and commercial interest along with some of the common use cases for BCIs. This introductory chapter also addresses some promising opportunities and obstacles in the field. The introductory chapter ends by touching upon some ethical challenges related to BCI research. The other chapters in Part I provide the more technical knowledge required for computer scientists in the field. Chapter 2 discusses the origin and measuring modalities for biomedical signals (biosignals) and brain signals in particular. Chapter 3 goes over some common BCI pipeline components for classifying motor imagery (MI) electroencephalography (EEG) data, the most common task of computer scientists in this field.

Part II puts this theory to practice and compares multiple state-of-the-art techniques in MI EEG classification. The focus of this part is on offline techniques with both two-step machine learning (ML) approaches and one-step deep learning (DL) approaches implemented. Some of the steps required to move to an online classification system and eventually a complete BCI system are also addressed. This master thesis ends with Part III where the results and added value of this work are reflected upon.

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Part I

Understanding brain-computer interfaces

Chapter 1

Brain-computer interfaces

1.1 Introduction to this chapter

Brain-computer interfaces (BCIs) are systems, consisting of hardware and software, that aim to read or even stimulate a user's brain signals for a wide variety of applications. Whilst many of these applications for BCIs revolve around providing novel interaction methods for computer applications, they are capable of fulfilling more general tasks as well. Because of this, BCIs are also referred to as brain-machine interfaces (BMIs) and can be seen as a special type of the more general human-machine interfaces (HMIs) and biological signal control (biosignal control) systems. A well-known Professor in this field is Jonathan R. Wolpaw who was also the guest editor for the first international meeting devoted to BCI research and development as part of the IEEE conference on Rehabilitation Engineering. During that meeting, a first formal definition for BCIs was given:

A brain-computer interface is a communication system that does not depend on the brain's normal output pathways of peripheral nerves and muscles.

J. Wolpaw et al. (2000)

Since then, Jonathan R. Wolpaw has (co-)authored a lot of influential papers in the field of BCIs (Daly & Wolpaw, 2008; Shih et al., 2012; J. Wolpaw et al., 2000) and created a great introductory textbook to the field (J. Wolpaw & Wolpaw, 2012). As a board-certified neurologist, Wolpaw's work is often centred around applications in a more medical setting rather than a commercial one. In this medical setting, his opinion on what defines a *perfect* BCI is often strived for and can be summarized as follows:

The perfect [medical] BCI is a safe and affordable system which works all the time, does not require the permanent assistance of a technician or a scientist, restores communication at "normal" speed, is aesthetically acceptable, is reliable and, for the same function, does not require more concentration for a patient user than what it does for an able-bodied person.

Peterson et al. (2020) and J. Wolpaw and Wolpaw (2012)

One of the things this thesis aims to study is how far BCIs have come concerning this definition of a perfect BCI. It is noted that the term communication in these definitions simply depicts the exchange of information rather than specific human communication such as speech. For example,

a computer mouse could be seen as a communication device that exchanges information about the user's intent to the computer. Many of these properties for a perfect medical BCI system would also be beneficial for commercial BCI systems.

Especially the commercial interest in BCIs has seen a recent spike, through multiple big-tech companies such as Meta (formerly known as Facebook), Valve (a major gaming company) and Neuralink (an Elon Musk company) showing interest in the field (Bernal, 2021; Facebook, 2021; Musk & Neuralink, 2019). This has given rise to the public interest for potential life-improving BCI applications as well as some public outrage on more ethical aspects that challenges these systems.

This first part of the thesis aims to provide all required background information needed for understanding BCIs. The remainder of this chapter further introduces the main rationale behind BCIs research by discussing the rise in popularity of both medical and commercial BCIs, some practical examples of BCI systems that have been developed and some of the opportunities and obstacles in the field. The chapter ends with a note on some of the ethical challenges for BCI systems and a discussion of the proposed system for this thesis. Chapter 2 gives more depth on the origins and measurability of brain signals while Chapter 3 addresses the techniques and technologies needed to process brain-signals and take actions based on their interpretation. As research on BCIs is highly multidisciplinary, entering the field as a computer scientist can be rather intimidating due to the steep learning curve of the ideas, technologies, challenges and terminology used in such research. To lower this initial learning curve, these first three chapters aim to introduce the most important concepts in an easy-to-understand manner for a typical computer scientist student with some artificial intelligence (AI) background. These first chapters follow no standardized procedure for systematic review. However, special attention was paid to favor papers from reputable sources, such as famous authors in the field (i.e. Jonathan R. Wolpaw). A focus was also put on articles which have been influential based on both the amount of times the work itself is cited in other articles and the performance of these other articles citing the original article. The latter was determined by using the connected papers tool¹.

The interested reader is also referred to the great introductory book on BCIs by J. Wolpaw and Wolpaw (2012) and the review article by Nicolas-Alonso and Gomez-Gil (2012) when more introductory insight is desired. Whilst these resources have dated a little and state-of-the-art has changed since then, the main ideas discussed in them remain unchanged. A more recent, systematic review article by Dillen et al. (2022) focuses on current deep learning (DL) techniques for use with BCIs among other biosignal control systems.

1.2 Growing scientific and commercial interest in BCIs

With brain signal measuring modalities such as electroencephalography (EEG) being over 100 years old, the idea of using those brain signals for a wide variety of use cases has been explored for many decades (Berger, 1929; Haas, 2003; Kübler, 2020). With feasibility studies of using BCIs already existing in the 1970s (for example by Vidal, 1973) showing that most of the ideas explored today are not new, a clear spike in both scientific and commercial interest can be seen after the 2000s. It is no coincidence that the first international meeting devoted to BCI research and development as part of the IEEE conference on Rehabilitation Engineering discussed in Section 1.1 was also from this period.

This rise in popularity can be explained by several events. Perhaps most importantly is the improvement of both brain signal measuring equipment and computational processing equipment in both efficiency, accuracy and portability. Recent improvements in machine learning (ML) and

¹<https://www.connectedpapers.com/>

DL after some AI winters between the 1970s and the 1990s are bound to also have played an important role. The interest of big tech companies such as Neuralink, Meta and Valve have also introduced unseen amounts of funds further accelerating BCI research.

This section focuses on discussing these most important contributing factors to the new rise of interest in BCI research. These factors are discussed in an arbitrary order, as most of them have influenced each other and it is hard to name a singular reason that explains this recent rise in interest. For a more in-depth overview of the rich history that BCI research has, the reader is referred to the work by Kübler (2020).

1.2.1 BCIs have gained big-tech interest and funds

Big tech has been catching on with the possibilities BCIs bring, and the amount of money they can earn from it. Although profitability is an important factor in most medical applications as well, the focus of medical applications lies on improving the life of a patient, whilst the focus of commercial applications can differ greatly. Since commercial BCIs are still in their early stages and the idea of constantly wearing a brain-signal recording headset has not been accepted by the wide public yet, many commercially oriented companies start with products that are a cross between medical and commercial applications.

Most noteworthy of these more commercially oriented companies is Neuralink, an Elon Musk company. Neuralink’s initial white paper discusses its aim to create a scalable high-bandwidth BCI system, focusing on its mechanical achievements (Musk & Neuralink, 2019). These mechanical achievements are rather impressive, with state-of-the-art robot surgery inserting ultra-thin sensors directly into the skull allowing for a sleek and visually pleasing package that is mostly hidden from the human eye. Comparing this to non-invasive methods of recording brain signals, which are methods that don’t require inserting machinery into the human body, the signal quality is also expected to be far greater. However, an invasive approach currently introduces added health risks and more ethical challenges making non-invasive methods often more suited for general use (Dadia & Greenbaum, 2019; Dillen et al., 2022; Jawad, 2020). Since the publication of the Neuralink white paper, the company has held live demos of their BCI implanted directly into the skulls of animals such as pigs and monkeys. A video by Neuralink of a monkey playing pong using brain signals as input² has gathered over 6 million views on YouTube already. Combined with many news articles, the kind of exposure that Neuralink has gotten is unseen compared to the regular exposure of literature in the field. This can be questioned, as earlier work by Ifft et al. (2013) demonstrated monkeys taking control over two avatar arms simultaneously, a task that is arguably even harder to accomplish than simply playing pong. Adding to this, the experiment by Ifft et al. (2013) has an appropriate peer-reviewed paper backing it whilst Neuralink among other commercially oriented companies in the field often lack scientific backing for the claims they make. Thus, the scientific value of these more commercial demos and applications can be argued for, but the funds for research introduced by these companies and the exposure to the field have accelerated research in the field and helped popularize the field. Adding to this, the proposed system by Neuralink is one of the most aesthetically pleasing compared to alternative invasive or non-invasive systems on the market, which is one of the properties of Wolpaw’s perfect BCI system given in Section 1.1.

Besides Neuralink, companies like Meta, Valve, Neurable, InteraXon and many more are exploring the commercial possibilities of BCIs as well. Some of the companies do this through direct internal research whilst others might provide funds for external projects (Alcaide et al., 2021; Cuthbertson, 2021; Moses et al., 2021; Stockman, 2020). There seem to be two main

²<https://youtu.be/rsCul1sp4hQ>

focuses of the technology in the commercial space. Either using the new interaction method to perform work more efficiently or using it for recreational purposes.

Using BCIs to boost work efficiency

Meta, formerly known as Facebook, has been playing with the idea of BCIs for quite a while but has been relatively quiet about it publicly. In 2021, Meta publicly announced it had provided funds for research on the use of a BCI-system to restore speech functionalities for people suffering from anarthria (Facebook, 2021; Moses et al., 2021). The system by Moses et al. (2021) achieved an average of 15 words per minute, decoded with a median error of 25%. Whilst this might not sound impressive, anarthria is a disease which causes patients to not be able to articulate speech at all due to lost control of the muscles required for making sounds. Adding to this, people suffering from anarthria often suffer from other lost muscle control as well, making alternatives such as keyboard typing or writing impossible. Taking this into account, these results should be seen as very impressive and such a system can be life-changing for certain patients. Whilst the system by Moses et al. (2021) was invasive just like Neuralink’s system, it was far from visually pleasing. The patient was fixed in a chair and physically connected to a bulky processing unit in the form of a small server rack, which makes the system non-mobile and makes the user stand out if it were to be used in the real world where discreteness is often desired.

The system by Moses et al. (2021) is an example of one that is backed by the funds that big-tech companies have and which is mainly focused on medical applications whilst the final intention of the funding company is most likely of commercial nature. Indeed, it is not hard to imagine the commercial interest of Meta in developing a more general *virtual keyboard* to enable fast *thought to speech* or *thought to text* applications usable by the masses. In fact, during the F8 conference (Facebook, 2017) a couple of years before the paper by Moses et al. (2021), Meta stated the following:

Specifically, we have a goal of creating a silent speech system capable of typing 100 words per minute straight from your brain - that’s five times faster than you can type on a smartphone today.

Facebook (2017)

Such a virtual keyboard could replace certain speech-to-text applications already broadly used for commercial purposes. In the same blog post by Facebook (2021) discussing the funding for the project by Moses et al. (2021), it is also mentioned that Meta has interest in using BCIs for high-bandwidth interactions in AR/VR. However, Meta has been subject to multiple privacy concerns lately (Fuller, 2019; Hu, 2020). The company’s reputation has been damaged from this which doesn’t help in selling the concept of them having a BCI which allows them to read the brain activity of the users. This could explain why they have recently started to shift their focus from BCIs towards muscle-based interfaces using electromyography (EMG) (Facebook, 2021).

A recent example of a BCI being used to boost work efficiency is covered by S. Chen (2022). He discusses how Chinese researchers have been working on a non-invasive and portable system that aims to detect if a user is watching pornographic content through brain signals. When presenting fifteen male participants aged between 20 and 25 with erotic content and regular content, an accuracy of over 80% was obtained for determining whether the user was watching erotic content or not. Such a system should aid in China’s content regularisation which often bans such erotic content on their domestic social-media platforms. Current systems rely on manual evaluation by a reviewer for removing or keeping content that is flagged as inappropriate by either the community or an algorithm. Further automating this task through a brain-controlled

system could boost the efficiency of this process significantly.

Using BCIs for recreational use

Whilst some promising results have been obtained when using BCIs in commercial settings to boost work efficiency, many of the systems still lack the desired performance to become truly viable. And thus, the most prominent type of commercial BCIs are those focusing on recreational use. In this regard, the headsets by InteraXon, produced under the Muse brand, are one of the earliest examples, with their first version being released in 2014. The first iteration of this product was advertised as a meditation aid. This headset relies on measuring Theta waves in the brain, which are lower frequency waves that suggest a user is meditating. Section 2.3.2 talks about these brain wave frequencies in more detail. The actual accuracy and usefulness of these types of systems are debated, as discussed by Stockman (2020). More recently, a newer version of the InteraXon headset came to market, named Muse 2, which also aids in sleep monitoring. This relies on detecting Delta waves among other patterns to determine the sleep quality of a user. Like before, this accuracy and usefulness can be argued for. A similar commercial product for sleep tracking is available from the company Dreem, under the name Dreem 2. Dreem has received more funding, as can be seen in Figure 1.1, but InteraXon, the company behind the Muse headset, has arguably contributed more to the field. Not only was it one of the first commercial BCIs that gained media attention, but the company also plays an important role in the commercialisation of BCIs as their headsets are cheap, non-invasive and visually pleasing whilst also being widely available. Adding to this, these headsets have pretty good supporting libraries in Python among other programming languages that allow developers to use these headsets for other purposes as well. Besides InteraXon, some other companies that specialize in providing commercially usable brain-signal recording headsets exist, as will be further discussed in Section 2.4.3.

Perhaps the most promising short-term commercial use of BCIs is in combination with virtual reality (VR) and augmented reality (AR). Besides Meta's interest in this region, as discussed earlier in this section, Valve has also said it is actively researching how to use BCIs as a novel interaction system in VR games (Cuthbertson, 2021). Valve is the company behind Steam, one of the world's largest game marketplaces and they are specialized in creating games and gaming hardware as well. To achieve the goals of this project code-named *Galea*, Valve is working together with OpenBCI, a well-respected company in the BCI research field that has provided open-source hardware and software for use in BCI systems. Tobii, a company that specializes in eye-tracking software, is also working on project Galea. With a final goal of creating an open-source BCI that can be used in gaming, the anticipation for the headset has been high. However, just as with deadlines from other companies such as Meta and Neuralink, the project has been postponed multiple times. This is not surprising as the promises of what a BCI can do are near endless and initial trials often offer promising results but going to a final product has been proven to be incredibly hard due to several open issues (Dillen et al., 2022).

A final stream of money that is important to mention, is coming from militaries around the globe. The U.S. military among others is known to invest a lot of money in any form of innovation, especially related to devices and technologies that can give them a strategic edge when fighting in a war (with examples of funds for AI research in Center for Security and Emerging Technology et al., 2020; Hunter Christie, 2022). Whilst most of this information is classified, it is known that the U.S. Department of Defense and others have shown interest in a wide variety of applications using BCIs (Binnendijk et al., 2020). Whilst one can only guess what these government organisations are developing, it is likely that over time these applications might become public knowledge and aid the research field of BCIs in creating even better systems. Tullis (2019) discusses the U.S. militaries interest in BCIs further.

Summary of big-tech using BCIs for commercial applications

To summarize, there have been a lot of big companies showing interest in commercial BCI applications in the past few years. Some might contribute directly to the field by funding scientific research, which is often still focused on medical applications but whose results can show potential for certain commercial applications (Facebook, 2021; Moses et al., 2021; Musk & Neuralink, 2019). On the other hand, some companies are working on commercial products internally, mostly for improving work efficiency (S. Chen, 2022; Facebook, 2017) or for recreational use (Muse and InteraXon headband, Cuthbertson, 2021). These commercial products have yet to see truly successful examples, as they are either questionable in delivering what they promise (Stockman, 2020), experience delayed deadlines or are even cancelled in their entirety. Nonetheless, these companies focusing on commercial applications often have high amounts of funding and a focus on the user experience (UX) of BCIs which could help accelerate research in the field and make BCI systems more visually pleasing and accepted by the broader public. In this way, they also contribute to Wolpaw’s vision of a perfect BCI system as discussed in Section 1.1.

Figure 1.1 shows the funding of BCI-related companies founded after 2010 as a rough indication of how much money is spent on start-up companies in the field. Interestingly, from the companies Neurobionics, Muse and Neuralink mentioned in this thesis, the funding amount is in proportion to the overall popularity of that company to the wider public, although this is by no means a proven relation. It also shows that whilst academic research on BCIs doesn’t require huge funding, with open-source datasets and relatively cheap hardware available as is further discussed in Section 1.2.4, 2.4.3, and 3.3.1, creating an effective commercial product can become an expensive affair rather quickly.

1.2.2 Improved brain-signal measuring facilities

As brain-computer interfaces (BCIs) are a type of human-machine interface (HMI) relying solely on brain signals to operate, the measuring facilities for acquiring data of those brain signals have a direct impact on the capability of those systems.

Most BCIs rely on non-invasive measuring equipment that uses EEG as a source of data and this paper will focus mainly on such measuring equipment as well. Chapter 2 explains in greater detail what EEG and some of its alternatives are, the equipment used for acquiring brain-signal data and more. For this introduction, it suffices to know that non-invasive EEG measuring equipment measures the electrical potential difference, often in microvolts (μV), between electrodes placed on the scalp.

Following Wolpaw’s definition for a perfect BCI given in Section 1.1, the recording hardware should ideally be aesthetically acceptable and shouldn’t require the assistance of a professional to install. In recent years, new developments in this hardware have made meeting these criteria more plausible, which are addressed in this section.

Hardware improvements in non-invasive EEG measuring equipment

Three major hardware distinction made between the electrodes used in non-invasive EEG measuring equipment is whether they are wet or dry electrodes, whether they are active or passive electrodes and whether communication to the processing unit happens wirelessly or not. When considering Wolpaw’s definition of a perfect BCI described in Section 1.1, dry-electrodes with passive amplification that connect wirelessly to the processing unit would be ideal. However, when looking at data quality, a wired wet-electrode with active amplification is best. Luckily, recent advancements have made these differences in data quality more acceptable, as will shortly be discussed in what follows.

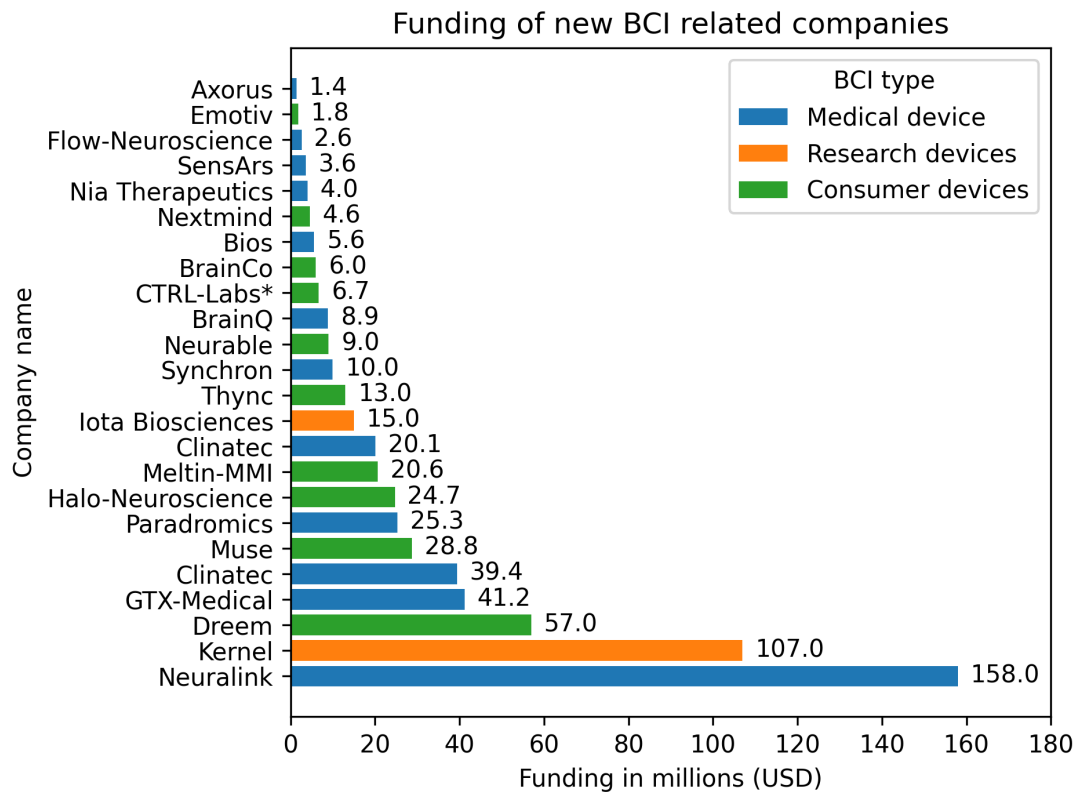


Figure 1.1: Funding of newer BCI related companies depicted in millions (USD).
 Figure based on data by Rao (2020) from 2019. It is noted this data is limited to companies that were created after 2010 where funding information is made available.

Wet EEG electrodes are electrodes which require an electrolytic gel to be applied between the electrode and the scalp. This gel functions as a conductor and, as discussed further in Section 2.4.3, currently allows wet electrodes to have better data quality compared to dry electrodes (Cruz-Garza et al., 2017; Mathewson et al., 2017; Tseghai et al., 2021). However, wet electrodes require the assistance of a professional to correctly apply the gel which leaves behind traces after use. Adding to this, the electrolytic gel could also cause allergic effects for the user. Due to the viscosity of the electrolytic gel changing over time, artefacts in measurements may also appear (Tseghai et al., 2021). These are unwanted properties and conflict with Wolpaw's vision of a perfect BCI. The medical-grade EEG equipment shown in Figure 1.2a uses wet electrodes with an electrode cap.

Advancements in dry electrodes are making the gap with wet electrodes smaller and smaller (Cruz-Garza et al., 2017; Mathewson et al., 2017; Tseghai et al., 2021). These dry electrodes don't require the use of an electrolytic gel and given the use of an appropriate headset can be installed on the scalp without the assistance of a professional. Both of these properties are in favour of Wolpaw's properties for a perfect BCI. The main reason dry-electrodes are becoming more viable to be used in real-life environments is due to improvements in active electrode technology (Mathewson et al., 2017). A relatively bulky setup of these dry electrodes with active

amplification is shown in Figure 1.2b.

Active electrodes are electrodes which do more than just forwarding their measured voltage fluctuation to the main controller board whilst passive electrodes do just that. This is often necessary since the measured signal is of such low strength that even a short distance cable from the electrode to the main board can cause a lot of noise due to electromagnetic interference (J. Xu et al., 2017). To reduce this noise, a preamplifier is used which additionally amplifies the signal before transmission over the wire as opposed to only being amplified in the main controller board. This makes the final system less compact and more expensive but is often required in anything but lab environments, especially for wireless dry electrodes, as further discussed by Mathewson et al. (2017).

