VRIJE UNIVERSITEIT BRUSSEL

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BRAIN CONTROLLED WHAT?

An in-depth guide to brain-computer interfaces and extensions to multiple state-of-the-art motor imagery EEG classification algorithms

Lennert Bontinck

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Promotors: Prof. Dr. Geraint Wiggins & Prof. Dr. Kevin De Pauw

Advisor: Arnau Dillen

Faculty of Sciences and Bioengineering Sciences

HERSENGESTUURDE WAT?

Een uitgebreide inleiding tot brein-computer interfaces en verschillende extensies voor de beste ingebeelde moteriek EEG classificatie algoritmen

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Abstract

This master thesis explores the field of brain-computer interfaces (BCIs). First, it aims to provide a great foundation for the knowledge required for working in the BCI field as a computer scientist. To accomplish this, an exhaustive literature review in the introductory chapter aims to provide a great general introduction to the field and current state-of-the-art as well as challenges and promises of the field. A chapter on biomedical signals (biosignals), the source of data for BCI systems, is also provided. It discusses how electroencephalography (EEG) can be measured and provides an overview of common hardware, issues and more.

Next, the viability of real-world applications using classification algorithms on live EEG measures collected from affordable BCIs hardware is explored. This is done by first introducing a general BCI pipeline and discussing all of its components. Afterwards, a three-signal control system is proposed as proof of concept (POC) based on this general BCI pipeline. Special care is given to include all important details of the system, in an attempt to improve reproducibility. The system is also evaluated taking into account best-practice techniques whilst also realising the BCI field lacks standardized testing strategies.

TODO: this abstract should be further completed after the thesis is finished.

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Todo: complete with additional people if need be.

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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 specific systematic review procedure. However, special attention was payed 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 tool[1].

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

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[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 input[2] 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

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[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 2.4.4.

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 Neurable, 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, 2.4.4, and 3.3.1, creating an effective commercial product can become an expensive affaire 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 adressed 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.
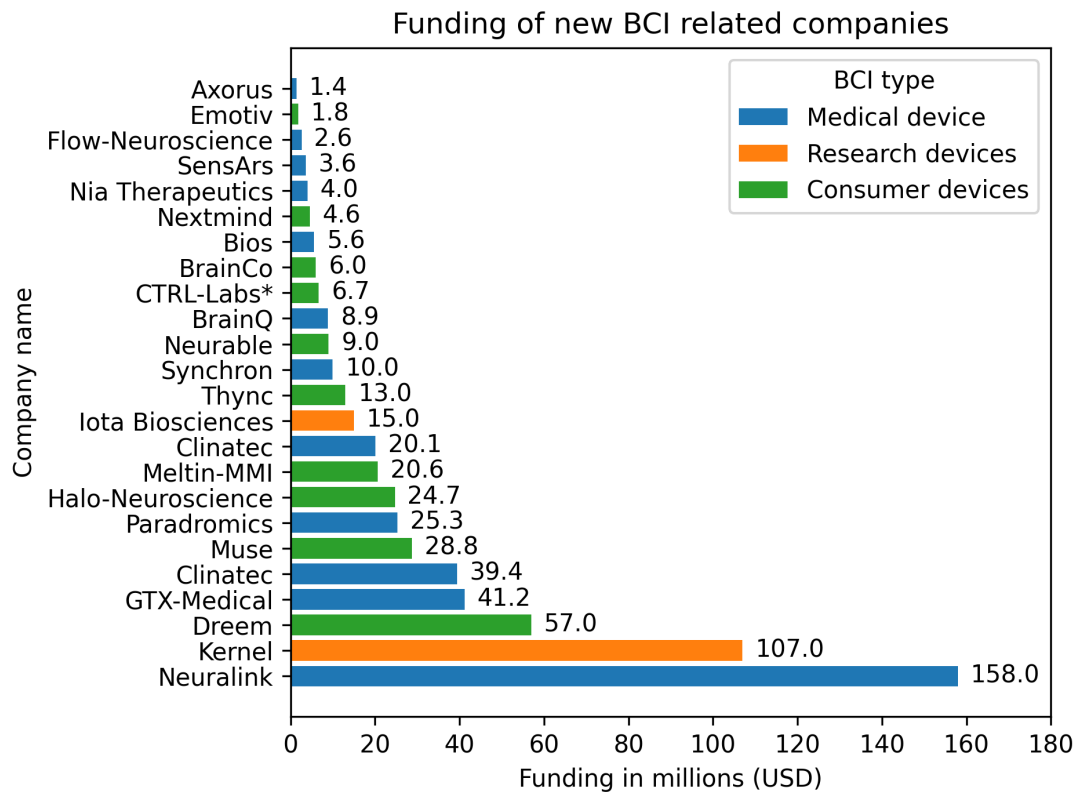
Figure 1.1: Funding of newer BCI related companies depicted in millions (USD). Figure based on data by Rao (2020) from 2019. It is noted this data is limited to companies that were created after 2010 where funding information is made available.