When talking about wireless electrodes, it is not the effective electrode itself that is wireless but rather the communication between the main controller board, a board to which all electrodes are connected by wire, and the processing unit such as a computer. Such a wireless setup is shown in Figure 1.2b. Whilst a wireless approach allows for the creation of an aesthetically more pleasing system where the measuring hardware and processing hardware are physically separated, a wired connection will always remain more efficient and reliable. However, as discussed by Tosi et al. (2017), Bluetooth (BT), an open standard for wireless communication, has seen extensions that are more reliable, power efficient and capable of higher transmission speeds. This has made wireless solutions more appealing in BCI systems but overall issues with wireless solutions, in general, will prevail. Most important is the risk of connection loss and a higher latency resulting in a longer time between the point a signal is measured and it is received by the computational unit.

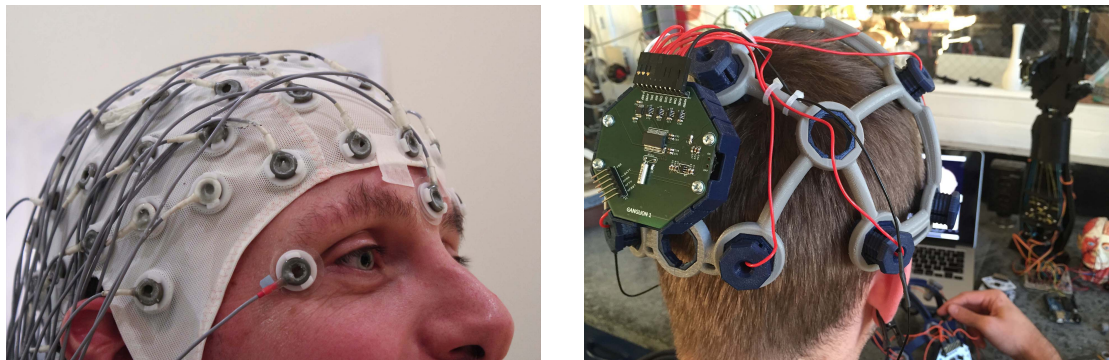
All of these advancements have enabled companies such as Muse, Dreem and OpenBCI to develop non-invasive, dry-electrode based EEG measuring equipment with active amplification in an affordable and often aesthetically acceptable manner. As BCIs become even more popular, a heavier focus on affordability and visuals with EEG measuring equipment is to be expected. These two properties were less important in previous medical settings where a patient would wear such equipment only when undergoing a test in the hospital. Figure 1.2 shows the contrast between a medical-grade EEG recording system and one that is consumer-grade.

Algorithmic improvements for non-invasive EEG measuring equipment

Whilst hardware improvements has made the collection EEG data more affordable, reliable and accurate, one important issue still remains. Even with the best active wet electrodes, The contrast between spatial and temporal resolution is enormous. EEG is known to have a good temporal resolution but rather poor spatial resolution. A good spatial resolution would mean that the measurement from electrodes corresponds only to a small, known region of the brain, typically underneath that electrode. Such a correlation is helpful as it reduces noise and increases interpretability of the signal. It also allows for fewer electrodes to be used if only the activity of certain areas of the brain is of interest.

Thus, many attempts have been made at improving spatial resolution of EEG but it has been proven to be a challenging task (Ferree et al., 2001). Besides potential noise of the measurements, this is also caused by the anatomy of the human head. Remember that the electrodes used for non-invasive EEG measuring are placed on the scalp, the skin of the human head. As shown in Figure 1.3, besides the scalp, different structures such as the skull and cerebrospinal fluid (CSF) are in between the electrodes and the actual brain. These components *blur* and *disperse* the perceived brain-signal, making it hard to track where the measured signal came from when looking at the electrical activity on the scalp.

Whilst increasing the number of electrodes placed on the skull physically limits the region



(a) Medical-grade EEG measuring equipment that uses wet electrodes which are each connected to a separate main board via a long cable. Image from Chris Hope, CC BY 2.0, via Wikimedia Commons.

(b) Commercial-grade EEG measuring device that uses dry electrodes with active amplification connected to an attached wireless controller board. Image from Conorrussomanno, CC BY-SA 4.0, via Wikimedia Commons.

Figure 1.2: The contrast between medical-grade EEG measuring equipment and a consumer-grade alternative.

under one single electrode, it doesn't guarantee an improve in spatial resolution. Indeed, clever processing algorithms are required to correct for overlapping signals between electrodes so that the overlapped signal is correct for and the effective spatial resolution is improved. Besides this, there is also the issue that decreasing the distance between electrodes introduces the need for placing more electrodes to cover the entire region of the brain. This increases cost, lowers user comfort and decreases the visual acceptance of the system. Another issue with increasing the number of electrodes and decreasing the spatial resolution means that the alignment of the electrodes on the skull is now even more prone to errors and change over time, e.g. due to movement of the user. This makes the need for a professional higher, which is also detrimental with respect to Wolpaw's criteria for a perfect BCI.

Ferree et al. (2001) has found 19-electrode EEG systems to have a highly varying spatial resolution in the 20 to 40 cm^3 range. Systems with 129 electrodes were found to have a spatial resolution of around 6 to 8 cm^3 (Ferree et al., 2001) when also using algorithmic tricks to further improve spatial resolution. However, according to Nunez and Cutillo (1995), around 10^7 parallel pyramidal neurons reside in each cm^3 of the brain cortex. This means the acquired data is still obtained from a incredibly large number of neurons even in the best spatial resolutions.

Whilst hardware improvements in both electrodes and headsets for better placement might improve the spatial resolution further, the spatial resolution improvements possible through hardware have been plateauing. As was the case for the comparison between few and many electrode systems by Ferree et al. (2001), appropriate algorithms have to be used to effectively increase the spatial resolution. Recently, these techniques often rely on using Laplacians (Liu et al., 2020; Srinivasan, 1999; Srinivasan et al., 1996), although other approaches using for example convolutional neural networks (CNNs) have been proposed (Kwon et al., 2019). These techniques also have the added benefit of cleaning the time-varying signal as described by Yao et al. (2019).

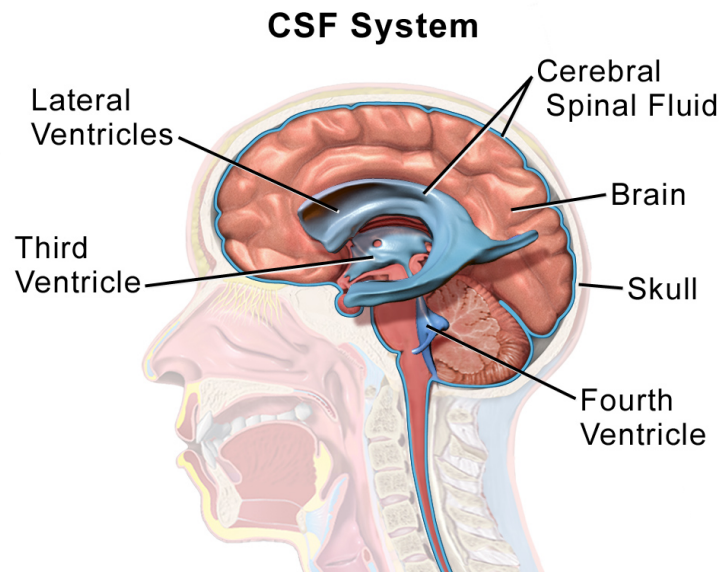


Figure 1.3: The anatomy of the human head, specifically of the cerebrospinal system. Non-invasive EEG measuring equipment is placed on the scalp, causing signals from the brain to be blocked by the skull and cerebrospinal fluid (CSF) among other structures. Free to use Figure by Blausen.com staff (Blaus, 2014).

Invasive BCIs try to combat the issues of EEG

The previous parts discussed how non-invasive EEG measurements have been improved. However, alternatives to EEG exist for measuring brain signals, some of which are further discussed in Section 2.4.1. Most notable in recent years is measuring modalities that rely on capturing brain signals by equipment directly inserted into the human body, making it an invasive approach. One such example of an invasive measuring modality is electrocorticography (ECoG) and the most popular invasive BCI at the moment is the one proposed by Musk and Neuralink (2019). The white paper by Musk and Neuralink (2019) has shown that invasive BCIs could greatly exceed the data quality and visual aesthetics of even the best non-invasive alternatives. As further discussed in 2.4.1, this invasive method places flexible electrodes directly inside the skull. These electrodes are invisible to the human eye with the only visual component being a rechargeable wireless transmitter that is magnetically attached to the skull. Neuralink's final aim is to make the brain-signal measuring equipment completely invisible to the human eye.

Musk and Neuralink (2019) has built robots to insert the electrodes inside the skull in a very precise location without the need for an open-skull operation or even anaesthesia. This allows for a magnitude more electrodes to be installed and is expected to suffer far less from noise resulting in a far greater temporal and spatial resolution compared to EEG. This suggests that invasive systems are superior to non-invasive alternatives, but the fact that they are more permanent, far more expensive and invasive gives rise to technical and ethical questions. These ethical questions are further discussed in Section 1.5. From a technical standpoint, maintaining and upgrading a non-invasive BCIs is far simpler and cheaper. The fact that you are inserting foreign objects into the brain also introduces far more health risks than non-invasive systems do. Convincing the user to put on a headset that can be removed will also be far easier than convincing the user

to get a BCI permanently implemented in their skull.

It has also been shown that the theoretical more precise temporal and spatial resolution doesn't linearly correlate with improved BCI accuracy/control, rather it seems to plateau relatively quickly with current state-of-the-art signal processing and classification techniques (Aflalo et al., 2015; Lebedev, 2014). Some critics point to the dropping curve found by Aflalo et al. (2015) to conclude that the increased electrode amount and reachable neurons achieved by Musk and Neuralink (2019) don't have a direct impact on the usability of BCIs in real-world applications. Because of these aspects, the ease-of-use appeal and far cheaper price for non-invasive alternatives still outweigh the benefits offered by invasive methods for almost all but highly medical applications, at least in the opinion of the writer of this thesis. Nevertheless, future improvements in signal processing and classification techniques could prove invasive methods to be far superior for BCI applications and the mechanical achievements so far are not to be underestimated. An invasive system is also promising concerning Wolpaw's definition of a perfect BCI discussed in Section 1.1. Once installed, it would ideally require no more assistance from a professional, is aesthetically acceptable as it can be invisible to the human eye, has signs of being far more reliable than EEG and more.

Summarizing the improvement of measuring facilities

Since BCIs rely solely on brain signals to operate, the measuring facilities for acquiring data of those brain signals have a direct impact on the capability of those systems. As was discussed in this section, the most commonly used modality for non-invasive data acquisition, EEG, has benefited from both hardware and software improvements. From a hardware point of view, the switch to dry electrodes using active amplification and wireless connection to a computational unit has made BCIs more favourable concerning Wolpaw's criteria for a perfect BCI (Mathewson et al., 2017; Tosi et al., 2017; J. Xu et al., 2017). From a software perspective, clever algorithms have enabled preprocessing of the signal to improve spatial resolution (Kwon et al., 2019; Liu et al., 2020; Srinivasan, 1999; Srinivasan et al., 1996). Improving the spatial resolution can also positively affect the temporal resolution due to inherent noise reduction as discussed by Yao et al. (2019). As is further discussed in Section 3.2.2, other preprocessing techniques have also been introduced and refined further aiding in improving the data quality.

1.2.3 More powerful, affordable and portable equipment

The improvements in brain signal measuring equipment have likely been influential in the gaining popularity of BCIs as it provides more precise data more affordably. However, having the possibility of obtaining clean data is only part of the way to a perfect BCI system. Other improvements concerning computational power, affordability and portability have also played an important role in BCI research, contributing to the rise of popularity in the process.

The emergence of faster and cheaper hardware

As chapter 3 will discuss in greater detail, working with EEG data, or other forms of brain signal data can require computationally very heavy operations to achieve desired processing results of that data. Luckily, together with the improvements in state-of-the-art measuring equipment, there is also an emerging supply of less accurate but far more affordable and portable EEG measuring equipment. Due to Moore's law (Schaller, 1997) and other advancements, central processing units and other computational hardware have also seen massive improvements in computational power. This has made algorithms previously requiring expensive specialized computational hardware possible on the average personal computer. All of these factors have made

BCI applications, which were previously limited to lab environments with a high financial cost, accessible to a far broader public. The availability of open-source datasets for common tasks related to brain signals has also allowed computer scientists to experiment in the field without additional hardware cost (Kaya et al., 2018).

Splitting BCIs into multiple major components for portability and reusability

Early attempts at making BCIs more portable and affordable include those by Lin et al. (2008) and Shyu et al. (2010). In essence, these applications rely on separating the data acquisition process and data processing into two standalone systems connected over Bluetooth (BT). Remember from Section 1.2.2 that BT is an open standard for wireless communication that has seen improvement in the last couple of years. Dividing a BCI system in a data acquisition and data processing system allows for creating a lightweight measuring device to be placed on the user's head, with a heavier and bulkier computational unit to process the signals which ideally is still pocket-able. The latter was not a trivial task and introduced the need for custom hardware at the time. Lin et al. (2008) used a custom-made digital signal processor (DSP) for the task whilst Shyu et al. (2010) opted for a more general field programmable gate arrays (FPGA) based DSP. Whilst these were great demonstrations of how the technology could be used outside the lab, the actual usage for a bci detecting driver's drowsiness (as proposed in the paper by Lin et al., 2008) and allowing multimedia control (as proposed in the paper by Shyu et al., 2010) was rather limited. The idea of custom-made and possibly proprietary processing hardware which focuses on a single task is also very limiting, although it does have commercial benefits.

What did stick, was the idea of splitting the hardware into two standalone parts, a wireless EEG measuring device and a processing unit. As discussed in Section 1.2.2, a wireless connection between these two components is also favoured when taking into account Wolpaw's criteria on a perfect BCI. It also makes it possible for smaller research teams or even individuals with a certain specialisation to take part in the highly interdisciplinary field by not requiring knowledge of all components but just the one that is of interest. As an example, it enables computer scientists to purchase off-the-shelf affordable EEG measuring hardware and communicate with it through provided libraries for their favourite programming language. In most cases, the personal computer they already own is powerful enough for the experiments, especially for offline systems. This allows for reusing existing hardware which is great from a financial perspective. Section 2.4.3 discusses some of the EEG measuring equipment available on the market. It is noted that EEG measuring hardware is not strictly needed for a computer scientist as researchers such as Kaya et al. (2018) have made excellent free-to-use EEG datasets available.

With the introduction of the iPhone in 2007, it didn't take long for researchers to explore the idea of using a mobile phone as a processing unit for a BCIs. Y.-T. Wang et al. (2011) were one of the first to explore this idea, with a steady-state visual evoked potential (SSVEP)-based BCI. Section 2.3.3 will go into further detail on the types of measurable brain-signals. In essence, such a system relies on a category of brain signals that are often easy to detect but require a specific stimulation. This type of system can be used for a wide variety of applications. Imagine an audio-guided tour in a museum where visitors only need to stare at a screen next to an item of interest to start hearing the explanation of that item. This could be achieved with only a couple of dry electrodes placed on the skull in a headset that also provides the audio to the visitor. This headset could then be connected over Bluetooth (BT) to the visitor's phone running an app for the museum tour. The technology needed for such a system would lean close to that of so-called *P300 spellers*, which have already been heavily studied (Capati. et al., 2016; Hussein et al., 2020; Won et al., 2019). Such a system would also fit perfectly with Wolpaw's definition of a perfect BCI, albeit oriented to a commercial setting rather than a medical one.

Making BCIs a one-in-all device again for profitability

Whilst the advantages of using the computational power of devices a customer already owns are clear, it also imposes some disadvantages. For one, the varying type of computational devices is bound to give varying performance results, compatibility issues and overall limits the guarantee of a pleasing user experience (UX). Adding to this, the measuring equipment and processing equipment can't be connected from the factory resulting in an experience that is not plug-and-play. From a commercial perspective, it would be easier if the system was all-inclusive and possibly patentable.

Recent trends in computing hardware where manufacturers are shifting away from general all-purpose CPUs and then developing their own custom CPU architectures have shown that custom chips can outperform their general counterparts. Patenting the architecture of those chips is possible making it commercially interesting. Apple's mac M series processors announced in 2020 are one such recent example. These M series processors have a neural engine that is stated to accelerate the time needed for ML tasks³. Graphics processing units (GPUs) used for autonomous driving systems also differ from general-purpose GPUs.

Because of this, the author of this paper believes custom-made chips could create a future where the headset has a directly integrated processing unit once again. Whilst this would make for a more attractive package for the customer and give commercial advantages to the manufacturer, it would be disadvantageous for research purposes. The manufacturer could limit the possibilities of using the BCI for different purposes, patent promising hardware and more. Another possible route the author of this paper sees is the use of cloud computing and fast 5G connections to also create a more simple user experience that doesn't require Bluetooth (BT) tethering to a close-by processing unit. This approach would still leave a separation between measuring hardware and processing hardware making changes to any of the two independently easier. Concerning Wolpaw's criteria of a perfect BCI, these approaches would also be acceptable. This belief of switching back to all-in-one devices or using a cloud service for processing the data is further endorsed by the findings of Dillen et al. (2022). In their systematic review of biosignal control systems, eight of the 46 studied papers used embedded hardware and one used cloud solutions.

Summarizing the improvements on computational power, affordability and portability

To summarize, due to Moore's law (Schaller, 1997) and other advancements, CPUs among other computational hardware have seen massive improvements in computational power. This increase in computational power has enabled more advanced processing of the data on more affordable and portable hardware. Early attempts at making BCIs more portable and affordable focused on splitting the brain signal measuring equipment from the data processing equipment (Lin et al., 2008; Shyu et al., 2010). The system by Y.-T. Wang et al. (2011) was one of the earliest examples of a true portable BCI-system that was affordable and relied on a smartphone as a processing unit. It showed how working with BCIs can be done using cheap and general-purpose hardware. The research was published at a turning point for BCIs where publication numbers on BCI-related papers started rising. This hints that the increased affordability and portability combined with more computational power played an important factor in the rise of interest in BCI. The rise of BCI-related papers is illustrated in Figure 1.4 based on data by Saha et al. (2021). Dillen et al. (2022) found that papers on biosignal control systems using DL have seen a steady increase over the last five years as well.

³<https://nr.apple.com/dH8i4U3v2w>

In the future, as BCIs see more commercial applications, this separation of a BCI in a measuring component and processing component might reverse to an all-inclusive device. This has potential downsides for scientific research but makes commercial sense. The replacement of physical computational units in close proximity to cloud solutions is another possible evolution.

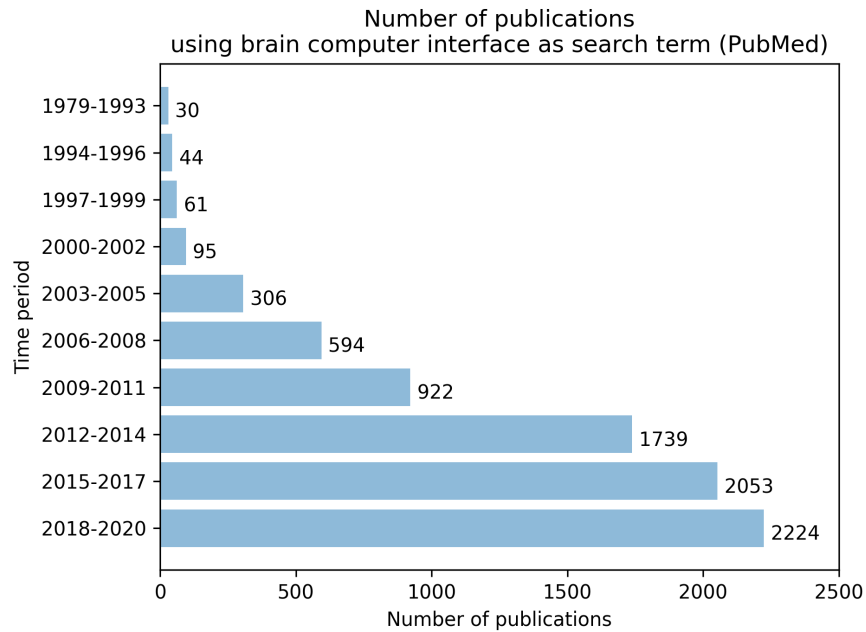


Figure 1.4: Number of BCI-related papers over time. Based on data by Saha et al. (2021) obtained by searching PubMed using the keyword: "brain-computer interface".

1.2.4 Specialized data processing techniques

The previous sections 1.2.2 and 1.2.3 discussed how both measuring and computational hardware have seen recent improvements. Another important part of the puzzle is the algorithms that convert data from the now more user friendly measuring devices to useful actions using the now more powerful, affordable and more portable computational hardware. Most of these algorithms are data-driven classifiers that use ML techniques. In more recent years, deep learning (DL) techniques and alternative approaches have been incorporated in the BCI pipeline as well, which has been proven to be very successful. Chapter 3 discusses commonly used techniques in more detail and multiple ML and DL based BCI pipelines are discussed in later chapters of this thesis. This section gives a more high-level summary of recent developments in the AI field that have likely contributed to the rise in popularity of BCIs.

Postponing another AI winter

Machine learning (ML) and deep learning (DL) are techniques that fall under the AI umbrella. These techniques are being used as buzzwords in a whole suite of applications and it seems as if every week there is yet another big promise or threat related to AI discussed in major news

outlets. Recent examples that have shown the world what new techniques in this field are capable of include the Go champion beating computer algorithm by Silver et al. (2016), the impressive text generation model GPT-3 by Brown et al. (2020) and the image generation model DALL-E by Ramesh et al. (2021). This abundance of new achievements and an overall high public interest in anything that mentions buzzwords from the AI umbrella has caused a long lasting AI summer since the last AI winter of the late 1980s and early 1990s. Such an AI summer means that there is incredible amount of funding available for improving ML and DL techniques among others. This in turn causes further advancements in the field of ML and DL which results in more impressive achievements.

However, an AI summer also implies that an AI winter will inherently return. An AI winter is a period of time where the interest in the field is reduced and thus funding and research is limited. As discussed by Floridi (2020), such an AI winter may be relatively close. This is in part due to new regulations and public backlash on the more questionable but highly profitable applications DL is involved in. A recent example of this is the controversy surround Clearview AI. Here, state-of-the-art DL image recognition algorithms are used on billions of images collected from all over the internet, including social-media platforms, to recognize almost anyone with a public profile linked to them. As further discussed by Rezende (2020), this technology conflicts with many EU laws yet was used by multiple police departments. Adding to this, new regulatory changes are being proposed to limit the use of algorithms which lack explainability and interpretability (European Commission. Joint Research Centre., 2020; The Royal Society, 2019). This challenges many ML and DL approaches currently used as explained further in Section 3.5.3.

Nevertheless, there is still a high amount of resources being put into ML and DL research. Throughout history, these technologies have been linked with the biomedical setting a lot. As explained by Baldi (2018), DL and biomedical data have directly influenced each other's evolution's since the 1980s. Because of this, applications that process biomedical data have been an important factor at prolonging the current AI summer. Since BCIs use biomedical data as well, they have been one of the applications keeping interest in ML and DL research high. This is in part due to the science-fiction properties BCI systems have creating a lot of public interest as already discussed when talking about Elon Musk's Neuralink in Section 1.2.1. Thus, BCI systems, which rely heavily on ML and DL, are one of the research areas in these technologies that are so promising they help prolonging the current summer of AI.

Improved and new ML and DL concepts have enabled more capable BCI systems

Most of the main concepts from both machine learning (ML) and deep learning (DL) are already multiple decades old. As DL is a subset of the ML techniques, pipelines for using these techniques are very similar. To illustrate this, a general pipeline of a computer-aided diagnosis (CADx) system used for classification is given in Figure 1.5 and commonly used techniques are discussed below. It is noted that besides classification tasks, some regression problems for CADx systems exist as well. However, such regression problems are far less common in BCI systems relying on EEG with the systematic review article of Dillen et al. (2022) only finding articles on classification problems for such systems. Because of this, this thesis focuses on classification problems. CADx systems are used extensively in hospitals for the interpretation of biomedical images and have been studied ever since computers were invented. The most common example of a CADx system is the classification of lung images as being either from a lung cancer patient or not, often also highlighting the nodules used for this classification. These pipelines are very similar to the ones used for BCIs, which is further discussed in Section 3.2.

Traditional ML is a commonly used name for the collection of ML techniques that are not DL. Such traditional ML rely on a *two-step* process where there is both a feature extraction step

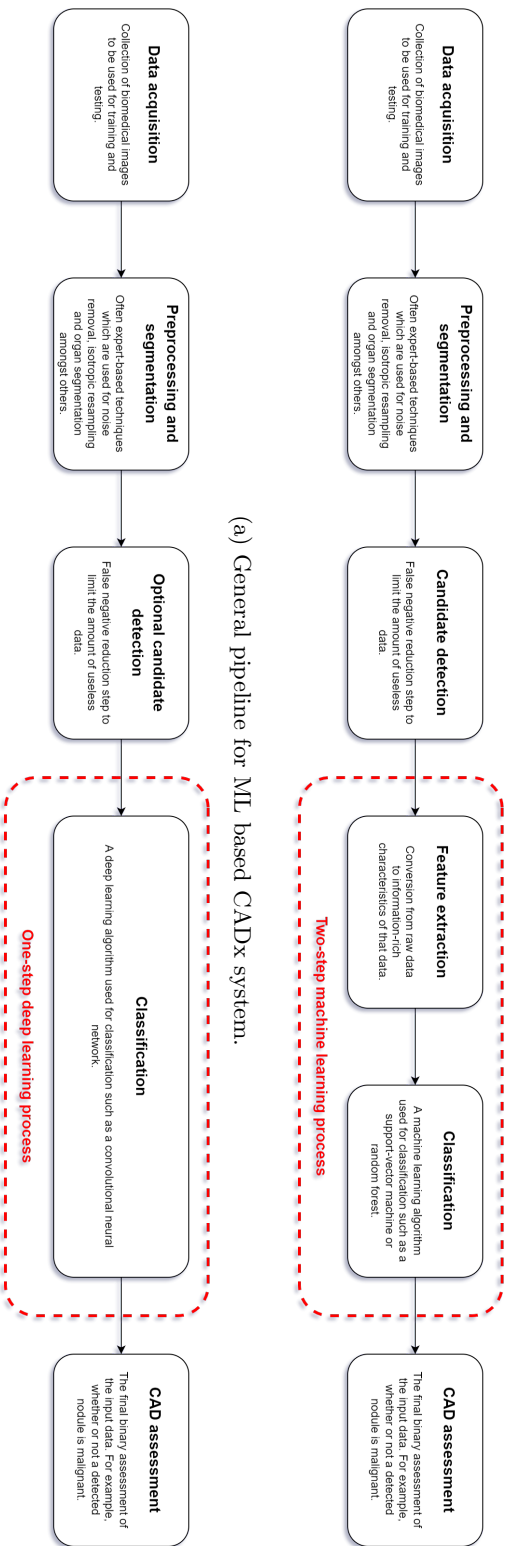


Figure 1.5: General pipelines of a CADx system used for classification. A ML approach is called a two-step approach as it exists from feature extraction and classification. A DL approach is called a one-step approach as it combines both of these steps into a singular classification algorithm.

and a regular classification step as is visualised in Figure 1.5a. Feature extraction is the process of representing the often highly dimensional and unstructured raw data using characteristic properties. These representations are often derived from expert knowledge and are chosen by the designer of the system rather than learned from data. With respect to a CADx system for classifying if a patient has lung cancer, these features might be the size of nodules in the lung, a metric of how round these nodules are, the Hounsfield unit (HU) of certain parts of the lungs and more. These features are then used for learning by a traditional ML classifier. The true challenge in these two-step traditional ML systems lies in finding appropriate features, which can be a very time-consuming task that requires a lot of domain knowledge. It isn't uncommon for features in CADx systems to be refined in the span of multiple years (van Ginneken, 2017). Section 3.2.4 discusses the feature engineering step in more detail and Section 3.4.3 discusses traditional ML in more detail.

Alternatively, a *one-step* approach in CADx systems denotes the use of DL in the pipeline, such as shown in Figure 1.5b. DL generally differentiates itself from the previously discussed two-step traditional ML approach by working directly on the preprocessed data rather than a feature representation of the data. However, this isn't necessarily the case as feature extraction can still be beneficial for some DL methods whilst others might even work better on the raw, non-preprocessed, data. Section 3.4.1 discusses the difference between traditional ML and DL in more detail. Intuitively, DL models exist of multiple layers which can be seen as a graph-like structure which becomes deeper as the number of layers increases, hence the name deep learning (DL). Typically, multiple types of layers are present in a DL approach, with the earlier layers focusing on what could be seen as gradual feature extraction steps whilst the later layers are often more tailored towards the classification of those data-driven feature outputs from the previous layers. Section 3.4.4 discusses DL and the common variations in more detail. A DL approach is interesting as it can allow for skipping the feature extraction process where good features have to be found by the developer of the system. Finding such good features can not only be time-consuming but limited expert knowledge can also make creating features that carry enough differentiating information impossible, meaning that even the best classifiers can't learn from them. Adding to this, DL approaches in CADx systems have also been proven to outperform state-of-the-art ML approaches (van Ginneken, 2017). However, DL models are more challenging in terms of explainability and interpretability as further discussed in Section 3.5.3. The challenge in DL approaches is finding a suitable model and training it in a way such that it doesn't overfit, a phenomenon further discussed in section 3.5.4. In a way, DL allows a person with limited domain knowledge of the data to obtain a better result as it bypasses the need for manual feature extraction. However, this is a double-edged sword as limited knowledge of the data increases the risk of bias, overfitting and other potential issues.

Relating this to BCIs, which have a very similar pipeline, and how the ML and DL techniques used often originate from older concepts, some of the most common BCI pipeline components are considered. A typical traditional ML BCI pipeline often relies on a form of the common spatial pattern (CSP) technique for feature extraction. This technique is quite old being introduced by Koles et al. (1990) around 30 years ago. Likewise, the traditional ML classification used is often a type of support vector machines (SVM). Once again, this technique was first introduced by Boser et al. (1992) around 30 years ago. Over the years, CSP has evolved and many extensions such as filter bank common spatial pattern (FBCSP) by Kai Keng Ang et al. (2008) have been introduced. Likewise, SVM has seen many extensions and improvements (Chervonenkis, 2013; V. Utkin, 2019). This has resulted in the combination of these two relatively old techniques, but with recent extensions, still performing among the state-of-the-art in BCI applications using traditional ML approaches (Rasheed, 2021; Tangermann et al., 2012). Likewise, when using a DL approach in the BCIs pipeline, CNNs are most commonly used (Dillen et al., 2022; Rasheed,

2021). This technique is again a rather old one, the foundations of which were first described by Fukushima (1980) over 40 years ago. Just as the CSP procedure, CNNs have seen multiple extensions and improvements over the years, just as other DL approaches. Most recent and noteworthy developments are works such as that by Schirrmester et al. (2017) which focuses on proposing CNN architectures that can learn from very few samples and for which a described method exists to visualize the model’s early layers. Other improvements, more general to DL, have also been made such as the development of new activation functions. D. Lee (2020) discuss how changing the activation function from CReLU to ReLU6 offered a 35% performance increase while keeping other components fixed for certain experiments relying on a neural network (NN) in a reinforcement learning (RL) setting. Thus, these improved versions of older concepts have enabled far better performance making it possible to create more capable BCI systems.

This doesn’t mean that all approaches used for processing the data in BCIs rely on decades-old techniques that have improved over the years. One interesting and relatively new approach is the use of transfer learning (TL) from drastically different domains. Previously, TL was mostly used in BCIs to train a model on data which may originate from different users performing similar but not necessarily identical tasks. This general model is then further refined on a specific patient and task, transferring the knowledge acquired from the previous data to the new data. When done correctly, this can provide far better performance compared to learning on the new data alone for problems where data is limited (Dillen et al., 2022). As available data specific to BCIs applications remains limited, some recent research has gone into transferring knowledge from completely different domains to BCI specific data. G. Xu et al. (2019) used a model pretrained on images and transferred it to EEG data for a motor imagery (MI) task with promising results. Other attempts at transferring knowledge from other domains, such as natural language, have also been made (De Wulf, 2022).

More open-source datasets and BCI related libraries

Whilst more affordable and portable measuring hardware has enabled a low-cost solution for researchers to acquire their own data, as discussed in Section 1.2.3, the process of acquiring BCI related data remains significantly time-consuming and can impose multiple challenges. As addressed by Dillen et al. (2022) many publications don’t properly report the data acquisition process, leaving a lot of ambiguity in both the meaning of data labels and how representative of the real-world the data is. Whilst two papers might discuss a MI task as being *imagined left-hand movement*, one might have collected the data in a lab-like environment from a trained user envisioning a single squeezing shut movement of the hand whilst another might have it correspond with any envisioned movement of the fingers on an untrained and non-focused user. On a legal aspect, as data on brain signals is biomedical data, heavy regulations are in place on how this data can be shared and used, next to the general data protection regulation (GDPR) (Malin et al., 2013; Vlahou et al., 2021).

Considering that many researchers in the field often focus on one specific component of the BCI pipeline, it is not feasible for them to go through the trouble of collecting data themselves. Adding to this, when a researcher wants to reuse a certain component of the BCI pipeline from another author’s work, the source code of their project is often not present, not well documented, or not compatible with their programming environment (Dillen et al., 2022).

Luckily, BCI specific data and coding libraries have been made available in recent years. Some of the earliest BCI related datasets that are still commonly used to this day are from the BCI competitions organised by the Berlin Brain-Computer Interface research program (BBCI)⁴. Of the four different competitions, two were in part organized by Jonathan R. Wolpaw, from who

⁴<https://www.bbc.de/competition/>

this thesis took the definition of a BCI and a perfect BCI, further demonstrating his importance in the field (Blankertz et al., 2004; Blankertz et al., 2006). The fourth and final competition provides three EEG datasets labelled with MI tasks, making it a popular choice in literature. More recent datasets include those by Kaya et al. (2018), who have put a tremendous focus on discussing all necessary details of the data acquisition process, including testing the MI skills of each subject and providing the software and instructions given to the subjects. Not only do these publicly available datasets allow researchers to skip the data acquisition step, but it also improves the reproducibility of their work and makes comparing it to other work using the same dataset easier. However, there is still far from an abundance of data that can be used for training BCI pipelines compared to other fields of research. Indeed, collecting datasets of books for natural language processing (NLP) learning applications or cat images for computer vision applications is a far easier task than collecting EEG datasets for identical MI tasks with equal data acquisitions methods.

From a code perspective, many authors still fail to deliver a copy of their source code along with their article (Dillen et al., 2022). Some websites, such as Papers With Code⁵ has been created to more easily find papers that do provide their code, but for BCI research this is still limited. Luckily, advanced libraries have been emerging which provide a multitude of common operations from the BCI pipeline. Perhaps the most famous of which is the Python MNE library by Gramfort (2013) which provides tools for organizing, visualizing and processing EEG data such as windowing the EEG data, performing baseline correction and determining the CSP features. Other famous Python libraries include Braindecode by Schirrneister et al. (2017) and EEG-DL by Hou, Jia, et al. (2020, 2022), Hou, Zhou, et al. (2020), Jia et al. (2020) among others. Whilst Python is the most commonly used programming language for implementing BCI pipelines and has by far the most supporting libraries, libraries for MatLab (e.g. EEGLab by Delorme and Makeig, 2004), C++ (e.g. Brainaccess by Neurotechnology⁶) and other popular programming languages are starting to emerge as well. Besides these general libraries, some of the most famous articles whose source code isn't provided have also seen open-source implementation based on the original author's description. Most noteworthy is the Army Research Laboratory (ARL) EEGModels Project which provides implementations of the EEGNet model proposed by Lawhern et al. (2016) and the ShallowConvNet and DeepConvNet models proposed by Schirrneister et al. (2017) written in Keras and Tensorflow (Python DL libraries by Chollet et al., 2015; Martín Abadi et al., 2015).

Summarizing the emergence of specialized data processing techniques

Besides improvements on a hardware level, both for the measuring equipment and the processing equipment, significant software improvements have also been made. Most importantly are the improvements made to two-step traditional ML approaches and single-step DL approaches. This includes improvements of the CSP feature extraction algorithm such as FBCSP by Kai Keng Ang et al. (2008), improvements to the SVM classifier (Chervonenkis, 2013; V. Utkin, 2019) and general DL improvements (Dillen et al., 2022; D. Lee, 2020; G. Xu et al., 2019). The introduction of more open-source datasets and libraries also aids in far faster development of new BCI pipelines and allows researchers to focus on a specific component of the BCI pipeline to improve. The fact that BCIs still provide a science fiction feeling to the general public has also made it one of the technologies that aid in postponing another AI winter.

Relating this to Wolpaw's definition of a perfect BCI, it becomes apparent that these software improvements play an important role in achieving the goal of a perfect BCI. Better pipelines

⁵<https://paperswithcode.com/>

⁶<https://www.neurotechnology.com/brainaccess-documentation/C++Api>

should allow a BCI system to function more reliably and in more challenging environments. Improved techniques could also improve the number of classifications a system can handle in a certain period. This can enable the BCI system to match or even surpass the conventional interaction method it wishes to replace. Whilst these are very important aspects of a perfect BCI, it should be remembered the user of a BCI will most likely not appreciate this evolution to the same degree a computer scientist will. At the end of the day, an ideal processing pipeline should be one the user never notices is there, whilst a wrong classification that results in the wrong command being executed or other issues with the pipeline will result in unpleasant experiences the user will remember.

1.2.5 Summarizing the cycle of increasing popularity

When looking at the number of papers published on PubMed with the keyword *brain-computer interface* visualised in Figure 1.4, a clear upwards trend is visible over the years. This upward trend seems to have started in the 2000s and the jump was most significant around 2012. Whilst proving which elements are responsible for this upward trend in both scientific and commercial interest isn't directly possible, this section has highlighted multiple potential reasons. It is unlikely any one of these potential reasons is the sole reason for the increased popularity of BCI systems. Rather, all of the discussed reasons likely influence each other as portrayed in Figure 1.6.

The potential reasons that were discussed can be separated into four major categories. First, an increased interest by big-tech companies causes big funds to get into the field. Secondly, improvements in measuring equipment allow for higher quality data and a more pleasant user experience (UX). Third, processing equipment has seen increased affordability whilst also improving the computational power and portability allowing systems to be more affordable and capable. Finally, more optimised software allows for better classification results and faster development of new systems. It is highly unlikely all of these reasons have equal influence or that they are the only reasons for the improved popularity, but they should give the reader a better understanding of the context BCIs are currently in without becoming too technical. The next section focuses on effective use cases for BCIs to let the reader understand the different capabilities of these systems even more.

1.3 Common use cases for BCIs

The previous section aimed to address potential reasons for the increase in popularity in BCI research. This already discussed multiple BCI applications, showing some of the use-cases for BCIs. When looking at Wolpaw's definition of a BCI, a BCI is nearly limitless in what it can be used for. Whilst it should be a *communication device*, this terminology can be seen rather broadly. Most obvious is perhaps the use of a BCI as a control system, which then communicates with an external device so that it can be controlled. Already discussed examples of this type include the multimedia control system proposed by Shyu et al. (2010) from Section 1.2.3. However, when using BCIs to detect common patterns of a disease, these patterns could also be communicated to a doctor and hence it could also be considered a communication device. It should also be noted that the given definition of both a BCI and perfect BCI from section 1.1 are around 20 and 10 years old respectively. During the time that has passed since then, many new use cases for BCIs have emerged, especially in a commercial setting. Thus, these definitions are by no mean the only definition for what a BCI system is and it is not uncommon to find varying opinions on what can be called a BCI system and what can't be called one. This section aims to familiarize the reader with a broad idea of possible use cases of BCIs and to give some concrete examples

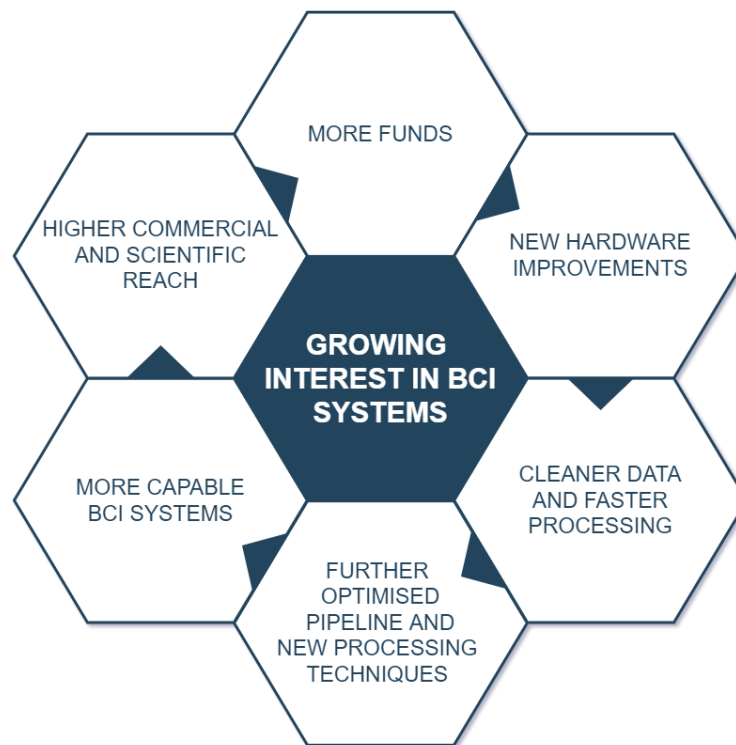


Figure 1.6: Summary of some of the potential reasons BCI research has seen its gain in popularity discussed in section 1.2. There is no clear chronological order for these events and they likely influence each other all at the same time.

whilst also addressing some of the shortcomings found in the articles describing them. As this thesis focuses on non-invasive EEG based BCIs, this section will also focus on non-invasive EEG related articles.

For the interested reader, Dillen et al. (2022) provides more examples of biosignal control systems, of which BCIs are a subset, that use DL. The focus of Dillen et al. (2022) is on articles that provide at least a completely working proof of concept (POC), from live data acquisition to external device control. Rasheed (2021) reviews several BCI specific papers and focuses on the type of ML task that is performed and which ML and DL techniques are used for this. Only a few articles discussed by Rasheed (2021) have a working proof of concept (POC) on live data with many simply looking at the evaluation metrics of the ML and DL strategies. Whilst the articles discussed by Dillen et al. (2022) are thus more representative of real-world performance and use-cases, finding such complete works is rather challenging. Because this section is only meant to demonstrate potential use cases of BCIs and common shortcomings in the papers discussing them, there is no enforcement of requiring the discussed papers to have a fully working POC. This allows for offline systems and articles focusing on only certain components of the BCI pipeline to be discussed as well. It also allows for discussing systems which may not strictly be BCIs but which do use almost identical pipelines, further demonstrating what is possible when working with brain signals as data. In this regard, it is similar to the work of Abdulkader et al. (2015)

who give an overview of the most common use cases for BCIs and the challenges they are faced with.

1.3.1 Using BCIs as an automated tool in all stages of medical phenomena

As EEG is relatively affordable and portable, it is an often used modality in the hospital. The visualisation of the measurements can be read by a specialist to diagnose a whole suite of diseases. Especially seizure-related disorders such as epilepsy are often diagnosed through EEG readouts (Rosenow et al., 2015). Other neurological disorders such as the locked-in syndrome (LIS) can also be correctly identified by EEG readouts (Markand, 1976). Even the psychological field uses EEG as a physiological measuring tool to aid in the diagnosis and psychological treatment of patients, although psychiatrists should be aware of the limitations EEG has for them as further discussed by Badrakalimuthu et al. (2011). Since EEG is used for a wide variety of diagnoses and by far the most common source of data for non-invasive BCI (as discussed by Dillen et al., 2022), much research has gone into how BCIs can be used as an automated aid for medical diseases throughout all stages of a medical phenomena. In general, three important distinctions are made for the stage of such phenomena and thus for the medical application of the BCI: prevention, diagnosis/monitoring and rehabilitation/restoration.

Using BCIs for the prevention of medical phenomena

One popular example of prevention relates to the use of BCI systems for continuously monitoring signs of decreased attention (Abdulkader et al., 2015). Such a decrease in attention might show an exaggerated usage of alcohol and other drugs, which allows the user to be alerted before drinking *just one more*. Whilst it is unlikely that alcohol addicts will wear a BCI to the pub, such devices can significantly help in the reduction of traffic accidents by becoming mandatory during driving. According to World Health Organization (2018), traffic accidents were the number 1 cause of death for children and young adults. Whilst many types of equipment are already in place to prevent traffic accidents from occurring, such as speed cameras and lane assist technology, it has been studied how BCIs can be used as a prevention measure as well.