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 2.4.4, 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, 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.

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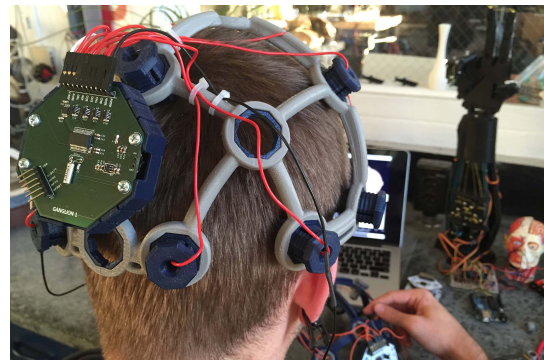
(b) Commercial-grade EEG measuring device that uses dry electrodes with active amplification connected to an attached wireless controller board. Image from Conorrussomanno, CC BY-SA 4.0, via Wikimedia Commons.

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

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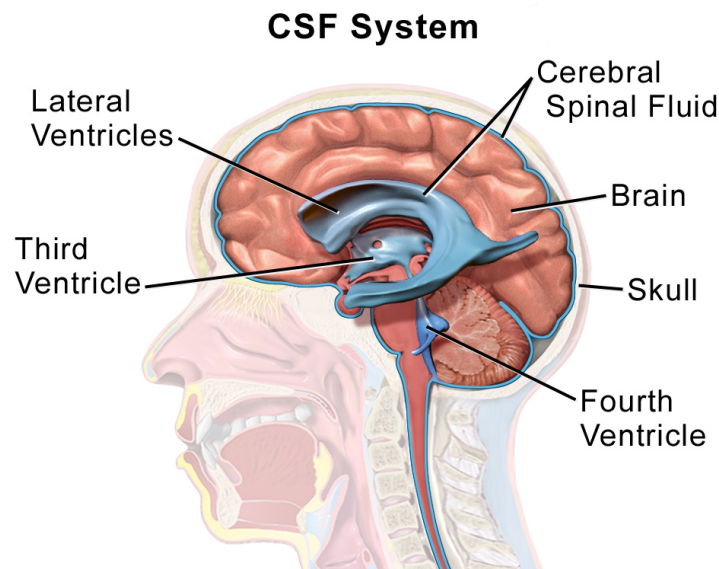
Figure 1.3: The anatomy of the human head, specifically of the cerebrospinal system. Non-invasive EEG measuring equipment is placed on the scalp, causing signals from the brain to be blocked by the skull and cerebrospinal fluid (CSF) among other structures. Free to use Figure by Blausen.com staff (Blaus,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

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 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).

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 2.4.2, 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 prepossessing 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. Remember from Section 1.2.2 that Bluetooth 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 digitial 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-shelve 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 2.4.4 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 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 them 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 tasks[3]. 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 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.

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.

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[3]https://nr.apple.com/dH8i4U3v2w
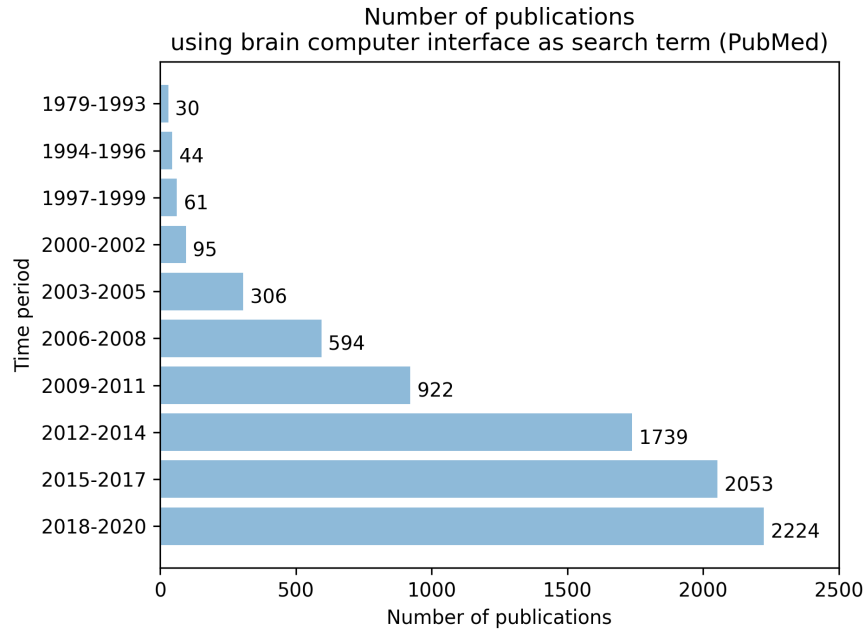
Figure 1.4: Number of BCI-related papers over time. Based on data by Saha et al. (2021) obtained by searching PubMed using the keyword: "brain-computer interface".