Section 1.2.3 discussed research by Lin et al. (2008) as one of the first attempts to make a fully portable BCI. As it measured drivers' drowsiness levels, the proposed system alerts or even enforces drivers to take a break from driving when drowsiness levels are too high. Research such as that by Fan et al. (2012) has discovered that emergency situations in vehicles can be classified faster from EEG data than the user's response, which could have a significant impact on reducing the number of traffic accidents. Fan et al. (2012) used a driving simulator to conduct a real-world experiment and they found that their proposed system has an accuracy of around 70%. One potential issue with this paper is the fact that their focus lies on this overall accuracy metric rather than providing the *sensitivity* and *specificity*. Sensitivity could be seen as the accuracy of the model on positive cases (i.e. identifying a dangerous scenario as dangerous) whilst specificity denotes the accuracy on negative cases (i.e. identifying a non-dangerous scenario as non-dangerous). However, Fan et al. (2012) do provide the receiver operating characteristic curve (ROC curve) and provide reasoning for choosing an optimal classification threshold that resulted in this 70% accuracy. This threshold specifies how certain the classification prediction should be before acting on its classification. This shows that it is important to look at more than just accuracy, as for this application being good at taking action in case a dangerous scenario is present is ideal, but taking action when there is no dangerous scenario could create a dangerous scenario itself. Section 3.2.7 discusses how to evaluate systems using different metrics and reasoning in

more detail. Many other examples of using BCIs for the detection of symptoms that can lead to traffic accidents exist. Chin-Teng Lin et al. (2013) developed a system that could estimate motion sickness levels, which in turn could again be used to alert drivers to take a break.

The three discussed examples show how BCIs can be used in a variety of ways for the prevention of traffic accidents. It also highlighted the importance of correct model evaluation and how a net benefit of a system is important. For example, if the system proposed by Fan et al. (2012) would use the emergency brake each time it detects a dangerous scenario but has a poor specificity, it would heavily break in circumstances where it is not needed. This in turn creates risk if nearby drivers don't pay attention and cause a collision due to the abrupt emergency braking. Thus, the question should be asked if a net benefit would be reached by those systems if the amount of prevented accidents outweighs the added risk of new accidents. Likewise, it has to be considered if a BCI system is the most viable option, even if it has promising results. Using a BCI to monitor if a driver is drunk and prohibiting him from driving if so might be more expensive and less efficient than breath alcohol ignition interlock device (BAIID) which already exist. Nonetheless, many applications exist for the prevention of traffic accidents and the prevention of other medical phenomena using BCIs, even if it is used as supplemental validation over existing devices and tests. Abdulkader et al. (2015) provides some extra examples of this type.

Using BCIs for the diagnosis and monitoring of medical phenomena

Section 1.2.4 already introduced the computer-aided diagnosis (CADx) pipeline. CADx systems, and the very similar computer-aided detection (CAdE) systems, using medical imagery are widely used for diagnosis and treatment monitoring in oncology and other fields. Comparable systems exist using EEG and other brain-signal measuring modalities for diagnosis medical phenomena and monitoring of the treatment. The commercial Muse headset for sleep tracking that was discussed in Section 1.2.1 is one example of a system that can be used for monitoring and diagnosing sleep patterns.

Whilst the Muse headset is a commercial product, medical BCIs exist which are made for detecting sleep patterns. One very popular example is using EEG for detecting sleep apnea, a medical sleep disorder. Taran and Bajaj (2020) proposed an EEG based BCI system for automating the detection of sleep apnea. Taran and Bajaj (2020) named their used ML approach *Artificial Bee Colony Optimize Hermite Basis Functions*. This paper is an example of a system that is highly specialized for a specific problem, namely detecting sleep apnea, requiring a lot of expert knowledge since it relies on a complex feature engineering step tailored towards detecting sleep apnea. Whilst this makes it unlikely the same pipeline can be used for the detection of other disorders, it does provide outstanding performance with a discussed sensitivity, specificity and accuracy of over 99%. The article by Taran and Bajaj (2020) focuses on the ML aspect of the proposed system, by re-using an existing dataset and describing only metrics related to the classification performance. Since this system doesn't take specific control over an external device, it isn't a control system. However, it could be argued it still communicates the detection of sleep apnea patterns and it can be deployed in a live system to alert a nurse when these patterns occur during a trial so that the nurse can pay additional attention during that period. In this regard, naming the system proposed by Taran and Bajaj (2020) a BCI is controversial, as is the case for most EEG based systems that diagnose and monitor medical phenomena. Whilst Taran and Bajaj (2020) don't mention the term brain-computer interface (BCI) in their article anywhere, in an article of a similar system, Poorvitha et al. (2020) do call their EEG based detection of sleep apnea a BCI.

Many other types of diagnosis and monitoring can be done by non-invasive EEG based BCIs.

The review article by Abdulkader et al. (2015) addresses the detection of brain tumours (Selvam & Shenbagadevi, 2011; Silipo et al., 2013) and breast cancer (Poulos et al., 2012). The review article by (Fadzal et al., 2011) discusses the use of BCIs for the detection of dyslexia. It should become apparent that many detection systems for medical phenomena can be made from non-invasive EEG data. Even if these medical phenomena seem unrelated to the brain, such as for the detection of breast cancer (Poulos et al., 2012). However, as these systems lack a true communication factor besides informing doctors or nurses, it can be argued if these systems are indeed BCIs w.r.t. Wolpaw's definition of a BCI given in Section 1.1.

Using BCIs for the rehabilitation and restoration after medical phenomena

Restoration of lost mobility and rehabilitation is the third and final stage of most medical phenomena. In this stage, a BCI can be of aid to both the medical staff and patient. Out of the three discussed stages it is also the one that has seen the most BCI related research. One reason for this is that many techniques for the restoration of lost mobility and rehabilitation rely on EMG, a modality used for measuring muscle-based biomedical signals (biosignals). Famous examples of such EMG based systems include prostheses which are connected to the remaining muscles of an amputated body part or an exoskeleton which is placed over body parts to strengthen their movement or re-enable them. Whilst in general EMG based systems far outperform EEG based systems for prosthesis and exoskeletons, the EMG modality does not apply to patients suffering from an impaired neuromuscular system. Thus, for these patients an EEG based solution may offer them a possibility of regaining mobility again. Since EEG based BCIs for prosthesis and exoskeleton control are very common research in the BCI field, it will be discussed further in its own section, Section 1.3.2.

BCIs have found their usage in other aspects of the rehabilitation and mobility restoration process as well. In neurological rehabilitation, BCIs can function as a tool for guiding both patients and medical staff in what abnormalities are present in the brain and how they can be circumvented. Intuitively, these BCI systems aim to improve the brain's ability to adapt itself based on experience. This self-adapting property of the brain is known as brain plasticity or neuroplasticity. A well-developed BCI system could show patients and medical staff which regions of the brain are currently being used and which types of brain signals and abnormalities are being detected. This information could then be relayed to the patient through various means so that it induces neuroplasticity. Such systems are still in development and require sophisticated neurological expertise that falls outside the scope of this master thesis. However, they are very promising and the interested reader is referred to the overview provided by Daly and Wolpaw (2008). It is noted once more this paper was co-authored by Professor Jonathan R. Wolpaw, which has been discussed in this paper multiple time for his definition of a BCI and a perfect BCI.

Another area that is often researched in the rehabilitation and restoration process, is using motor imagery (MI) tasks to improve recovery of control over certain body parts. The main idea behind such systems is to let the patient perform a MI task, which doesn't require effective movement of the body part with reduced control. This MI task can then be classified by the BCI system based on the EEG data and an exoskeleton is used to perform that motion as passive feedback. Most commonly, a pedalling MI task is used to control a motorized pedal, which evokes event-related desynchronization (ERD) patterns resulting in a greater potential for lower-limb recovery. The works by Cardoso et al. (2021) and Cardoso et al. (2022) discuss such systems in greater detail. Likewise, stroke rehabilitation and a reduction of the effects from the Parkinson's disease can be achieved with BCI guidance as well, as further discussed by Adama and Bogdan (2021).

It is noted that many more BCI applications exist for preventing, monitoring and controlling diseases than those discussed here. The work by Shih et al. (2012) highlights some use-cases of BCI in medicine for example.

1.3.2 Using BCIs for prosthesis and exoskeleton control

Arguments were given why the medical applications of EEG processing systems discussed in Section 1.3.1 can or can't be considered BCI systems. The main discussion revolves around the kind of communication that the system does. To some authors, a system that alerts or visually informs medical staff based on processed data from EEG can be considered a BCI system whilst others specifically expect an external device to perform a specific action based on the brain signals to name a system a BCI system. The latter would be a type of control system, as the BCI controls an external device. In a review article by Dillen et al. (2022), it is found that among EEG based BCI control systems using DL, the control of robotic arms is most popular in research. This section will discuss the use of BCIs as a control system for prostheses and exoskeletons.

Why BCIs are used for prosthesis and exoskeleton control

Most of the current robotic prostheses and exoskeletons rely on muscular activity in the body. Just like brain activity can be measured by non-invasive electroencephalography (EEG), muscular activity can be measured by non-invasive electromyography (EMG). For example, patients who have had a partial loss of a body part often still have muscular activity in the remaining body part. In the case of surgical amputation, the amputation is often done such that as much muscle remains to ensure as much possible muscular activity also remains. These patients can then often still generate the muscular activity that would have been required for moving the missing body part. This muscular activity can then easily be measured with the EMG modality, which is in general of higher signal quality than EEG (Bakshi et al., 2018). This EMG data can then be processed to classify the wanted movements and control robotic prostheses. Sudarsan and Sekaran (2012) discuss the design and development of such a system based on EMG in greater detail. Since the overall pipeline of such EMG based systems is quite comparable to the pipeline of EEG based BCIs, many of the processing techniques are similar to those discussed in this thesis. Alternatively, when the body part is still fully intact but the control over that part is lost or requires extra support, an exoskeleton may be used similarly. Just like robotic prostheses, most exoskeletons rely on EMG. A thesis by the German Fleischer (2007) highlights the fundamentals of EMG based exoskeletons.

As was already touched upon in the rehabilitation and restoration part of Section 1.3.1, EMG measurements are not applicable for all patients. In particular, people who have neurological diseases, limiting the production of the required muscular-based biosignals, fall outside the scope for these solutions. However, the viability of robotic prostheses and exoskeletons for these patients has been steadily on the rise as EEG based BCIs have been proposed for this purpose. AL-Quraishi et al. (2018) give an in-depth systematic review of upper and lower limb exoskeletons and robotic prostheses controlled by EEG-based BCI. Just as was the case for rehabilitation and restoration discussed in Section 1.3.1, these systems often make use of brain signals measurable after imagined movement. This process of thinking of movement but not doing the movement is known as motor imagery (MI) and further discussed in Section 2.3.3.

The risk of using BCIs for prosthesis and exoskeleton control

Whilst it is clear to see why EEG based BCIs are promising for prosthesis and exoskeleton control from the discussion above, it should be noted that there is also a great risk in doing so. AL-Quraishi et al. (2018) address the high risk associated with failed instructions for robotic prostheses and exoskeletons. This means that the risks that can follow from misinterpreted instructions of exoskeletons and robotic prostheses are of such a degree that even high accuracy systems might not be good enough to guarantee a net benefit for the user. This could be the reason that the review article by Dillen et al. (2022) didn't find any proof of concept (POC) applications for exoskeleton or prosthesis control using EEG based BCIs. However, Dillen et al. (2022) did find many papers controlling an external robotic arm which is not connected to the body and thus not seen as a prosthesis.

AL-Quraishi et al. (2018) also highlight that whilst multi-label classification of EEG is possible with considerable accuracy in an offline lab setting, the number of detectable classes is limited in a real-time and real-life environment. Because of this, EEG-based systems in these applications still have some challenges to overcome to match the precision and reliability of EMG counterparts. Whilst improvements regarding these aspects have been made since the work of AL-Quraishi et al. (2018) was published, the main challenges remain to this day, especially when using affordable systems. Because of this, widespread adoption of EEG-based exoskeletons and robotic prostheses is still very limited.

Promising steps towards BCI controlled prosthesis and exoskeleton control

Whilst the discussed risk has caused widespread adoption of EEG-based exoskeletons and robotic prostheses to still be very limited, promising steps are being made to bring them to market. These systems mainly focus on robotic arms, which are not strictly a prosthesis but they pave the road to BCI controlled arm prosthesis in the future. These proposed systems often rely on incorporating supplementary information such that risky movements are cancelled, even if the BCI requests them. B. Xu et al. (2022) proposed such a system to control a robotic arm not only through a EEG based BCI working with MI tasks but also by using obstacle avoidance algorithms to reduce the risk of harmful contact, computer vision for object detection to get a better idea on the possibly wanted interaction and eye-tracking to gather extra information surrounding the user's intention. Other successful research on making more reliable BCI systems for controlling robotic arms is done by Kuhner et al. (2019), Sahaya et al. (2020), Shim et al. (2019), and Tayeb et al. (2019), these articles are also included in the review article on DL based biosignal control systems by Dillen et al. (2022).

Whilst limb prostheses, currently being pilot run through robotic arm research, are one of the most common and researched types of prostheses, they are only a fraction of all prostheses in existence. Everything from dentures to artificial breasts can also be labelled as a type of prostheses. For example, visual prostheses such as bionic eyes are another type of prostheses that has active research in the BCI field. Not only can BCI systems improve visual prostheses, many of the existing visual prostheses could be seen as a special type of BCI system as a whole. Both the works by Ptito et al. (2021) and Niketeghad and Pouratian (2019) give an overview on the progress in visual prostheses in the BCI field. These BCIs are often invasive and opposed to only reading brain activity, they can also stimulate the brain and other parts of the body. Through this stimulation or by other means, the user can regain some form of vision from these BCI systems. Second Sight is one of few companies that has commercially made visual prostheses with approval from the Food and Drug Administration (FDA). Their system is discussed in the overview on BCI-related vision restoration systems by Niketeghad and Pouratian (2019). The international trial by Humayun et al. (2012) on the products of Second Sight shows promising

results, although it is noted the study is performed by Second Sight employees and not by an independent research team. The exact working of visual prostheses or, more specifically, Second Sight products is not of interest for this work, but the recent decisions of Second Sight company reveal one of the largest risks of invasive BCIs and BCIs in general. Due to the discontinuation of some of the Second Sight products, hundreds of users are left without product support for a system that shaped their everyday life. Besides this, the now non-functioning product is still present inside their body. The issues and ethical questions this brings to the table are discussed further in Section 1.5.2.

In summary, hybrid systems like the one by B. Xu et al. (2022) are very promising as they can greatly reduce the risk involved in many BCI systems, such as prostheses-related applications, whilst also increasing the overall accuracy of the system. Section 1.3.3 discusses more of these hybrid systems but where BCIs are used as supplementary component to an existing system.

1.3.3 Using BCIs to improve the working of existing systems

The previous sections discussed the use of BCIs as a control system for prostheses and exoskeletons. Whilst this approach was promising for certain patients, the high risk associated with such systems meant that developing reliable systems relying solely on EEG based BCIs was not yet possible (AL-Quraishi et al., 2018). One area that did see success was the use of *hybrid BCIs* as a control system for robotic arms. Such hybrid systems combines BCI techniques with other techniques to create an overall system that is more accurate, safe and reliable and thus complies more with Wolpaw's definition of a perfect BCI.

The discussed hybrid systems from Section 1.3.2 considered the BCI as the main component with the other techniques, such as computer vision, added as support and improvement to it. There are also multiple examples of where a BCI system is added as an *extra component* to an existing system and thus not considered the main component. This allows for BCIs to find use cases in non-trivial domains. To demonstrate this, an extension to classical hearing aids using an EEG based non-invasive BCI is discussed in this section. This section also addresses the use of BCIs to make *smart homes* more accessible for people with a handicap and the elderly. It also addresses some other examples of hybrid BCIs.

Extending hearing aid systems with BCIs

According to Seol et al. (2020) over 450 million people suffer from disabling hearing loss. Most solutions to hearing loss rely on a microphone to capture environment audio which is then amplified and played through a speaker that is placed in or near the ear. Most commonly, the microphones used for amplification are integrated inside the speakers that are placed in the ear to form a stereo setup that mimics regular hearing. This is not always ideal when there is a lot of ambient noise. Sometimes using an external directional microphone placed closer to the audio source of interest can form a solution. For example, placing a microphone on the desk of a professor teaching in a noisy room of students. However, this solution is not applicable in all situations. Thus, most hearing aids include some noise suppression on the microphones directly to filter out ambient noise and amplify noise coming from human speech. Wong et al. (2018) evaluated such noise suppression for Mandarin-speaking users and found the results to be good but not ideal, as there is a lot of variation in human speech tone making it hard to detect what is and what isn't ambient noise.

Even when such a noise suppressing filter would work optimally, people with hearing aids often still have trouble understanding people when multiple speakers are close-by at once. Recent research by da Silva Souto et al. (2016) has shown that using a non-invasive EEG based BCI

can improve traditional hearing aids in solving this problem. Da Silva Souto et al. (2016) does this by determining which speaker a user is listening to by analysing directional queues from the measured brain-signals. If this information would be communicated to the hearing aids, it can allow them to optimize the microphones to pick up speech from that area only, filtering out other speakers. Whilst great in theory, da Silva Souto et al. (2016) discuss how a long waiting time to determine the area of interest challenges the practical usability of their system as of now. Nonetheless, it shows one of many non-trivial ways a BCI could be used as an extension of existing systems to improve them.

Using BCIs to improve accessibility of existing applications

There are still a lot of applications which lack support for people with disabilities or people with less technical skills. Take for example the growing ecosystem of smart home applications, since it aims to automate many tasks such people might find difficult or impossible to perform, it can be very beneficial to these people. However, conventional interaction methods are app-like through touch screens mounted all around the house. Such interaction methods are not fit for people with limited movement capabilities or technical knowledge.

Since EEG based BCIs are known to work well for conscious people that can learn how to effectively do motor imagery (MI) tasks, it is often seen as a solution to provide novel interaction method with existing applications to improve accessibility. W. T. Lee et al. (2013) were one of the first to explore the idea of using a BCI for smart home control as they believed it could greatly improve the quality of life for the elderly and people with a handicap. They used the Emotiv EPOC headset as a non-invasive source for the EEG using dry electrodes and achieved high accuracy results through a primitive binary selection interface. This means that it seems to comply with most properties of Wolpaw's definition for a perfect BCI except for one of the most important ones, it is not at all as fast as the regular interaction method. Adding to this, their system doesn't make use of actual brain signals but rather relies on muscular activity, such as smirks and eyebrow movement. This movement of the facial muscles is known to provide an easily detectable artefact in the EEG and is often used as a supplementary input for the BCI system. As section 2.4.4 will discuss in greater detail, such an approach has many negatives. Finally, the system of W. T. Lee et al. (2013) was tested on four subjects but the article fails to deliver exact details on this experiment and it is assumed the participants were neither elderly nor people with a handicap.

Whilst this means the system by W. T. Lee et al. (2013) isn't a true brain-computer interface (BCI) due to the use of EEG artefacts and the paper has questionable scientific value, it was one of the first to explore the idea of using a BCI for smart home control. Since then, more articles have studied this idea using effective brain signals. Kosmyna et al. (2016) discuss this in their feasibility study about using BCIs for smart home control. The article by Kosmyna et al. (2016) does include clear details on the experiment setup which includes two people with a handicap among 12 other healthy subjects. It was found that the people with a handicap had an 81% average accuracy whilst the healthy subjects only had a 77% average accuracy. Due to the low sample size, this difference in results is likely not statistically significant but these accuracy numbers are usable when taking into account the small risk of failed actions in basic smart home control systems.

Other examples of hybrid BCIs

Section 1.3.2 already discussed the use of a hybrid BCI system where computer vision, eye tracking and other technologies were used in combination with a BCI system to create a more reliable and accurate final system for robotic arm control (as proposed by B. Xu et al., 2022).

With existing algorithms such as the real-time grasp detection algorithm, GraspNet, by Asif et al. (2018) for low-powered devices, it is very easy to envision how they can be used to improve a BCI related system. Articles which propose a fully working POC, such as the ones reviewed by Dillen et al. (2022), often require these additional algorithms to ensure safe working in real-world environments.

One very interesting hybrid solution is the use of a non-invasive EEG based BCI system with measurements from non-invasive EMG. Bakshi et al. (2018) proposed such a hybrid EEG-EMG system for upper limb prosthesis control. Since EMG is known to be a more accurate modality for prosthesis control, the system by Bakshi et al. (2018) uses EMG for movement of the prosthesis where possible and supplements it with EEG data for determining the other wanted movements. In particular, the proposed prosthesis by Bakshi et al. (2018) uses EMG present in the remaining upper arm muscles for elbow motion and EEG for determining the desired wrist, grip and finger motions. The EMG part, which also imposes the greatest risk, had an accuracy of over 90% whilst the EEG part has an accuracy of over 65%.

The combination of EEG and EMG can also be used for other purposes. Dillen (2018) proposed the use of both EMG and EEG data for training a classifier which then relies solely on EEG input for making final classification predictions. Since the number of combinations to create hybrid BCI systems are nearly endless, it is left to the reader's imagination to come up with other potential use cases.

1.3.4 Using BCIs as an alternative for eye tracking

BCI systems relying on P300 signals were already briefly mentioned in Section 1.2.3. As further discussed in section 2.3.3, a P300 signal is a positive bio-electrical wave measurable with EEG around 300ms after a specific stimulus occurred. This specific stimulus consists of a rare and contrasting stimulus when the user was focusing on what is otherwise a relatively static object with a frequent stimulus (Halder et al., 2018). The most famous example is the use of a computer screen showing elements in a grid-like pattern as the static object with a frequent stimulus and flashing one specific element as the rare and contrasting stimulus. If the element the user was focused on flashes, the P300 signal will be present and relatively easily detectable in non-invasive EEG measures. A clever design of the interface can enable a wide variety of BCI applications. This section will highlight a few of these applications. It is noted that other types of stimulus can be used, such as auditory ones, to evoke a P300 signal. However, this section focuses on the discussed, visual, grid-based methodology.

With such visual P300 based BCI relying on the before-mentioned method of focusing on a part of the screen and using flashing patterns to recognise which part the user is focused on, a viable alternative would be eye-tracking technology. This makes the effective use of these types of BCI systems debatable, an issue that is also further discussed in this section.

Why a low learning curve makes P300-based BCI systems attractive

In general, BCIs using the P300 signal are often used as they have a low learning curve and there is a relatively low variation in performance between users compared to other types of BCIs (Hussein et al., 2020; Won et al., 2019). The reason these systems have a low learning curve is due to their simple user interface and a combination of a system that generalises well and that has been studied thoroughly for the use of transfer learning (TL). Early examples of using TL for P300 related BCIs include those by Kindermans et al. (2012). Adding to this, P300 signals can be detected with non-invasive EEG using dry electrodes, which are available in multiple EEG measuring headsets at affordable prices in a comfortable and visually pleasing package, as

further discussed in Section 2.4.3. Whilst these factors hint that such BCI systems comply with Wolpaw’s definition for a perfect BCI addressed in Section 1.1, it will become clear in this section that the communication rate of these systems is still a limiting factor.