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 term 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 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) General pipeline for ML based CADx system.

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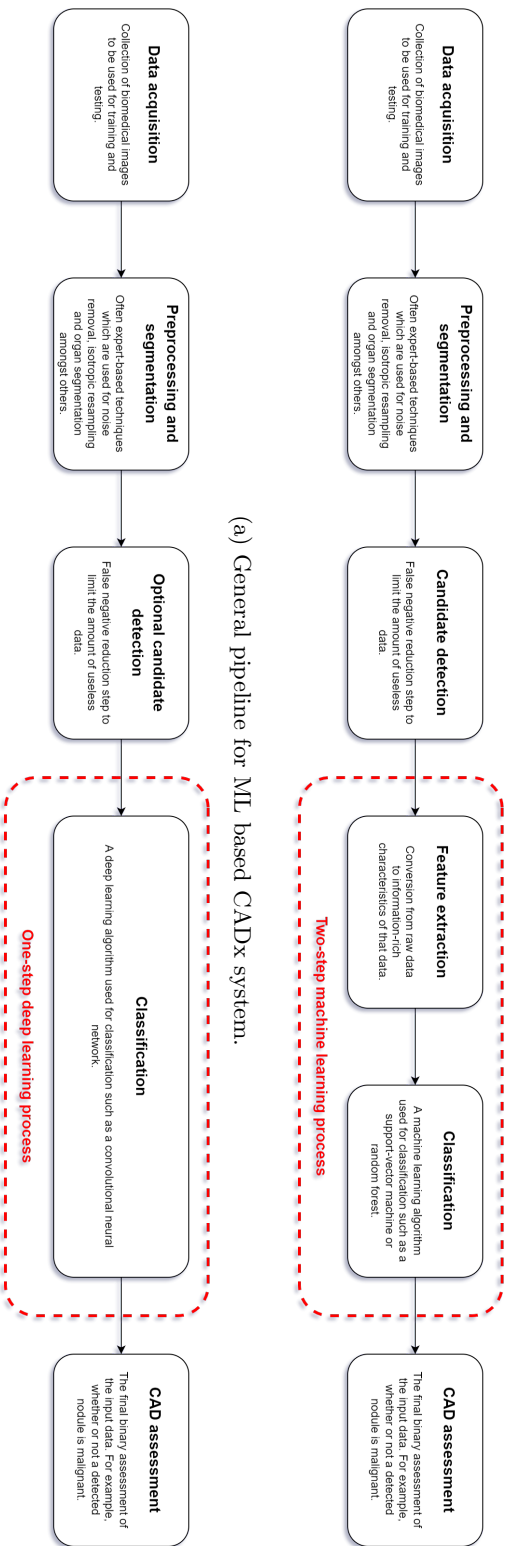
Figure 1.5: General pipelines of a CADx system used for classification. A ML approach is called a two-step approach as it exists from feature extraction and classification. A DL approach is called a one-step approach as it combines both of these steps into a singular classification algorithm.

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 challanging 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 year, just as other DL approaches. Most recent and noteworthy developments are works such as that by Schirrmeister 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) discus 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 this thesis took the definition of a BCI and a perfect BCI, further demonstrating his importance in the field (Blankertz et al., 2004, 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

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[4]https://www.bbci.de/competition/

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 Code[5] 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 Schirrmeister et al. (2017) and EEG-DL by Hou, Jia, et al. (2020), Hou, Zhou, et al. (2020), Hou et al. (2022), and 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 Neurotechnology[6]) 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 Schirrmeister 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 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

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[5]https://paperswithcode.com/
[6]https://www.neurotechnology.com/brainaccess-documentation/C++Api