However, these aspects do make it possible for P300-based BCIs to be rapidly configured and used by a new user. All of this aids in creating a pleasant user experience (UX) even if the communication rate is low, as shown by user studies such as the one by Utsumi et al. (2018). Other types of BCI systems, such as those relying on Motor imagery (MI), can have a tedious training procedure in advance. This can cause psychological burden and other side effects for the user. This gives rise to multiple ethical challenges, some of which are discussed in Section 1.5. Considering these things, P300 based BCIs are an interesting choice as a *first BCI* to introduce the user to the possibilities of BCI systems. This might make it easier for the user to move to a more capable and sophisticated system that has a steeper learning curve, higher cost and more demanding training.

Research on the UX is often overlooked by initial BCI system proposals, where the focus is often on objective numerical measures such as speed, accuracy, sensitivity and specificity. However, as discussed by Dillen (2018), user studies are essential to even consider using a proposed BCI system in the real world.

Using BCIs for P300 spellers

By far the most common usage of the P300 signal is to create *p300 spellers*, an idea first described by Farwell and Donchin (1988). In its simplest form, P300 spellers simply show the alphabet as grid elements and let the user spell words letter-by-letter. More complex forms can use auto-correction to correct faulty classifications, reducing the effective error of the system. Advanced text prediction can also be used to show complete words or sentences for selection, increasing the communication rate as opposed to letter-by-letter input. Other techniques can also further increase the reliability and communication rate of the system.

As such, P300 spellers are examples of novel interaction methods that aim to replace keyboards for those who don’t have the required capabilities to operate them. Especially patients with severely limited motor skills and communication capabilities such as people suffering from serious cases of amyotrophic lateral sclerosis (ALS) or locked-in syndrome (LIS) can benefit from these systems by regaining basic communication skills (Hussein et al., 2020; Won et al., 2019). Whilst wrong classifications in a speller application could result in unpleasant situations, it is clear that the risk involved is far smaller than with BCI system used for controlling prostheses and exoskeletons such as discussed in Section 1.3.2. This makes P300 spellers one of the few types of BCI systems that are actively being used in the real world.

Guy et al. (2018) performed a usability study of P300 spellers with 20 ALS patients in a real-life environment. According to Guy et al. (2018), most participants achieved over 70% accuracy, which is in line with the findings of Hussein et al. (2020) and Utsumi et al. (2018) in similar studies amongst other types of patients. More interestingly, even though the accuracy wasn’t extremely high, all participants of the experiment by Guy et al. (2018) succeeded in the given tasks. This is in part due to our ability as a human to understand typo’s in words and sentences relatively easily. Another important factor is that the studied system makes use of the earlier discussed auto-correction and text-prediction techniques. Whilst far from advanced variants of these techniques were used, it almost doubled the communication rate of the P300 speller already with the mean number of correct symbols per minute going from 3.6 to just over 5.

Whilst 5 symbols per minute is significantly slower compared to traditional communication skills, it enables useful communication for those who can’t communicate through regular means. It should also be considered that these results are for people suffering from ALS. These people can

have difficulties with controlled eye movement or rapid eye movement which results in a slower operation speed compared to able-bodied persons. However, since it is so slow compared to the regular interaction method of able-bodied persons, it is far from a perfect BCI when taking into account Wolpaw's definition of a perfect BCI. A similar study by Utsumi et al. (2018) focuses more on the UX for duchenne muscular dystrophy (DMD) patients using P300 spellers. This study has shown that P300 spellers can be used by DMD patients with satisfactory results in a pleasant manner for the user, even if the communication rate is slow.

Using the P300 signal for other BCI applications

When taking a broader look at P300-based BCI systems using a visual grid system, they are just a mechanism for recognising which portion of the screen a user is looking at. These grids are often of a limited size, such as 6 by 6, for the best trade-off between accuracy and communication rate. The effective content of the grid and the actions taken upon classification can vary widely. This has enabled the exact technology of P300 spellers to be easily adapted for other applications.

One such example is the *Facebrain* application by Warren and Randolph (2019). Facebrain provides a non-invasive EEG based BCI for interacting with the social media platform Facebook. In essence, it's a regular P300 speller with the first screen(s) representing possible actions to take on the platform. When text input is required, a regular P300 speller user interface is presented. This allows a user to operate almost all of Facebook's functionalities with only a P300-based BCI. The application by Warren and Randolph (2019) is one of many that shows the same strategy and classification algorithms as P300 spellers can be used for a wide variety of applications by changing the meaning and functionalities of the shown grid elements. Rather than showing symbols, a complete image could be shown and separated into grid elements as well. Kapgate (2022) used this idea by showing a live video stream from a quad-copter and moving it towards where the user is looking based on the P300 signal after flashing different portions of the image. However, as the video live stream is not static, the contrast between the flash and regular screen content shrinks making the P300 signal less noticeable and thus the classification task harder.

Why eye tracking may still be preferred

Whilst the discussed P300 applications have shown success in achieving their goals, the effective real-world use of such systems can still be debated. The communication rate is slow and for able-bodied users, traditional eye-tracking can far outperform these systems (Halder et al., 2018). Adding to this, as P300 signals are a type of event-related potential (ERP), there are some known limitations and issues with techniques relying on them as well. The BCI handbook by Nam et al. (2018, Chapter 26) discusses the crowding effect, adjacency problem, repetition blindness and user discomfort amongst other issues ERPs have. Most of these problems arise from the often limited space for sending visual stimuli without overlap and the changing behaviour of both the brain and participant's experience after a prolonged session where many stimuli have been applied.

Multiple articles have been written on when and why a P300-based BCI might be preferred over a regular eye-tracking system (Halder et al., 2018; Pasqualotto et al., 2015). The experiments performed by Halder et al. (2018) compared the accuracy and communication rate of visual P300 based BCIs against traditional eye-tracking solutions. Halder et al. (2018) found the accuracy of both systems to be comparable but the communication rate of eye tracking solutions was around 50% faster. However, when questioning the ten participants of the study, it was found that there is a higher preference for the BCI system than the eye-tracker. Whilst favourable for the BCI alternative, the results of the study by Halder et al. (2018) should be interpreted with caution. The participants of their study were all able-bodied persons and the eye-tracking experiments

were always performed last. This and other aspects of their methodology are bound to introduce bias in the results.

A study by Käthner et al. (2015) compared the use of eye-tracking software and auditory P300 based BCIs for a patient suffering from the locked-in syndrome (LIS). Whilst the patient was able to work with both systems autonomously, there was a strong preference for the traditional communication strategy which relied on a human to determine the wanted communication of the patient. This preference was purely based on the UX rather than the communication rate. Whilst only being an experiment based on a singular participant, it does show how automated systems for regaining basic communication might cause a negative psychological impact on the user. Thus, the results found by Halder et al. (2018) on UX are in direct contrast with the results from the experiment by Käthner et al. (2015). However, Käthner et al. (2015) lacked a study of visual P300 based BCIs, so it could be that such a system would be preferred.

Similar conflicting results are present on other aspects of visual P300 based BCIs as well. One debate that has been active for years is the dependence of P300-based BCIs on the capability of a user to look directly to a single target for a prolonged time. As discussed by Brunner et al. (2010), it has been argued that this dependence is low as peripheral vision allows the user to focus on the desired element even if the eyes aren't directly rotated towards the element. This would be favourable for P300 solutions compared to eye-tracking solutions as some users might not have the required muscle control to point their eyes to a specific point for prolonged periods, a task known as eye gazing. However, the study by Brunner et al. (2010) does show a dependence of P300-based systems on eye gaze and they argue the effective uses of visual P300 systems should be reconsidered. Yet, the review article by Riccio et al. (2012) addresses multiple articles which concluded through real-world tests that being capable of eye gazing is not necessary for effective use of P300-based BCIs.

These contradicting results on the use of P300-based BCI applications make it hard to determine which kind of system would be usable in the real world, providing a net benefit for the user. It also shows that promising objective results such as a high accuracy and communication rate are not guaranteed to provide a system which is enjoyed by the end user. Thus, many proposed systems require follow-up articles focusing on performing in-depth real-world experiments with the target population to conclude if they are worthwhile. However, doing such a study in the same article proposing the new novel system would mean that one singular article takes an incredible amount of time. This is contradictory to the expectations of many researchers in the field to publish a certain amount of articles yearly. However, the latter is an ethical dilemma that entails a higher risk of *sloppy science*.

1.3.5 Summary on the use cases for BCIs

Since BCIs can be seen as a novel interaction method for controlling external devices, the possible use-cases are endless. Even for the discussed P300 based BCI systems alone, a huge variety of applications can be created as addressed in Section 1.3.4. This has caused review articles to focus solely on these types of BCI systems or even subset of those types of systems (Alrumiah, 2020; Fazel-Rezai et al., 2012; Rezeika et al., 2018).

Thus, addressing all possible use cases for BCIs is far outside the scope of this thesis. For this section, the goal was for the reader to obtain a more general insight into the most studied uses for BCIs. In this regard, it succeeded in addressing all of the most popular use cases of BCIs as biosignal control systems in the real world as found by Dillen et al. (2022) and the most interesting use cases of BCIs addressed in the review article by Abdulkader et al. (2015). It also highlighted that current real-world applications still rely on other technologies to limit risk and improve accuracy as standalone non-invasive EEG based BCIs are still not accurate and reliable

enough for most real-world usage. Some of the main positive and negative points of the discussed articles were also addressed.

Most notable from this section is the fact that objective measures are only a small part of making a system that can be used in the real world. Take for example the discussed experiment by Guy et al. (2018) which studied the use of P300 spellers by patients suffering from ALS. With a classification accuracy of 70% and only 5 symbols per minute, the objective measures from this system look terrible compared to able-bodied alternatives such as regular keyboard typing. However, Guy et al. (2018) found the users to have enjoyed the use of the P300 spellers and when taking into account the options available to the target users rather than able-bodied users, the objective measures are far more impressive.

However, even the articles which perform experiments that take into account the user experience (UX) can sometimes cause conflicting results. Take for example the discussed differences between the found user experience of P300 based BCIs between the experiment by Halder et al. (2018) and Käthner et al. (2015). Able-bodied persons from the experiment by Halder et al. (2018) mentioned a pleasant UX. A more representative real-world study by Käthner et al. (2015), who looked at a singular patient suffering from LIS showed that this person had no interest in using such systems as a replacement for the existing human-based communication system which was already present. Even-though speed and autonomous use were far better and the UX according to the able-bodied persons was great, the UX for this person suffering from LIS was not good enough. Thus, the UX is something that can only truly be measured when performing the experiments for an extended period with the target audience of the system, not through a single experiment on able-bodied participants. It is hard for an able-bodied person to understand that the confrontational aspect of BCIs on the limitation a user has can outweigh the benefits it seemingly offers. This and other more ethical questions are also addressed in Section 1.5.

To summarize, as a BCI performs actions based on brain signals, a very fitting analogy could be made: *a BCI could do anything you can think of*. That is, of course, only true in theory. Due to limited knowledge of the brain (Hodson, 2019) and limitations in what can be measured, a BCI can only truly do what you can think of in a *measurable way*. Still, this is a whole lot of applications and an overview diagram of the most important ones is given in Figure 1.7. This diagram is not only based on the use cases discussed in this thesis but also those discussed in the articles by Dillen et al. (2022) and Abdulkader et al. (2015) among others (Kübler, 2020; Nam et al., 2018; Nicolas-Alonso & Gomez-Gil, 2012; Panoulas et al., 2010; Shih et al., 2012; Sonam, 2018). From Figure 1.7, it should become apparent that most short-term goals of BCIs still lie in improving the quality of life for people with disabilities. However, the rise in popularity of BCIs in the gaming industry and amongst other big tech companies, as discussed in Section 1.2.1, shows there is a potential future where BCIs find more real-life use-cases in other fields as well.

1.4 Opportunities and obstacles for BCI research

The most likely factors of why BCIs are gaining popularity and what the most common use cases are for BCIs were already discussed in Section 1.2 and 1.3 respectively. From these sections, an interested reader could have already spotted some opportunities and potential obstacles for doing research in the field themselves. This section discusses some opportunities and obstacles present according to the author of this paper. The aspects that are covered in this section are oriented towards the interests of the author from this master thesis and aim to explain why this master thesis came to fruition. They also lay the foundation to the proposed BCI biosignal control system of this master thesis, which will be further discussed in Section 1.6.



Figure 1.7: An overview of some of the many use cases for BCIs.

1.4.1 Seemingly small projects with huge impact

As BCIs and other technologies become more commercially oriented, the main focus is often shifted to providing products that can be used by the masses to provide the highest possible revenue. Whilst BCI research sees its foundation from the medical world and most of the current users are people with a certain medical condition, a similar shift is likely, especially for the larger projects funded by big-tech companies. This isn't necessarily a bad thing for medical applications, since this doesn't mean academic research focusing on those people with a certain medical condition disappears, rather it becomes a smaller portion of all research in the field. The new technology and knowledge commercial products deliver can directly contribute to academic research focusing on medical applications. This may include cheaper and more capable measuring equipment, a more socially acceptable picture of BCIs aiding the aesthetic aspect of Wolpaw's definition for a perfect BCI and better performing classification algorithms. It is also possible that a commercial BCI application which is meant as a novelty for most, is life-changing to some.

Take the evolution of live captions as a recent example from a different domain, it has found its way directly into the Android smartphone operating system. Whilst initially implemented for users to enjoy video content in situations where they can't listen to the audio, people with hearing difficulties now have a direct way to enjoy more content too. The push for autonomous cars will allow those that are traditionally unable to drive a car to finally enjoy the freedom a

car can offer as well without being dependent on others to do so. Object and scene recognition algorithms made for optimizing smartphone cameras can also be used as a way of describing what is on a photograph for those who have limited vision.

Likewise, as more people are exposed to complex medical and commercial applications, many individuals start to envision seemingly small applications that could have a major impact on them or people they know. This has been the case with smartphone applications for a long time. A colour picker app that uses the camera to describe the colour of the central pixel is something that can be implemented with very limited resources. Yet, such an application has already proven to significantly aid people who have colour blindness. For example, they may use this application to determine whether a banana is ripe or not, something they can't visually determine but is easy with a textual description of the colour. For such small applications to be feasible, an abundance of open-source material to re-use existing code for operating the camera, getting a textual colour description of an RGB colour code and more is required.

This presence of open-source code has started to emerge for the BCI field as well, as discussed in Section 1.2.3. Combined with publicly available EEG dataset such as the one by Kaya et al. (2018), it has become possible for developers to work on a pipeline without needing the monetary investment in EEG measuring equipment. If desired, the affordable headsets by OpenBCI and others, further compared in Section 2.4.3, make it possible to have EEG measuring equipment with good open-source libraries for well under 1000 euros. This has made individuals such as the author of this paper excited to create a wide variety of smaller applications that could have impactful meaning to some very specific people. Especially the possibility of regaining even the simplest form of mobility through some very basic controls derived from motor imagery (MI) is what motivated the author of this master thesis to study the field.

1.4.2 Motivational aspects for this master thesis

The discussed use cases from Section 1.3 were motivating examples for this master thesis in themselves. However, there are some specific articles and aspects from the field that have motivated the creation of this master thesis which will be discussed in detail here. These are mainly related to motor imagery (MI) based BCIs working with affordable consumer-grade and non-invasive EEG measuring equipment. Whilst many articles have demonstrated the potential of such BCI systems, the lack of widespread adoption suggests there are still hurdles to overcome for them to become a reality. When discussing these motivating examples, some of these hurdles will already be discussed, the main obstacles for BCI research are further discussed in later subsections.

Consumer-grade EEG measuring equipment has promising potential

Section 1.2.2 and 1.2.3 have already discussed the evolution of EEG measuring equipment as a potential reason for the increased popularity of BCI research. Multiple studies comparing different aspects of cheaper consumer-grade systems to the more traditional medical-grade BCI systems have already been done (Cruz-Garza et al., 2017; Frey, 2016; Hinrichs et al., 2020; Rashid et al., 2018; Tseghai et al., 2021). In general, cheaper systems work with dry electrodes at a lower electrode count and have a lower signal quality compared to medical systems. This means the cheaper systems provide poorer data quality, resulting in a more difficult classification problem.

This raises the question if useful applications can be made using data from these cheaper systems. One of the best-known providers of EEG equipment is OpenBCI and their products are further discussed in Section 2.4.3. This OpenBCI headset makes use of the Texas Instrument ADS1299 chip to convert the analogue signal of EEG electrodes to a digital one. Whilst affordable

and widely available, it has been shown that this chip is comparable to far more expensive alternatives that have been used in the laboratory for years (Frey, 2016; Rashid et al., 2018). However, a cheap consumer-grade system differs from medical systems in more areas than the general chip responsible for EEG amplification and digitalisation.

Studies comparing the use of cheaper dry electors against medical wet electrodes have already been discussed in Section 1.2.2. Whilst the obtained results from these studies show the gap between both is shrinking but still present (Cruz-Garza et al., 2017; Mathewson et al., 2017; Tseghai et al., 2021). However, the experiments used for obtaining these results come from very controlled experiments in lab-like environments. This is to be expected, as most comparisons aim to eliminate as many random factors as possible. However, this means that these experiments don't give great insight into the real-life usability and applicability of these cheaper BCI systems. Taking into account that none of the academic research discussed in the systematic review article by Dillen et al. (2022) makes use of such cheap systems hints that real-world usage of these systems remains hard.

Trainable motor imagery as input thoughts for the BCI system

Section 1.3.4 discussed P300 based BCI systems. Whilst the P300 signal is relatively easy to detect and evoke, the discussed visual stimuli used, have many limiting factors. Perhaps most limiting is that the user can not evoke the signal without requiring external stimuli. This is undesired in several ways. This external stimulus requires an additional system to be present, such as the flashing grid commonly used for visual P300 BCI, which adds to the cost and complexity of the system and limits portability. A system where a person sits behind a flashing screen is also hard to call aesthetically acceptable, making it unsuitable for Wolpaw's definition of a perfect BCI.

Detectable signals that can be evoked voluntarily by the user are more interesting for most BCI applications. Likewise, the process to evoke this detectable signal should be one that doesn't require physical movement so that it is applicable for users suffering from limited muscle control. It should ideally also be a process that is invisible to those around the user, making it aesthetically ideal for Wolpaw's definition of a perfect BCI. Motor imagery (MI) is such a cognitive process and is often used for controlling BCIs and in other fields such as sports, psychology, music, medicine and education (Schuster et al., 2011). Mulder (2007) defines the MI process as follows:

Motor imagery is a cognitive process in which a subject imagines that (s)he performs a movement without actually performing the movement and without even tensing the muscles. It is a dynamic state during which the representation of a specific motor action is internally activated without any motor output. In other words, motor imagery requires the conscious activation of brain regions that are also involved in movement preparation and execution, accompanied by a voluntary inhibition of the actual movement.

Mulder (2007)

MI does have some drawbacks as well, mostly following from MI being a cognitive process with no visual clues. Firstly, explaining how to *do MI correctly* is a difficult task. Whilst it can be trained, it has a far steeper learning curve to obtain pleasing results than the earlier mentioned P300 systems relying on ERP-based signals for example. Alimardani et al. (2018) describes this problem and tips for teaching MI in greater detail. The most general procedure of explaining the MI task to a user consists of verbally explaining the MI task. This can be further supported by a physical example of the task that should be envisioned. People with the capabilities of performing the envisioned task physically can also be asked to perform the task

whilst simultaneously thinking about it as a first step too. After this, a training procedure of the user performing the MI task without physical movement starts.

This introduces the second problem, evaluating the users *capability of doing MI*. Such an evaluation exists of two parts, a survey taken beforehand and feedback during or after training. Multiple types of surveys have been proposed to determine beforehand if a person will be good in MI tasks (Gregg et al., 2010; Malouin et al., 2007; McAvinue & Robertson, 2008; Vuckovic, 2010; Vuckovic & Osuagwu, 2013). Most of these surveys are empirically created and based on the found correlations between the answers given by participants and their performance on a MI BCI for those participants. However, correlation does not mean causation, and it has been the case that these questionnaires do poorly at predicting a survey respondent's capability of doing MI in a detectable manner. For example, Peterson et al. (2020) found no statistically significant correlation between the KVIQ-10 score of participants and the found classification accuracy. Thus, determining beforehand if a participant will have pleasant accuracy results beforehand through the KVIQ-10 questionnaire by Malouin et al. (2007) wasn't reliable for the experiment by Peterson et al. (2020). This is an issue, as knowing this information beforehand can give a potential buyer a better indication if the system would be fit for them or not. Other surveys have been proven more successful at predicting MI capability of a user but further research in finding a survey that is reliable at predicting a user's MI skills is still required (McAvinue & Robertson, 2008). Besides this survey that is taken beforehand, evaluating the MI tasks performed by a user is also not an easy task. Most of the time, a model is trained or calibrated after obtaining training and test samples of the user performing the MI tasks. The accuracy of this trained model can then be used as an indication of how good the user is at the MI task. Alternatively, the user might be exposed to live feedback during data collection in the form of a visual or physical stimulus that indicates the BCI is detecting a specific MI task. Including live feedback has been proven highly beneficial in training MI, although it makes the training procedure even longer (Alimardani et al., 2018). As evaluation in this way is mainly empirical based on the obtained classification result, it is not uncommon to see varying ways of doing the MI task between users. Some might perform the MI tasks by envisioning the task from a third-person perspective whilst others opt for a first-person perspective. This introduces many variables in the data, causing a high variability between users and even between sessions of the same user. Visualisation of the brain signals and their decoding might aid in guiding users to perform a more equal MI task, reducing the variability of the data. However, since brain signals are non-stationary and the visualisation techniques are limited, variability will always remain an issue. Forcing a user to perform the task in a specific manner also has downsides. Their personal accuracy for the BCI system may be poorer when forced to do the MI task in a very specific way compared to finding the optimal method for them. The psychological burden of the long MI training process will also be higher if the task is very strict, requiring more focus. Finally, the data may be so strictly obtained that it is far from realistic and the system performs well in the real world.

This highlights the third and final important issue with MI, the issue of generalisation. This issue is present in two different forms. First, there is the general issue not strictly limited to MI that training and testing data is often obtained in strict manners and thus lab-like. When used in the real world, more noise is present in the signal resulting in far poorer results. The trained system does not generalize well to new, unseen data from the real world. Second, as discussed the brain signals produced during MI tasks can vary greatly between participants and sessions. This variability means that creating a general model is far less successful, the trained model does not generalize well to other users. This makes transfer learning (TL) far more difficult. This issue cascades to making the training procedure longer and having higher inter-patient variability in terms of accuracy results (Alimardani et al., 2018; Peterson et al., 2020). The generalisation issue is an important one in many ML applications and is discussed further in Section 3.5.2.