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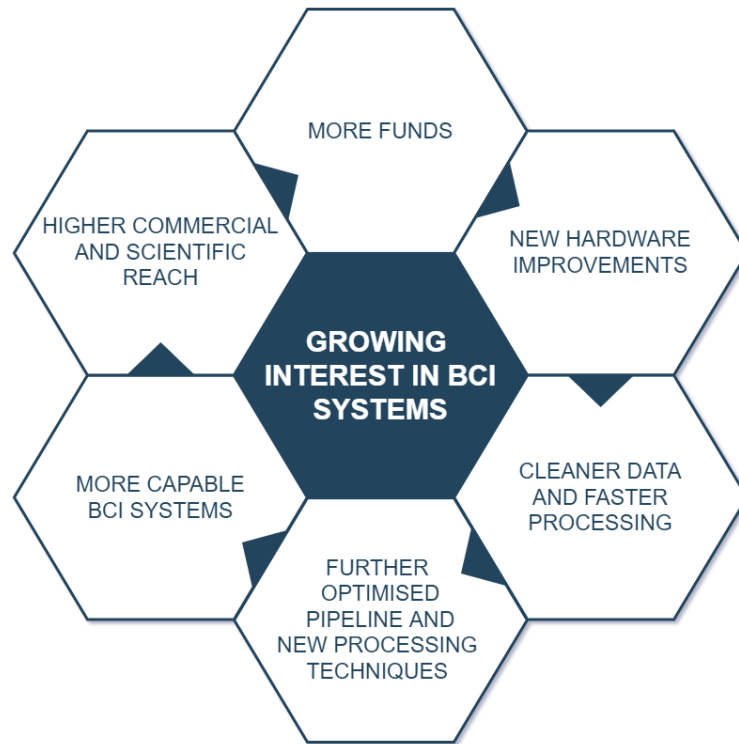
Figure 1.6: Summary of some of the potential reasons BCI
research has seen its gain in popularity discussed in section 1.2.
There is no clear chronological order for these events and they
likely influence each other all at the same time.

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 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 term 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 it's 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 1.5.6.

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 2.4.5 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 where 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 2.4.4. 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 form 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's thesis and aim to explain why this master's 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.

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

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

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 2.4.4, 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's thesis to study the field.

1.4.2 Motivational aspects for this master's thesis

The discussed use cases from Section 1.3 were motivating examples for this master's thesis in themselves. However, there are some specific articles and aspects from the field that have motivated the creation of this master's 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 promosing 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 2.4.4. 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 extension, 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's 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 explicitely use internal memory to explicitely 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 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
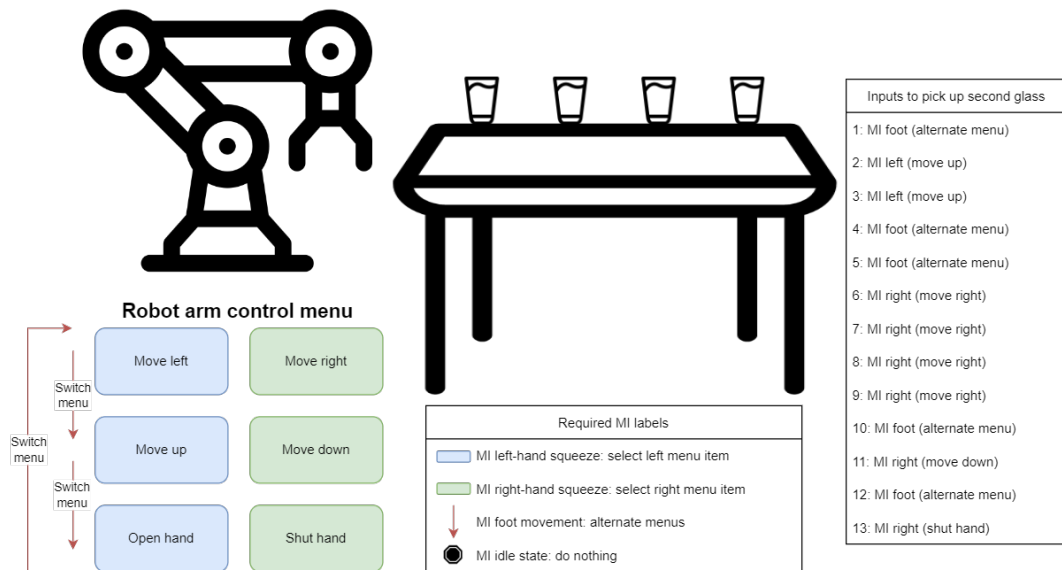
(a) A BCI system that offers complete control over a robotic arm but with poor efficiency.
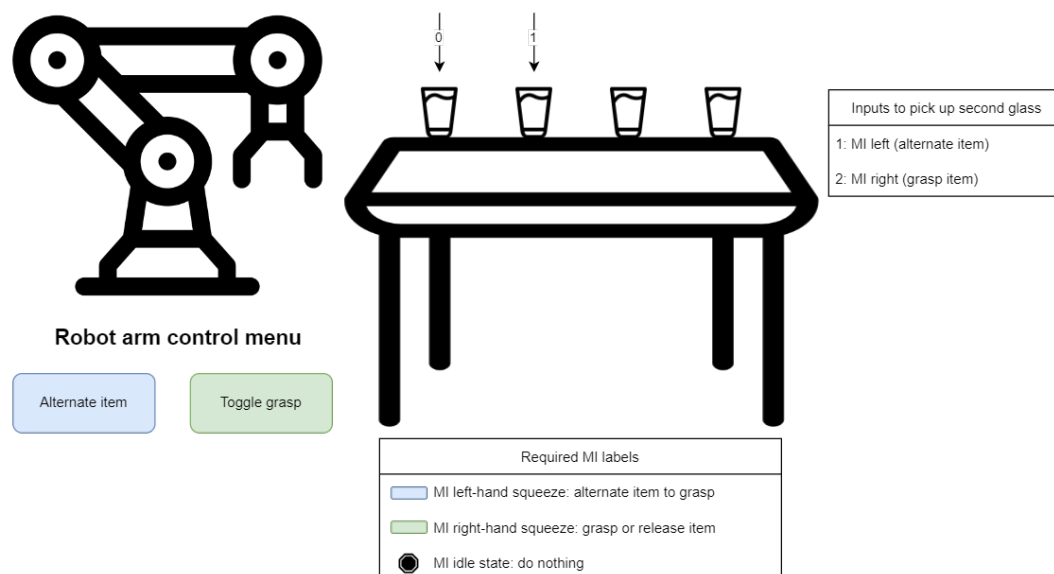
(b) A BCI system that offers limited control over a robotic arm but with great efficiency.