These issues with MI result in datasets that seem comparable from a high-level description of the performed MI task but are very different in the used training procedure and data acquisition process. The general MI capabilities of the participants can also differ greatly between datasets, with some performing a survey beforehand to only include participants with a high possibility of being good at MI. This means that choosing datasets from *well capable MI performers* will result in higher accuracy scores as the data is easier to learn from. Even when open-source databases are re-used between articles, it is not uncommon to find articles where the authors left out certain data in the training and testing procedure, arguing these users had poor MI capability. This makes a comparison of results between articles far more difficult. This is an issue of not having standardized testing, which will be discussed in Section 1.4.4.

Detailed literature on MI pipelines

Section 1.2.4 discussed the emergence of more open-source datasets and code-providing libraries for BCI research. However, many articles still fail to provide their source code and lack the required detail to fully recreate the used pipeline. This makes articles describing their pipeline and design decisions in great detail stand out. In general, these articles don't aim to improve the state-of-the-art in any component of the pipeline. Rather, they contribute to the field by providing a detailed look at the working of pipelines based on available state-of-the-art solutions and a correct evaluation of them.

The article by Peterson et al. (2020) discussing the feasibility of a complete low-cost consumer-grade BCI system is one that focuses on these aspects. Peterson et al. (2020) performed their feasibility study by discussing the steps required to make an offline binary MI classification system using common low-cost consumer-grade hardware. The BCI distinguished two cases, the MI task of a grasping movement with the participants' dominant hand and a rest condition. They compare three traditional ML approaches for this classification task in growing complexity. These approaches differ in the feature extraction used, namely the use of traditional CSP and that of two extensions, penalized frequency band common spatial pattern (PFBCSP) and penalized time-frequency band common spatial pattern (PTFBCSP). The work by Peterson et al. (2020) has five interesting aspects worth highlighting here.

First, whilst they did use the consumer-grade OpenBCI Cyton and Daisy board they did not use the 3D printable Ultracortex Mark IV headset from OpenBCI. They argued that this is due to the Ultracortex Mark IV headset becoming uncomfortable quickly due to the use of dry electrodes combined with limited adjustability. This complaint on user comfort for the Ultracortex Mark IV headset is recurring with other authors including the one from this master thesis. Because of this, they opted for wet EEG electrodes attached to a very flexible and far more comfortable Electro-Cap. Peterson et al. (2020) opting for wet electrodes is slightly odd, as it is not really consumer-grade nor does it fit well with Wolpaw's definition of a perfect BCI.

Secondly, for the data gathering of their system, Peterson et al. (2020) used a *common office room*, rather than a lab-like environment. Except for a 3D printed holder for the OpenBCI board, there was no specialized shielding in place to protect the electrodes or OpenBCI boards from unwanted interference. They argue this makes the data more realistic. Whilst this is true to a certain extent, it is important to note there is still far less stochasticity than there would be in real life. The office room and hardware were identical for each of the participants in the data collection stage. The room was free of external stimuli with the participant *left alone* to focus on the task and the task only during the entire trial. All participants were right-handed and thus the dominant hand used for the MI task was always the right hand. Adding to all of this, the dominant hand of the participant was placed inside a box to not allow them to see their hand. This makes the data acquisition procedure used by Peterson et al. (2020) far from comparable

to a real-world use case. Still, Peterson et al. (2020) found that the non-shielded regular office already caused significant noise compared to full lab settings. In one trial the electromagnetic noise amplitude was four times higher than the meaningful EEG data.

Third, during the data collection, an EMG system was also in place. This EMG system was used to filter out samples of the collected EEG data where the envisioned movement was also physically performed, meaning it wasn't true MI. Whilst this forms an interesting and automated approach to data filtering when collecting training samples, the supplemental hardware that is only used during the training phase is probably a tough sell in a commercial application.

Fourth, they used the KVIQ-10 questionnaire by Malouin et al. (2007) to determine how good a participant would be in MI, a task that is proven to be harder for some individuals. As discussed earlier, the results of these surveys are not reliable and only give a rough indication with many exceptions and surprising results possible.

Finally, even though the data acquisition happened under guidance in the work of Peterson et al. (2020), there were still issues with the recordings. Out of the 12 participants, there were multiple moments where connection loss with the OpenBCI main board occurred and for one participant a defect rendered the data useless. These issues are probably related to the quality of the consumer-grade hardware. Part of the reason medical-grade hardware is about 5 to 10 times as expensive for a similar experiment is due to the strict certification medical-grade BCI should comply too. This certification guarantees some form of quality and reliability from which it is expected connection issues and defects wouldn't appear as frequently. Besides this, for one participant there were EMG detected movements of the hand for more than half of the MI tasks rendering the trial of that patient useless as well. Whilst this is an issue independent of the hardware used, it does indicate that learning how to do MI requires training which takes time and effort.

To conclude, the work by Peterson et al. (2020) discusses the creation of a complete low-cost consumer-grade BCI system. This system consists of the OpenBCI measuring equipment where the dry electrodes on the 3D printed Ultracortex Mark IV are replaced with electrodes in a more comfortable Electro-Cap. The effective classification of the system is a binary motor imagery (MI) classification on whether or not the participant imagines a grasping movement of the right, dominant hand or not. Peterson et al. (2020) achieved an average accuracy between 70% and 85%, scaling with the complexity of the used CSP variation. It is important to note that the evaluated models are on a patient-per-patient basis. This means that each patient has their own uniquely trained model and that data from the same patient is used in the evaluation process. Whilst the binary nature of the system makes it hard to find viable real-life applications, the performance reached is almost identical to those of medical-grade systems and follows from a slightly less lab-like environment than is typically the case. The system proposed by Peterson et al. (2020) is of less importance in their work, rather the steps and pitfalls highlighted are of value.

Detailed literature on complex classification pipelines

The above discussed article by Peterson et al. (2020) provides great insight on the steps required to develop an EEG-based consumer-grade BCI which uses MI related signals. Since Peterson et al. (2020) uses a binary classification model, there are only two possible outputs of the classifier, which is too limited for most applications. However, when working with BCIs, a lack of training samples combined with noisy and often high-dimensional data makes multi-class classification considerably harder than binary. That being said, spatial filters such as the CSP approach and its extensions used by Peterson et al. (2020) have been extended to support multi-class feature extraction. The articles by Abdeltawab and Ahmad (2020) and Olivas-Padilla and Chacon-

Murguia (2019) have also studied the use of spatial pattern techniques for feature extraction. This is done in combination with traditional ML classifiers and DL ones, both with promising results.

Many other multi-class classification pipelines have been proposed in literature that work well with MI related EEG data (Abdeltawab & Ahmad, 2020; Z. Chen et al., 2021; Hou, Zhou, et al., 2020; Kai Keng Ang et al., 2008; Lawhern et al., 2016; Mane et al., 2021; Mussi et al., 2019; Olivas-Padilla & Chacon-Murguia, 2019; Schirrmeister et al., 2017). These proposed pipelines generally work on both consumer-grade and medical-grade systems, although consumer-grade systems can often benefit more from pipelines with specific noise-reduction steps. Some of the proposed pipelines also focus on providing a general model which has been trained on data from multiple users and has usable performance for unseen users. Whilst such models have poorer performance compared to one trained for a specific user, they can be used as an initial model to allow the user to explore the possibilities of the BCI without having to undergo the often tedious training data collection process. Such a general model can also be used as a base model for calibration, a process based on the idea of transfer learning (TL) further discussed in Section 3.3.2.

A complete in-depth review of all of the different approaches that have been proposed for EEG classification falls outside the scope of this research paper. Guerrero et al. (2021) compared logistic regression (LR), artificial neural network (ANN), support vector machines (SVM) and convolutional neural network (CNN) for a binary classification task of either being epileptic EEG data or not. Whilst this is a binary classification task that is more tailored towards computer-aided diagnosis (CADx), the techniques used in the experiments are often used in the multi-class classification of EEG data for common BCI purposes. Guerrero et al. (2021) found that artificial neural networks (ANNs) performed best for their classification task. In general, ANNs and other DL models such as CNNs have proven to be more successful at EEG data related tasks compared to traditional ML approaches.

Because of this, many of the current state-of-the-art models for EEG classification rely on DL models. Especially classification pipelines that include CNNs have proven to be successful for EEG classification (Hou, Zhou, et al., 2020; Lawhern et al., 2016; Mane et al., 2021; Mussi et al., 2019; Olivas-Padilla & Chacon-Murguia, 2019; Schirrmeister et al., 2017).

The CNN-based approach by Schirrmeister et al. (2017) is commonly regarded as current state-of-the-art for MI classification. The article by Schirrmeister et al. (2017) includes two different models, a deep CNN named DeepConvNet and a shallower one named ShallowConvNet. In Chapter 4, both of these models will be implemented and discussed further. Schirrmeister et al. (2017) also describe a method of extracting a visualisation of the used brain signals by the model, which can aid in the explainability and interpretability of the model. Explainability and interpretability are further discussed in Section 3.5.3, Chapter 4 further addresses the visualisation technique.

One issue with more complex CNN-based pipelines such as the DeepConvNet variant by Schirrmeister et al. (2017), is the time and computational resources it takes to train the model and do predictions with it. The latter is an issue for real-time classification, something that is needed for an online BCI system which often works with relatively low-powered computational units. Pipelines such as the one by Lawhern et al. (2016) have been developed to use CNNs in such a way that real-time classification is possible. The model proposed by Lawhern et al. (2016) also has promising results and will also be implemented in Chapter 4 where it is discussed in greater detail as well.

Whilst CNN-based pipelines are among the most popular for the classification of MI EEG data, they fail to use a fundamental aspect of EEG data. CNNs are not designed to perceive the input data as sequential data, which EEG data is. As such, they do not explicitly use

this property of the data for learning. Recurrent neural networks (RNNs) and long short-term memory networks (LSTMs) in particular are a type of DL networks that do explicitly use internal memory to explicitly use the sequential property for learning, as Section 3.4.4 will discuss in greater detail. These approaches are most popular in speech processing as it is the sequence in which words are spoken that gives meaning to a sentence rather than individual words. P. Wang et al. (2018) used a traditional LSTM pipeline for MI EEG data classification with satisfactory results whilst Garcia-Moreno et al. (2020) combined both ideas from CNNs and LSTMs into a singular network that rivals CNN-based state-of-the-art for MI EEG classification.

Some more noteworthy MI related EEG classification approaches include the one by Z. Chen et al. (2021) and the one by Hou, Zhou, et al. (2020). Z. Chen et al. (2021) took an interesting approach by first visualizing EEG data as an image and using techniques from image processing for classification. This yields decent results but doesn't reach the same level as the discussed state-of-the-art models. However, the approach by Hou, Zhou, et al. (2020) which incorporates the technique of scout EEG source imaging (ESI) has shown to be as good or even better than state-of-the-art in specific experiments.

Connecting the classification model to physical devices

As was discussed in Section 1.1, there is no exact definition of a BCI. In general, a complete BCI system is seen as a combination of three different processes: a data collection process, a data processing step and a step where effective actions are taken by the BCI based on the processed data. It is this last process that forms some ambiguity in what can be considered a BCI and what can't be, as was already discussed in Section 1.3. BCIs that functions as biosignal control systems, which explicitly control an external device in real-time, are included in each definition of a BCI. However, how such an external device is controlled can vary greatly and requires special attention which may influence all other components of the BCI as well.

The labels provided by the classifier can be seen as an incoming input stream for the process responsible for mapping those classifications to an action on the external device. When using MI EEG, it is intuitive to link the envisioned task with a similar action on the external device. For example, an envisioned left-hand squeeze corresponds to a left movement whilst an envisioned right-hand squeeze corresponds to a right movement. However, nothing is stopping the implementer from doing this mapping differently and in some scenarios, a less intuitive mapping might provide a more reliable and capable system that is easier to use.

This follows from some of the challenges with MI EEG classification, in particular a limited amount of output classes and the fact that it is easier to distinguish between major MI tasks such as left-hand and right-hand movement rather than individual finger movement for example. Since classification accuracy should be sufficient to operate the external device safely and reliably, a limited number of different and easy to distinguish MI tasks are often used.

To illustrate how such limited classes can be used for effective biosignal control systems, imagine the movement of a robotic arm to pick up objects using MI EEG data through a classifier that can distinguish 4 MI tasks: left-hand squeeze, right-hand squeeze, foot movement and an idle state. Intuitively, one might want to obtain complete control over the robotic arm but the limited MI tasks render a direct mapping between the classification label and all possible movements of the arm impossible. The most intuitive solution is the creation of a menu for movement options as illustrated in Figure 1.8a. Using the foot MI task, the user switches between 3 operation modes of the robot arm: horizontal movement, vertical movement and grasping movement of the hand. Dependent on the active menu, the left-hand squeeze and right-hand squeeze MI tasks can be used to move the robot arm left and right, up and down or to open and shut the robot hand. This provides the user with all available control whilst remaining relatively intuitive. However,

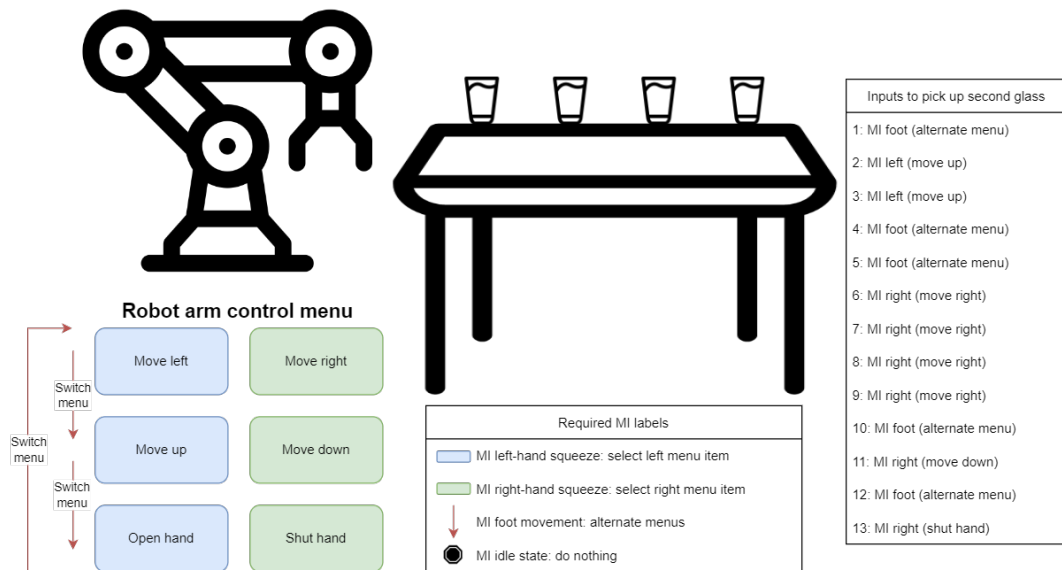
this assumes all commands are interpreted correctly. When taking into account that state-of-the-art struggles to reach an average of 80% accuracy for classifying four MI tasks in favourable conditions, it is not unreasonable to think that best case there will still be a misclassification once every five steps on average (Khan et al., 2020; Mishra et al., 2018; Rahman et al., 2019; Zhang et al., 2019). Taking into account that for picking up the desired object, the robot arm needs to be perfectly aligned both vertically and horizontally and the user needs to switch to the menu for grasping through envisioned foot movement and then chose the desired grasping movement through envisioned hand movement, it is highly unlikely this sequence of events will happen without misclassification. This long sequence will not only make the system inefficient to use, but it will also expose one user’s intention to more points of failure as it will require many steps.

Stepping away from the idea of wanting to control every movement of the robotic arm, a huge improvement in the efficiency of the system can be made. With grasp detection algorithms such as the one proposed by Asif et al. (2018), the detection of objects of interest for the robot arm to interact with can be detected through computer-vision algorithms. Using such algorithms, another way of controlling the robotic arm could rely on only three MI tasks: left-hand squeeze, right-hand squeeze and an idle state. Using the left-hand squeeze MI task, the robot arm could be alternated between all possible items to grasp as detected by the grasp detection algorithm. Using the right-hand squeeze MI task, the item could be picked up or set down depending on the current state and computer-vision-aided tools. This limits the amount of successful consecutive steps needed and being a three class MI classification, the accuracy is expected to be higher. Thus, the system would be less intuitive but far more usable. This proposed design is shown in Figure 1.8b. When comparing both subfigures of Figure 1.8, it becomes apparent that the less intuitive system is far more efficient at the given task, requiring only two actions to pick up the second glass rather than 13. It is noted this is only an educational example and real systems would likely still require a more complex interface. It is also noted that it is common to reduce misclassification by basing the taken actions on multiple classifications rather than one.

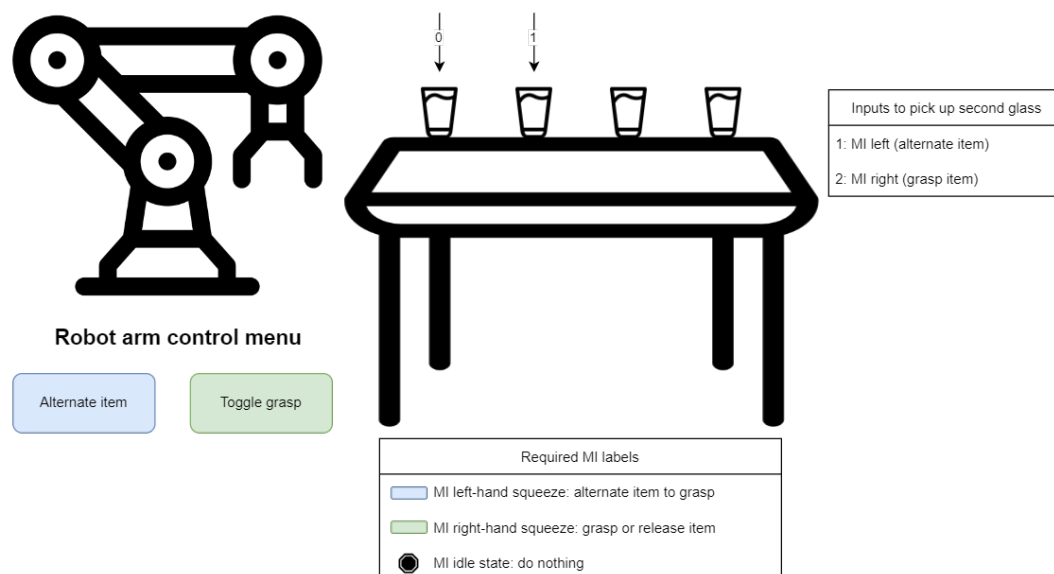
Cong Wang et al. (2011) use comparable reasoning to propose a MI-based BCI system to control a robot arm. Cong Wang et al. (2011) use only three distinct MI classifications: imagined right-hand movement, imagined left-hand movement and imagined foot movement. These three controls enable the user to select eight different possible actions through a menu where two options are always shown that can be controlled using either an imagined left-hand movement or an imagined right-hand movement. Scrolling through the menu to show two other possible actions is possible through the imagined foot movement. This shows that with the right system design, few controls can still allow for many actions to be taken. However, they lack a detection of the idle state. This is possible by determining the idle state based on the certainty of the model that a certain prediction is correct. If the model is uncertain, it is likely the user wasn’t performing any of the MI tasks and thus the system should not do anything.

1.4.3 The potential of an AutoML variant for BCI pipelines

People that are first introduced to machine learning (ML) and especially deep learning (DL) might think that these techniques provide a *one-click solution* for data classification. Whilst in some cases, re-using existing complex DL methods can give satisfying results when providing it with enough training data, creating high-quality ML and DL systems still requires a lot of human expertise. However, attempts are being made at providing such one-click solutions through a process called automated machine learning (AutoML), which is reviewed in detail by He et al. (2021). The idea behind AutoML is self-explanatory. Rather than having an expert design a ML pipeline, an automated system tries all sorts of combinations for a pipeline based on provided



(a) A BCI system that offers complete control over a robotic arm but with poor efficiency.



(b) A BCI system that offers limited control over a robotic arm but with great efficiency.

Figure 1.8: The contrast between mappings of MI EEG for controlling a robotic arm to grasp an item. One approach allows for full control but requires four MI classes and many steps. One approach offers less control but succeeds in the task with three MI classes and very few steps.

labelled data and perhaps some general preferences in techniques to be tested. The problem then boils down to an optimisation problem where the combination of fine-tuned components that maximizes a certain metric such as accuracy on test data has to be found. AutoML facilities have not yet been made for BCI specific pipelines, but with Google providing AutoML as part of their cloud infrastructure for computer-vision, the AutoML idea is becoming more and more popular (Dillen et al., 2022).

One library to develop a complete BCI pipeline

When taking into account the discussed literature so far, it is clear that many techniques for each component of the BCI pipeline already exist and that certain combinations have proven to be very successful. With more and more of these components being provided through open-source libraries as discussed in Section 1.2.4, it is not unreasonable to think that an AutoML library for BCI pipelines might be introduced in the future. If done right, this pipeline can set standards for the expected output of each component meaning that newly proposed components can be directly provided to the framework by the author of that new component. Whilst this would require a lot of commitment from the authors in the field, it could lead to newly gained insight on uncommon component combinations that provide a pipeline which performs best for certain problems. Such a framework would also enable new research to re-use existing components much faster as they would ideally all be present in the library with some form of a standardized output.

As this library would require a lot of maintenance, it should be provided by a team that has sufficient resources on maintaining it and updating it to support newer techniques in the field. Whilst there is currently no big organisation in the field that is likely to take this task upon themselves, the rise in popularity might attract such big corporations.

One library to develop multiple variants of one component from the BCI pipeline

Besides aiming to provide a complete pipeline, a library that focuses on providing all alternatives of one component following a specific standard would already be incredibly handy. Take for example a library that provides all open-source BCI datasets from one singular library, with all of the datasets following a specific standard. This would allow for testing a model on a whole suite of BCI data, such as MI EEG, and thus make it easier to compare results with existing literature as these would also use datasets from this common library. This has already been proven possible in other fields. For example, in reinforcement learning (RL), the environments used for training, which could be seen as the training data, are often environments provided by the OpenAI Gym library (Brockman et al., 2016). This library is maintained by OpenAI, a big company interested in RL among other AI techniques. Due to its popularity, many other authors contribute to this open-source library by providing their custom environments in a format that is directly supported by the OpenAI Gym library. A similar system for providing all sorts of BCI data would be incredibly helpful for the field of BCI research. It could also cause a chain reaction, with the introduction of other libraries that include state-of-the-art classification algorithms which work directly with this common data-providing library. This is also the case in the RL field with libraries providing algorithms for these mentioned Gym environments (Liang et al., 2017; Weng et al., 2021). Thus, providing such a library as the first step to an AutoML revolution in the BCI field might be a good idea.

1.4.4 A lack of standardized testing and reporting

The evaluation and comparison of different BCI systems is not an easy task. This is in part due to the many components a BCI system consists of, making direct comparisons often impossible.

Is comparing the performance of a classification model from a BCI system that works with dry electrodes in a real-world setting to one that works with data from medical equipment in a lab environment fair? Is it fair to compare traditional two-step ML approaches that have great explainability and interpretability with black-box one-step DL approaches? Many more of these questions exist and they remain mainly unsolved for the BCI field.

The issue with individually evaluating BCI pipeline components

One potential approach is evaluating each component of the BCI system individually. However, whilst these may make comparisons between the different components easier, these individual metrics don't tell the whole story for the complete system. To truly test the capabilities of a proposed BCI system in the real world, intensive user studies should be performed. Even in its simplest form, such a user study should validate if the BCI system succeeds in its advertised tasks in both a timely and reliable manner that is pleasant to use for the target audience (Dillen et al., 2022). It should also be compared to existing solutions to ensure that there is an added benefit compared to these alternatives for the user. To avoid biases, these user studies should not only include enough participants but the participant group should also be heterogeneous.

Doing even the most primitive version of such a user study takes significant resources to perform. As such, it is rather uncommon to see these user studies in the same paper that proposes a BCI system. Initial articles of a new proposed BCI system often focus on providing only objective evaluation metrics of the classification system. These objective measures include accuracy, sensitivity and specificity. Simple proof of concept (POC) experiments are sometimes also included in these initial articles but these are tested only on a small group of participants, which are often not from the target audience. The earlier discussed system by Halder et al. (2018) was user tested on able-bodied participants whilst the target audience was not. As discussed in Section 1.3.4, this study gave promising results while a comparable system tested for a person in the target audience found that the user wasn't interested in using the proposed BCI system as existing solutions were more pleasant to use (Käthner et al., 2015). Some of the articles included in the review by Dillen et al. (2022) also performed user tests on participants that are not part of the target audience. However, with many current BCI systems focusing on providing systems for medical purposes, finding enough participants from the target audience to form a heterogeneous group can be challenging.

Proposing a complete BCI system throughout at least four articles

The above-mentioned points make the author of this master thesis believe that the development of a BCI system should take place over at least four separate articles. The first article should focus on data acquisition. It should discuss the equipment used for recording the brain signals. It should also address which kind of brain signals are extracted and where they are expected to originate from on an anatomical level. The exact procedure used for effective data collection should also be detailed. This includes details on what participants are included, if there were surveys used to test their capabilities both before or after the experiments, if the participants were trained, how many trials over which periods were performed per participant and much more. Such an article may contribute to the field by providing an open-source dataset, describing a novel training technique, discussing a more user-friendly data collection procedure, proposing new hardware and more. What kind of evaluation should be done in this type of article depends mainly on what the contribution of the article is. When proposing completely new hardware, a comparison between comparable hardware may be done in the same manner as Zerafa et al. (2018) compared different consumer-grade EEG headsets. When testing a new training procedure, the data may be fitted to a common classifier to compare its learnability with the data of participants

that followed a different training procedure. Discussing all possible evaluation metrics falls outside the scope of this master thesis, but the most important factor is discussing the exact data acquisition process, as important details such as if live feedback was used often lack in existing work providing open-source datasets.

A second article should focus on the classification pipeline. It can contribute by proposing a novel combination of existing pipeline components or completely new components altogether. The type of components such a pipeline has and the evaluation that can be done will be discussed in detail in Chapter 3. These articles will make use of the data from the first article on data acquisition and should thus briefly summarize the used dataset. The experiments that will be done in this master thesis relate mainly to this type of article.

A third article should focus on linking this system to an external device such as a robot arm. This might involve changes to the classification pipelines, especially in the cutoff values for specific classes. Rather than optimizing global accuracy, it might be preferred to tune the system such that it makes more, but predictable errors. To illustrate this, a pipeline might be tuned such that it has a high true positive rate and a low false positive rate for actions that have significant risk. This means that when these actions with certain risks are performed, the system is almost certain the classification was correct. Doing this will make more false classifications for the other classes, but if these classes are neutral classes that don't perform actions, it has less risk associated. This corresponds to preferring a BCI for biosignal control over a robot arm that has a global accuracy of only 80% but makes almost all of its errors in not moving when movement was desired over one that has 85% global accuracy but has most errors in it moving when no movement was desired. The focus of this article is not on obtaining the best classification metrics anymore but rather on providing the safest and most predictable system that is still useful. This third article might perform a simple POC to validate that the desired action taking is possible, even if this is only tested for best-case scenarios. It can contribute to the field by proposing more intuitive interaction methods, a new form or external device, a clever way of boosting reliability and predictability and more.

A fourth article should then focus on an in-depth user study with a heterogeneous group from the target audience. Ideally, this study should be performed over multiple sessions to study long-term impacts on the user's life, including an idea of the public acceptance of the proposed system. It should review all previous articles and is likely to require most resources, but is also the most important for bringing the proposed BCI to the real world. It contributes to the field by addressing the good and bad points of a proposed BCI system being used in the real world. It may highlight points that went undetected in the previous articles.

Comparing these different articles

Some metrics for comparing each type of article with each other were named in this section already. However, standardized tests should be introduced to fully ensure comparability between results and that a correct evaluation is done in each article. These are not yet present in the BCI field and proposing them is a difficult task as the proposing authors should be respected so that other authors are even willing to accept their proposals. It is also not easy to propose testing and reporting standards that fit all variants of these proposed articles. Do you train the models on a single patient and test them on the same patient or do you test for generalisability? Do you allow it to run on very capable hardware or limited but very affordable hardware? It should be apparent that there is no straightforward way of proposing standardized testing and reporting for all variants of these articles.

This master thesis only aims to highlight these issues as solving them is an open issue and standardized methods would need the consensus of the field, which a master thesis is unlikely

to obtain. For now, creating at least four different papers to propose a complete BCI system and focusing on being as transparent as possible in each is already a good step in the right direction. However, transparency lacks in many papers, albeit due to page constraints or a lack of standardized reporting. Providing the source code with additional notes through an external source such as GitHub may help combat the page constraint issue. Following guidelines from related fields such as PROCAST (Wolff et al., 2019) and TRIPOD (Collins et al., 2015) originally proposed for CADx and CADe research can help in determining a new reporting standard for BCI research. Such a reporting standard will also aid in the repeatability and reproducibility of articles, especially for those where sharing the source code and data is not possible.

1.4.5 Challenges from the highly interdisciplinary nature of BCI systems

The idea of splitting the development of a complete BCI system into at least four separate articles discussed in Section 1.4.4 can also help with the challenges that the highly interdisciplinary nature of BCI systems offers. This is because each of those articles limits itself to a couple of domains rather than all domains present in BCI research. In practice, many articles aim to provide a system that is as complete as possible but this results in a system where many components, that fall outside the knowledge domain of the authors, are adopted from previous literature providing little to no scientific value.

Disciplines needed for each of the four proposed articles

When taking into account the four separate articles needed for proposing a complete BCI system proposed in Section 1.4.4, the following experts may be required. For the data acquisition article, a neuroscientist can greatly improve the value of the article by understanding in detail what brain signals can be measured and what interpretation they may have. They can also help in determining the optimal placement of the electrodes based on the anatomy of the brain and the expected source of the signal of interest. To create the hardware for the headset that captures the wanted brain signals, e.g. an EEG headset, engineers capable of reliably measuring and transmitting these incredibly low voltage and noisy signals are needed. A graphical designer can help with making the headset aesthetically acceptable.

The article related to data classification can be done mainly by a computer scientist specialised in machine learning (ML). However, when making visualisations and features, knowledge from neuroscience may still be needed. Because of this, a neuroscientist may still be very helpful for this article. Likewise, whilst a computer scientist may be able to reduce noise in a software manner, having an understanding of how the headset works and what types of noise and artefacts can be expected is also incredibly helpful. Whilst a well-documented data acquisition article may cover all these points, some aid from engineers in understanding the headset hardware can still be helpful.

For the third article, where the connection to an external device is discussed, a wide variety of experts may be required. For example, the previously discussed robotic arm with example menu's shown in Figure 1.8 requires computer vision knowledge for grasp detection, engineering knowledge to make the robot arm and general computer science knowledge to create a working link between classification labels and action controls. A graphical designer may once again help with making the external device aesthetically acceptable. General user experience (UX) knowledge can help in creating a great mapping between the detected brain signals and the control over the external device.

The fourth article may require all previous experts to finetune and configure the system.

Since these trials involve human participants and often people suffering from a handicap, an ethics expert should also be consulted. Adding to this, by surveying the users in a manner that truly captures the UX and net benefits, both a psychologist and an expert of comparable systems may be needed. These discussed experts may vary greatly based on the type of BCI system that is proposed.

The issue with wanting to propose a complete system directly

The idea of proposing a BCI system as a result of four articles is proposed in this master thesis and is currently not present in the field. Whilst some researchers do focus on some components of a BCI system only, in the same spirit the division in multiple articles would do, most researchers aim to also propose a complete working BCI system in terms of a proof of concept (POC). Take for example the BCI system proposed by Herath and de Mel (2021). It has a significantly sophisticated robotic hand that functions almost completely as a human hand does. The effective hardware used for the complete BCI system, including the processing unit, are also well detailed. This shows that the authors have a significant understanding of the hardware a BCI system requires. However, the methodology used for data acquisition, the used classification algorithms and the user interface to the external system as proposed by Herath and de Mel (2021) could benefit from improvements. Since this is mostly a straight copy of existing methods and models not optimized to their proposed BCI system, one could argue they have little scientific value. The simple POC experiments are also of low value as discussed in Section 1.4.4. This means that these added components to create a POC, which take significant time, have a limited scientific value. This is by no means a criticism to Herath and de Mel (2021) but demonstrates the interdisciplinary nature of BCI systems and how researchers that are specialized in one of these disciplines will outperform certain aspects of a BCI system while leaving room for improvement in other aspects. This interdisciplinary nature of the BCI field is part of what makes it so fascinating yet also very sophisticated with a steep learning curve. The above-proposed idea of splitting the development of a complete BCI system into multiple papers could limit the amount of time put into creating components that fall outside the scope of expertise and thus have less value in the article.

1.4.6 Brain signals are a complex data source

The human brain is an incredibly complex system of billions of neurons and trillions of synapses. Whilst great efforts are being made in mapping all of these neurons and synapses, faster than predicted, a complete mapping remains unavailable. The lack of such a complete mapping directly implies that research is unable to simulate the brain in silico. It also implies that there are still many unknowns in the complete structure of the brain and its internal working. Hodson (2019) talks about the efforts in mapping the brain and the many unknowns still present in the working of the brain in more detail. This limited understanding of the brain makes it a highly complex source of data, even when working with well-understood brain signals.

The most difficulties in using brain signals as a data source arise from the fact that the brain is a dynamic, nonstationary and non-linear system (Abdulkader et al., 2015). Non-linearity is a common challenge in many research fields and many ML and DL models can work with non-linearly correlated data. However, the dynamic and nonstationary nature of brain signals is less common in applications of ML and DL. Intuitively, this dynamic and nonstationary property results in measurements that can differ greatly for the same patient during the same trial doing the same task. For example, an envisioned MI task of the right-hand movement can be repeated by the user multiple times. However, the user's mental and emotional state, their focus and fatigue levels and many other aspects that will influence the brain signals will change continuously.

Both due to the limited spatial resolution of measuring modalities and our limited knowledge of the brain, it is impossible to measure the wanted brain signal without measuring any other brain activity. Thus, this change in the brain activity that is not of interest makes the measurements nonstationary and dynamic, making the learning task significantly harder and more complex.

Adding to this, neuroplasticity, which was already discussed in Section 1.3.1, can change the structure and working of the brain. This makes the brain even more dynamic. Adding to what could be seen as internal noise factors of the brain, external noise can also be present in a nonstationary and dynamic manner. This external noise includes common artifacts such as electrical interference and the detection of EMG, which will be discussed in more detail in Section 2.4.4.

All of these factors already makes brain signals an incredibly complex data source for ML and DL, as is used in BCI systems. The limited knowledge of the brain's inner working and the dynamic, nonstationary and noisy nature of brain signal measurements also challenges the explainability and interpretability of these signals. This issue of explainability and interpretability is further discussed in Section 3.5.3. Besides these factors, brain measurements are far harder to collect resulting in an often very limited amount of training data (Abdulkader et al., 2015). This makes many of the techniques used in fields where gigantic datasets are available, unapplicable for BCI research. Take for example the EEG MI dataset by Kaya et al. (2018), which is one of the largest publicly available datasets of this type. This dataset by Kaya et al. (2018) has around 60 000 combined usable samples over many different MI tasks and paradigms. Taking into account that only a subset of these samples can be used for training, this collection is multiple orders of magnitude smaller than datasets from other ML and DL applications. Take for example the commonly used ImageNet dataset by Deng et al. (2009) which contains over 3 000 000 images for training an image recognition classifier. The high dimensional and time-dependent nature of brain measurements also makes it harder to re-use common ML and DL approaches from other fields.

1.5 Ethical challenges for BCIs

The field of brain-computer interfaces (BCIs) has many promising aspects, with Sections 1.2, 1.3 and 1.4 discussing the rise in popularity, the growing amount of use cases for BCI systems and some of the opportunities in the field. These evolutions in the field have made BCIs present in more than just research labs (Abdulkader et al., 2015; Bernal et al., 2021). Widespread adoption of BCI systems is still unlikely in its current state, with some obstacles that need to be overcome first. This relates to creating a system that fits Wolpaw's definition of a perfect BCI and overcoming at least the challenges discussed in Section 1.4. However, with the recent news coverage of the Elon Musk company Neuralink (Musk & Neuralink, 2019), discussed in Section 1.2.1, it has become clear that ethical challenges might be tougher to overcome than technical ones. Even if Wolpaw's vision of a perfect BCI can be met and a net benefit to the user has been proven, some users' moral intuition may refrain them from using such a system.

Whilst the author of this master thesis is by no means an ethics expert, he believes that it is important for any researcher interested in the BCI field to be aware of some of the many ethical challenges BCIs have. This section aims to illustrate what kinds of ethical challenges are related to BCI research and how there is no clear solution for them. The interested reader is invited to consult the interesting articles on the ethics of BCIs by Drew (2019) and Bernal et al. (2021) for a more in depth ethical study. Some articles have also been made focusing solely on ethical questions surrounding the Neuralink proposed BCI (Dadia & Greenbaum, 2019; Jawad, 2020).

1.5.1 Painfully confronting users with their brain

When a BCI system is used by patients suffering from a brain disorder, it is easy for the user to be confronted with their disorder by that system. Take for example an invasive medical BCI used to predict when an epileptic seizure would occur such that it can alert the user to take the right medication to prevent the seizure from occurring. Each time the system alerts the user, the user is confronted with the fact that they have epilepsy and a potential epileptic seizure coming. Gilbert et al. (2019) performed a clinical trial on six users suffering from epilepsy that use such a BCI system. Whilst positive results in seizure reduction were found for all patients using the system, the user experience (UX) differs greatly between all six participants.

From all six patients, four expressed how they felt more in control of their daily life thanks to the system. They reported a pleasant overall experience with the system. Another patient, *patient four*, expressed that he saw epilepsy as part of his life and himself. As a result, he wasn't interested in being dependent on the BCI system to warn him and ignored it most of the time. More worryingly, *patient three* said the following:

[The BCI] made me feel I had no control. So I didn't have control over what I was going to do. [...] It made me feel that I was always different [from] everyone not just in the moment of the seizure [...] I got really depressed

Patient three from the study by Gilbert et al. (2019)

Being aware that the system was constantly monitoring her brain activity and an alert could be sent at any time, the patient felt *different to everyone else* all of the time, whilst without the system, this feeling was only present when a seizure occurred. The BCI system constantly reminded her that she has a brain condition which had a significant psychological burden. Whilst this is only the experience of one patient from a small trial, it was an important finding that has given many ethicists reason to question the use of BCI systems for all patients (Drew, 2019). It is not unreasonable to think that similar feelings might occur when using BCIs for neurological rehabilitation through neuroplasticity, a use case discussed in Section 1.3.1. Neuroplasticity may take a long time or even be impossible for some users. Having constant feedback that shows no or poor progress can be very confronting for the user. Even in commercial settings, when a person tries to calibrate a headset relying on MI tasks and the calibration fails due to the user being poor in envisioning the MI task, a feeling of *lacking this capability compared to others* might cause a dramatic UX. This poor UX for certain users is something that can only be found with thorough trials and further shows how important it is to do real-world experiments.

1.5.2 E-waste inside your skull

Section 1.3.2 already addressed Second Sight, one of few companies providing visual prostheses with approval from the FDA. This company discontinued support for some of its earlier visual prostheses. This resulted in all of the users from those early products losing any form of support. As discussed by Strickland and Harris (2022), this has major consequences. First, the technology that has enabled them to restore their vision to a certain extent can fail at any time. If this happens, this results in an indefinite loss of vision again due to the lack of support. Second, the company refuses to make the required data for the maintenance of the system public. This means that no third party can ever work on it. Third, due to no third party being capable of removing the system, the users are essentially stuck with what is or will become e-waste inside their skull. This has already caused major issues for one user, Ross Doerr. As discussed by Strickland and Harris (2022), Ross can't get the help he needs with a brain tumour due to doctors not having

the required information about the brain implant to ensure a safe operation. Even a simple magnetic resonance imaging (MRI) scan can't be planned safely due to this lack of information surrounding the brain implant.

With commercial companies showing interest in invasive BCIs, such as the earlier discussed Elon Musk company Neuralink, it is not unreasonable to think a similar situation might occur from the manufacturer of such systems. What happens to an invasive BCI system once the manufacturer doesn't support it anymore or the patient isn't interested in using it anymore? It becomes clear that some form of regulations should be in place to ensure that users of such invasive systems are always able to get the information needed from the manufacturer to ensure they are not restricted in getting needed care. It also begs the question if invasive BCIs is really the road to go and how dependent we want to be on these technologies, taking into account they might fail for an unspecified period at some point.

1.5.3 Changing peoples personal identities

Section 1.5.1 already addressed the trial conducted by Gilbert et al. (2019). In this trial, six patients suffering from epilepsy using an invasive BCI for epileptic seizure reduction were monitored over a long period. Besides the finding of extreme psychological burden for one patient, the following words from *patient six* are also eye-opening:

[The BCI] was me, it became me. [...] I found myself changing. [...] I felt like I could do anything. [...] With this device, I found myself.

Patient six from the study by Gilbert et al. (2019)

Whilst this is a positive experience according to the user, Gilbert et al. (2019) described this as a radical symbiosis between the patient and the system. The idea of users feeling themselves becoming one with technology, creating a symbiosis, has multiple ethical concerns (Drew, 2019). These concerns fall outside the scope of this small ethical discussion on BCIs. However, this change of personality is something that can influence the patient's life in a manner that perhaps wasn't initially expected. For example, when someone goes through major weight loss, they have more chance to see a marital status change. Both in terms of getting married or having a divorce (King et al., 2022). Similar trends might occur due to behaviour changes as a consequence of having a BCI.

Likewise, some people that suffer from a medical condition might embrace their condition and share some sort of culture with people that have the same condition. People suffering from major hearing loss may enjoy parties oriented toward them where bass-heavy music is played at loud volumes such that they can feel the vibrations of the music throughout their body. For them, this is how they can enjoy music without hearing music. If such a person were to regain hearing through a BCI, it is unlikely they will enjoy hearing the loud and constant bass. Similarly, people suffering from major vision impairment might enjoy tactile art. When vision is restored, their impressions of these kinds of artworks are bound to change.

In both of these situations, the interest in the events they once liked might faint and the connection to the community surrounding them might vanish. They lose touch with the *community they were once part of* (i.e. the blind and deaf community). These are things that might go unthought of when looking at the added benefits of a BCI system might offer. However, they can cause major identity issues where users are left in a quest of finding who they are after a major change in their daily life. This quest is one that not many look forward to doing and maybe a reason some people opt to not use a BCI system.

1.5.4 A great risk of sloppy science

With a lack of standardized testing and reporting as discussed in Section 1.4.4, it is easy for researchers to perform *sloppy science*. It allows them to report and compare only those metrics that have the desired outcomes rather than performing time-consuming user trials that have the most scientific value. With many authors wanting to propose complete systems over singular components, the risk of sloppy science is increased even further as the other components are highly likely to receive less thought resulting in poorer quality, as discussed in Section 1.4.5. However, respected journals have appropriate mechanisms in place, such as peer reviews, to stop published articles from performing sloppy science.

More worryingly, private companies aiming to commercialise their BCI systems as soon as possible are less subject to these mechanisms of protecting against sloppy science. Willingham (2021) expresses some of her concerns with Elon Musk’s Neuralink company in this regard. Willingham (2021) refers to an interview with ex-employees by Brodwin and Robbins (2020). In that interview, it is discussed how more than half of the initial researchers have left the Neuralink company already and how these ex-employees experienced a rushed timeline which wasn’t compatible with the slow pace of science. This led to multiple internal discussions between the initial researchers wanting more time and shareholders wanting a sellable product quickly. Whilst these ex-employees were also quick to state that they see Neuralink as an incredibly innovative company in the BCI field and believe they will succeed in their mission, these words about a rushed timeline are worrying. As discussed in Section 1.4.4, thorough experiments take a lot of time, so it isn’t surprising that this isn’t compatible with a commercial aim of providing a product to market as soon as possible. However, when considering that Neuralink’s proposed system is an invasive one and the ethical questions about e-waste in your brain discussed in Section 1.5.2, the worry of such companies performing sloppy science to be among the first on the market only grows. Whilst some legislations are in place that should ensure safe human trials, only time will tell how much these commercial companies respect the time-consuming nature of research.

1.5.5 Advertisements based on your thoughts

Big tech companies such as Meta, formerly known as Facebook, aren’t known for respecting the privacy of their users and protecting their data (Fuller, 2019; Hu, 2020). Besides multiple court cases, the European Union (EU) and individual governments have made multiple efforts to protect their citizens against the malicious use of their data. This includes legislations such as the general data protection regulation (GDPR). Whilst this is great, it hasn’t stopped companies from continuing their excessive data mining to sell it to advertisement companies. As discussed by S. Lee (2020), the advertisement industry functions more or less the same since the introduction of the GDPR. Advertisement companies are still able to purchase a lot of personal and sensitive data from users to use for targeted ads. The only real difference for users is that they are now presented with ambiguous popups and opt-in data sharing they have to accept to enjoy all available content a company offers. In many of these cases, the user isn’t aware of what they are accepting, and the user protection that the GDPR tries to offer gets lost.

With Meta having shown interest in BCIs and Steam, a marketplace for games, showing interest in integrating a BCI with a VR headset, the question remains how these companies will use the acquired brain signals. If they process them in the cloud, it is a necessity that the acquired signals are transferred to their servers and the risk of data leaking and other scandals increases. It is also expected for these companies to have long, complex and ambiguous terms of service (ToS). This could be paired with the previously mentioned opt-in data processing agreements that have to be accepted to use all functionalities of their product or which are designed in such

a way that it is hard to not opt-in for them. This raises the question if it is desired that a commercially oriented company, which makes a large amount of money from selling user data, sells BCI systems. New legislations are likely required to limit the amount of processing that can be done on acquired brain signals, even if consent is given that the data may be used by the company to *improve their services*.

1.5.6 Hacking BCI systems

It is impossible to fully protect any system against hacking, hijacking or any other malignant use. Locks can be picked, databases can be breached, Bluetooth (BT) connections can be spoofed and even the most secure encryption algorithms are prone to hacking (Castelvecchi, 2022). Martínez Beltrán et al. (2022) have shown that an EEG based BCI working with P300 signals can be hacked by generating fake P300 waves from an external device. These generated waves are recorded similar to other electrical interference, such as the typical 50Hz or 60Hz alternating current (AC) interference, but the processing algorithms see them as effective P300 signals and thus the system is now controlled by those artificially generated waves rather than the user's brain signals.

More traditional hacks such as BT spoofing can also be performed when BT is used in a wireless BCI. Even if the data transmitted over BT is encrypted, flaws in the encryption methodology may be found that enable hackers to decrypt the encrypted data. Whilst none of this is exclusive to BCI systems, it is something that raises ethical questions. If BCIs are ever used for controlling many devices, some having certain risks, the hacking of these BCI devices can impose fatal consequences. Will all companies put in the required resources and effort to protect their BCI systems from malignant attacks?

1.6 Chapter conclusions and system proposal

NOTE: this will be edited once the thesis is "finished"

This first chapter gave an in-depth but intuitive introduction to brain-computer interfaces (BCIs). Section 1.2 discussed the growing scientific and commercial interest in BCIs. Sections 1.3 and 1.4 provided some more insight on the common use cases for BCIs and some of the opportunities and obstacles for BCI research. This chapter ended by addressing some ethical challenges any researcher interested in BCIs should be aware of. Throughout this chapter, many articles were discussed and some strong points and weak points were explicitly mentioned. Many of the discussed BCI systems were also compared to Wolpaw's definition of a perfect BCI given in Section 1.1.

From this chapter, it should become clear that BCI research has grown and matured significantly over the last few years. Positive human trials have been performed showing that BCIs can improve the quality of life for people with certain medical conditions. However, many systems can still see improvement and it is incredibly hard to meet Wolpaw's definition of a perfect BCI. This is great news for researchers interested in the field, as it means that there is still a lot of work that can be done. Some of the biggest current challenges with BCIs lie in the fact that the amount of open-source data and code-providing libraries is rather limited and that there is no standardized way of testing and reporting on a BCI system. It was also discussed that BCI research is highly interdisciplinary which makes it hard for individual authors or authors from the same expertise domain to provide a complete BCI system. To tackle some of these challenges, Section 1.4.4 proposed that the proposal of a complete BCI system should happen over at least four different papers. In order, they should focus on data acquisition, data classification,

connecting the classifier to an external device and testing the whole system in a thorough human trial.

Since this master thesis is from a computer science student, the following chapters will focus on what is important for a computer science student that wants to contribute to this field. The remainder of Part I will provide some more general BCI knowledge required to fully provide an article on the data processing of a BCI system. To do this, Chapter 2 will discuss in greater detail what biomedical signals (biosignals) such as brain signals are, where they originate from and how they can be measured. With a deeper understanding of what EEG data is, Chapter 3 discusses in greater detail how they can be processed. All of the components from a common BCI pipeline are discussed and some examples of these components are given. Alternatives to this common BCI pipeline are also discussed together with the role of ML and DL and some of the issues that often arise when creating classifiers for these systems.

The next part, Part II puts this theory to practice by discussing the development of multiple BCI pipelines. This includes the implementation of state-of-the-art two-step ML approaches and one-step DL approaches. Whilst focusing on an offline BCI system in Chapter 4, the required steps to go to an online system are discussed in Chapter 5. The implemented system makes use of existing EEG data from multiple MI tasks for classification. All of the implemented variants of the BCI pipeline are compared and the results of this master thesis are further discussed in Part III, the final part.

Chapter 2

Origins and acquisition of biomedical signals

2.1 Introduction to this chapter

Whilst Chapter 1 has provided an in-depth intuitive introduction to brain-computer interfaces (BCIs), some more technical aspects need addressing as well to provide a computer scientist with all of the required foundational knowledge for BCI research. This chapter provides the required technical knowledge on the data that BCI systems use, brain signals. Brain signals are only one of the many types of biomedical signal (biosignal) present in the human body. Whilst from a computer scientist's perspective brain signals may just be another type of input data to a classification model, having at least a basic understanding of this data is crucial in making good classification algorithms for BCI systems. Even when using deep learning (DL) approaches where no manual feature engineering has to be done and where basic models without much thought may have pleasing results, understanding the data will allow for the creation of better models. This understanding of the data also helps in troubleshooting why some models may not have the desired results.

To provide this basic understanding, this chapter starts by briefly discussing biosignals in general. It is discussed what biosignals are and where they originate from in the human body. After this general discussion on biosignals, a focus is put on the different biosignals from the human brain, with brain signals measured using electroencephalography (EEG) in particular. This EEG measuring technique and other measuring techniques are also discussed in greater detail. Whilst it is addressed that EEG has some fundamental shortcomings over other measuring modalities, it also has some attractive properties over these alternatives. These attractive properties are listed and provide an argument as to why the remainder of this master thesis will focus on EEG and motor imagery (MI) EEG in particular.

2.2 Biosignals in the human body

In theory, a biosignals is nothing more than a measurement over time of a living being. In practice, these biosignals are closely related to physiological processes. This makes it possible to monitor or detect those physiological processes using biosignals. Biosignals can be produced by different energy forms, such as the electrical energy form when measuring EEG in microvolts (μV). Table 2.1 summarizes some of these energy forms and which type of biosignals they can

Energy form	Variable type	Biosignals
Chemical	Chemical activity and/or concentration	Blood ions, O ₂ , CO ₂ , pH, hormonal concentrations, and other chemistry
Mechanical	Position, force, torque or pressure	Muscle movement or cardiovascular pressures, muscle contractility, valve and other cardiac sounds
Electrical	Voltage or current	EEG, ECG, EMG, EOG, ERG, EGG, GSR and EDA
Thermal	Temperature	Body temperature and thermography

Table 2.1: Some of the different energy forms in living beings and the measurable biosignals they produce. Data from Semmlow (2018).

produce. Whilst living beings, including humans, produce many different types of biosignals, this master thesis will only consider time-varying electrical biosignals. These types of biosignals, sometimes referred to as electrical biomedical signals (bioelectrical signals), are the ones used as input data for BCI systems. Semmlow (2018) discusses these and other types of biosignals in greater detail.

2.2.1 How the human body produces electricity

Electricity in the human body, better known as bioelectricity, can be seen as the generation or action of tiny electric currents and voltages in physiological processes. As shown in Table 2.1, the measurement of this bioelectricity is what enables the monitoring of bioelectrical signals. This is one of the reasons biosignals are closely related to physiological processes since it measures the bioelectricity used in some of these processes. A complete understanding of how bioelectricity is made, maintained and transmitted in the human body isn't required for a computer scientist to contribute to the BCI field. However, a superficial understanding of this process makes it easier to understand the limits of the accompanied bioelectrical signals. For this reason, the remainder of this section gives a simplified explanation of how bioelectricity is made, maintained and transmitted in the human brain. This explanation is based on chapter 12 of the recently renewed book by Betts et al. (2022), an EEG focused explanation of bioelectricity by Kirschstein and Köhling (2009) and multiple YouTube videos by Neuroscientifically Challenged¹²³.

Resting membrane potential causes negatively charged neurons

As was already addressed in Section 1.2.2, the human brain has billions of neurons with Nunez and Cutillo (1995) stating that around 10^7 parallel pyramidal neurons reside in only a single cm^3 of the brain cortex alone. A neuron, also known as a nerve cell, is an electrically excitable cell. Being an electrically excitable cell, a neuron has a resting membrane potential. This resting membrane potential is around -70 millivolts (mv) and expresses the difference in electrical charge

¹<https://youtu.be/tIzF2tWy6KI>

²https://youtu.be/W2hHt_PXe5o

³<https://youtu.be/WhowH0kb7n0>

between the inside and the outside of a neuron. This negative difference is maintained by the sodium-potassium pump which is responsible for the hydrolysis of ATP to ADP. During this hydrolysis process the sodium-potassium pump releases three positively charged sodium ions (Na^+) whilst only taking in two positively charged potassium ions (Ka^+), this difference causes the membrane potential to remain negative.

Action potential allows for neuron communication

Whilst the sodium-potassium pump inside the neuron explains why there is a negative resting membrane potential of around -70 mv, it doesn't explain the variable volt measurements of EEG. The change in membrane potential occurs when the neuron gets excited. The most common way a cell gets excited is through the process known as an action potential. An action potential forms the basis for electrical signalling within neurons, enabling some form of communication between them. To do this communication, neurotransmitters released by another neuron bind to receptors on the dendrites of the receiving neuron which has a depolarization effect.

This depolarization causes the neuron to become less polarized, resulting in its membrane potential moving close to zero. When sufficient depolarization occurs, the action potential process could start. This process is visualised in Figure 2.1. For the action potential process to start, the depolarization should be of such a magnitude that the neuron reaches its threshold membrane potential, which is around -55 mv. This is achieved through the repeated binding of neurotransmitters to the receptors. The annotation for "failed initiations" in Figure 2.1 denotes the common situations when the threshold membrane potential is not reached.

When the threshold is reached, a large number of sodium channels open, allowing many positive sodium ions (Na^+) into the neuron, causing the membrane potential to rise quickly. This depolarization is what creates the electrical signal known as the action potential that travels down the neuron to eventually release neurotransmitters itself. Eventually, a peak is reached, after which the sodium channels close, not allowing any further sodium ions (Na^+) to enter the neuron. To return to its resting membrane potential, the neuron opens its potassium channels to release many potassium ions (Ka^+). This is known as the falling phase where the neuron repolarizes. However, the release of positive potassium ions (Ka^+) happens so quickly that the membrane potential falls below the resting membrane potential. The neuron is now hyperpolarized, denoted as undershoot in Figure 2.1. During this hyperpolarized state, also known as the refractory period, failed initiations occur more often as it is very difficult to fire the neuron again. Eventually, the resting membrane potential is reached again and the neuron functions like before.

EEG measures postsynaptic potentials

Whilst the action potential explains how most changes in membrane potential of an individual neuron occur, it is highly unlikely to be measured by EEG and other measuring modalities. This follows from the fact that, as discussed earlier, many billion neurons make up the brain making it impossible to monitor a singular neuron. Since action potentials are such rapid current flows, it is highly unlikely enough neighbouring neurons will have an action potential at the same time resulting in a measurable signal. However, whilst it was discussed how neurotransmitters can cause depolarization which can initialize action potentials, these neurotransmitters can also influence the membrane potential in the opposite direction by causing further polarization. The release of these neurotransmitters and the binding to the receiving neuron also causes currents known as postsynaptic potentials. Whilst these are not action potentials, they are essentially what causes an action potential to take place and the action potential can also cause the release of neurotransmitters. These postsynaptic potentials are present for a longer period than action

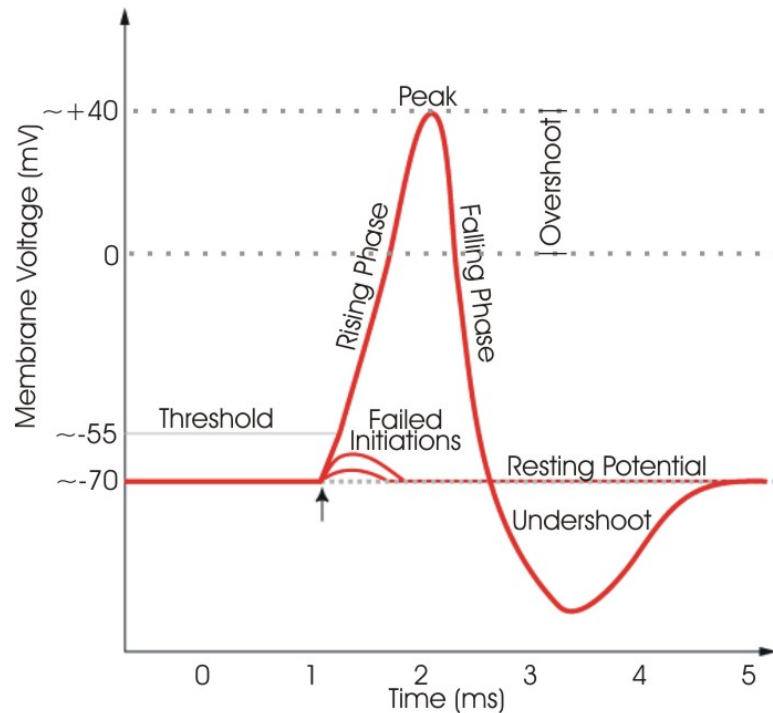


Figure 2.1: Chart of the membrane potential during the action potential process in a neuron. Figure from Synaptitude, GFDL 1.2, via Wikimedia Commons.

potentials. Thus, it is more likely for many neighbouring neurons to have active postsynaptic potentials simultaneously. The summation of these postsynaptic potential currents from many millions of neurons is what is detected by EEG. However, neurons experiencing action potential at that same time are among many other things sources of noise in this summation of these currents.

2.2.2 The function of bioelectricity in the human body

Bioelectricity is omnipresent in the human body. The human nervous system relies on bioelectricity to quickly carry *messages* from the human body to the brain and the other way around. The process of muscle contraction is started when action potentials, which are tiny bursts of bioelectricity, from motor neurons are transmitted to muscle fibres. Levin (2012) explains how bioelectricity even plays a crucial role in developmental biology. As discussed by Robinson et al. (2021), bioelectricity can even be *hijacked* as a way of novel medicine and treatment, i.e. for cancer treatment. Listing all of the uses for bioelectricity falls outside the scope of this master thesis but it should be apparent that bioelectricity is one of the more vital phenomena in the human body.

2.3 Biosignals in the human brain

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2.3.1 Anatomy of the brain

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2.3.2 Brain waves

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2.3.3 Common brain signal inducing methods

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MI is the process in which a person generates brain-activity in the motor cortex merely by imagining motor movements. MI-based BCIs are interesting because they don't require any external stimulus nor effective motor movements

event-related potentials (ERPs) and the measurable signals they produce, such as the P300 signal, are only one of many sources for detectable brain signals. In general, ERP related signals are easier to detect reliably, as the stimulus can be controlled, giving a hint when and where to look for signals and what to look for.

An alternative to ERPs is using a mental phenomenon called MI as source of signals for a BCI system. MI is the process in which a person generates brain activity in the motor cortex merely by imagining motor movements. Section 2.3.3 explains in further detail how MI is not dependent on an external stimuli nor actual motor movements. This makes MI-based BCIs extra appealing as they don't require external stimuli and are applicable for people with motor disabilities. Pfurtscheller et al. (1997) were the first to experiment with the idea of using MI in an EEG classification task. Since then, many MI-based BCIs have been proposed.

2.3.4 Generalisation issues of brain activity

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2.4 Measuring brain-signals

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Many comparisons between different types of measuring equipment, often with greatly differing costs, have already been made (David Hairston et al., 2014; McCrimmon et al., 2017; Nijboer et al., 2015; Pathirana et al., 2018; Ratti et al., 2017). The main consensus is that the cheaper consumer-grade equipment has the potential to reach similar performance of a conventional, often medical-grade, BCI system. These results are promising but due to the controlled nature of the experiments, they might not reflect real-life applications accurately. As discussed before, the user experience of a BCI system is as important if not more important than the raw performance of the system.

2.4.1 Measuring modalities

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Research by Berger (1929) is the first in describing the measurement of brain waves from the human skull in a non-invasive manner. Because of this, the German neuroscientist and psychiatrist Hans Berger is often seen as the inventor of EEG. Whilst he was one of the first to use the term *elektrenkephalogramm*, it was Richard Caton who first described the findings of brain waves in general. He found this phenomena in animal brains as early as 1875 (Haas, 2003). Since then, EEG methodology and equipment has matured and evolved a lot.

2.4.2 Standards for EEG measuring systems

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2.4.3 Comparison of available EEG measuring equipment

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2.4.4 Common EEG artefacts

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2.5 Motivation for using non-invasive MI EEG and chapter conclusions

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Chapter 3

Processing brain-signals and taking actions from their interpretation

3.1 Introduction to this chapter

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3.2 A general EEG-based BCI pipeline

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3.2.1 Data acquisition

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3.2.2 Preprocessing

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3.2.4 Feature engineering

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3.2.5 Classification model

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3.2.6 Performing an action

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3.2.7 Evaluating the classification system

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3.3 Alternative BCI pipelines

3.3.1 Using existing open-source data for training and testing

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3.3.2 Calibrating an existing system

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3.3.3 Neglecting preprocessing and feature engineering

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3.3.4 No action performing step

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3.3.5 Offline vs online BCI systems

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3.4 The role of machine learning and deep learning

3.4.1 Difference between traditional machine learning and deep learning

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3.4.2 Supervised, Semi-Supervised, Unsupervised, and Self-Supervised Learning

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3.4.3 Common regular machine learning classifiers

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3.4.4 Common deep learning classifiers

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3.5 Common issues when processing brain-signals and how to avoid them

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3.5.1 Biased data

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3.5.2 Incorrect or ambiguous evaluation

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3.5.3 No explainability or interpretability

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Deep learning (DL) often requires significant processing power and time to train, impacting the affordability of brain-computer interface (BCI) research. This is especially true when working with many electroencephalography (EEG) sensors and features, and thus a high dimensional setting. DL is often also used in a black-box principle. This means that the trained system lacks explainability and interpretability. Recent governmental reports have suggested that laws will be coming in place to require these properties (European Commission. Joint Research Centre., 2020; The Royal Society, 2019).

3.5.4 Overfitting

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3.6 Chapter conclusions

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Part II

Development of state-of-the-art motor imagery EEG classifiers

Chapter 4

EEG-based offline classification system for motor imagery tasks

4.1 Introduction to this chapter

TODO

4.2 CSP-based two-step ML approaches

TODO

4.2.1 Traditional CSP with LDA, SVM and RF

TODO

4.2.2 The issue with a traditional CSP approach

TODO

4.2.3 Improving traditional CSP

TODO

4.2.4 Common CSP extensions and alternatives for feature extraction

TODO

4.3 Convolutional-based one-step DL approaches

TODO

4.3.1 EEGNet

TODO

4.3.2 DeepConvNet

TODO

4.3.3 ShallowConvNet

TODO

4.3.4 Interpreting these black box models

TODO

4.4 (not sure) Adding memory to one-step DL approaches

TODO

4.4.1 (not sure) Using the time series property of EEG data

TODO

4.4.2 (not sure) LSTM and other recurrent neural networks

TODO

4.4.3 (not sure) Adding LSTM to XXX

TODO

4.5 Chapter conclusions

TODO

Chapter 5

Moving from an offline classification system toward an online BCI system

TODO

5.1 Introduction to this chapter

TODO

5.2 Common problems with going to an online BCI system

TODO

5.3 Realistic calibration procedure

TODO

5.4 Working with continuous data

TODO

5.4.1 Using a fixed timing for instructions

TODO

5.4.2 Sliding windows

TODO

5.5 Working with low computational power

TODO

5.6 Other required changes and chapter conclusions

TODO

Part III

Reflection on the results of this master thesis

Chapter 6

Evaluation of the proposed pipelines

TODO

6.1 Introduction to this chapter

TODO

6.2 Three class MI EEG data source

TODO

6.3 Intrasection evaluation

TODO

6.4 Intersession evaluation

TODO

6.5 Intersubject evaluation

TODO

6.6 Calibration evaluation

TODO

6.7 Comparing complexities

TODO

6.8 Expected results of moving to an online system

TODO

6.9 Chapter conclusions

TODO

Chapter 7

Self-reflection and conclusions

TODO

7.1 Introduction to this chapter

TODO

7.2 Real world usability of the obtained results

TODO

7.3 Added value of this master thesis

TODO

7.4 Future work

TODO

7.5 Final remarks and a personal endnote

TODO

List of abbreviations and acronyms

Symbols

μV microvolts.

A

AC alternating current.

AI artificial intelligence.

ALS amyotrophic lateral sclerosis.

ANN artificial neural network.

AR augmented reality.

AutoML automated machine learning.

B

BAIID breath alcohol ignition interlock device.

BBCI Berlin Brain-Computer Interface research program.

BCI brain-computer interface.

bioelectrical signals electrical biomedical signals.

biosignal biomedical signal.

biosignal control biological signal control.

BMI brain-machine interface.

BPNN back propagation neural network.

BT Bluetooth.

C

CADe computer-aided detection.

CADx computer-aided diagnosis.

CNN convolutional neural network.

CPU central processing unit.

CSF cerebrospinal fluid.

CSP common spatial pattern.

D

DEEG digital electroencephalography.

DL deep learning.

DMD duchenne muscular dystrophy.

DSP digital signal processor.

E

ECG electrocardiography.

ECoG electrocorticography.

EEG electroencephalography.

EMG electromyography.

ERD event-related desynchronization.

ERP event-related potential.

ESI scout EEG source imaging.

EU European Union.

F

FBCSP filter bank common spatial pattern.

FDA Food and Drug Administration.

FN false negative.

FP false positive.

FPGA field programmable gate arrays.

G

GAN generative adversarial network.

GDPR general data protection regulation.

GPU graphics processing unit.

H

HMI human-machine interface.

HU Hounsfield unit.

L

latex Is a markup language specially suited for scientific documents.

LDA linear discriminant analysis.

LIS locked-in syndrome.

LR logistic regression.

LSTM long short-term memory network.

M

MEG magnetoencephalography.

MI motor imagery.

ML machine learning.

MRI magnetic resonance imaging.

mv millivolts.

N

NLP natural language processing.

NN neural network.

P

PFBCSP penalized frequency band common spatial pattern.

POC proof of concept.

PTFBCSP penalized time-frequency band common spatial pattern.

R

RF random forest.

RL reinforcement learning.

RNN recurrent neural network.

ROC curve receiver operating characteristic curve.

S

SNR signal-to-noise ration.

SSVEP steady-state visual evoked potential.

SVM support vector machines.

T

TL transfer learning.

topomap topographic map.

ToS terms of service.

U

UI user interface.

UX user experience.

V

VR virtual reality.

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