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.

of their cloud infrastructure for computer-vision, the AutoML idea is becoming more and more popular (Dillen et al., 2022).

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.

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

Evaluating and comparing different BCI systems is not easy. This is in part due to a BCI system consisting of different components. Thus, evaluating a BCI system purely on the tasks it can achieve and with which accuracy doesn't tell all that much. Evaluating the system for the above discussed three different components can improve on this, but a lack of standardized testing also makes this rather challenging.

Take for example the comparison and evaluation of the performance of the measuring equipment of a BCI system. Many BCI systems use the noisy EEG modality, but others make use of EMG and other modalities which can be more or less prone to noise. Some make use of easy to use dry electrodes, whilst others make use of wet electrodes that require considerable preparation. One could use the signal-to-noise ration (SNR) to compare and evaluate the EEG measuring device. However, this doesn't take into account affordability and user experience. A

higher SNR but with more predictable noise is also preferred over a lower SNR with completely stochastic noise. Comparing the classification accuracy for specific tasks might seem like a better option then, but how do you make a fair classification pipeline for all different headsets. It should become visible that there is no easy solution to evaluate the (e.g. EEG) measuring equipment of a BCI system.

Similar issues arise for the data processing component. For starters, whilst relatively complete datasets such as the one by Kaya et al. (2018) exist, there is no real *reference dataset* for BCI systems. In computer vision, for example, popular datasets such as MNIST (Li Deng, 2012) and ImageNet (Deng et al., 2009) are often used to train and evaluate image classification algorithms. But EEG classification algorithms are optimised to the input data. For example, some work better with noisy data whilst others are optimized for MI specific classification tasks and so on. 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? Again, it should be apparent that there is no straightforward way of evaluating the data processing step.

This thesis only aims to highlight the issue that arises when trying to evaluate and compare different BCI systems. These problems such as a standardized testing suite are open problems in the field and one that could greatly improve the field's work once a solution is proposed and accepted by the community. For now, focusing on reproducibility and specifying the data used and potential ways it makes tasks easier or harder is the best most researchers can do. It becomes apparent that a 90% accuracy for a model that can be used on any user without re-training is far more impressive than one custom made for a specific user. Likewise, 80% accuracy on non-lab environment data with high stochasticity is far more impressive than the same accuracy on the best measuring hardware in the most controlled environment.

1.4.5 Challenges from the highly interdisciplinary nature of BCI systems

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As discussed, the field of BCI is highly interdisciplinary. The EEG data collection part relies heavily on neuroscience for the working of the brain to know what signals can be extracted and where they originate from. To extract those signals, engineers should develop hardware capable of measuring the tiny electrical current that is EEG. Whilst those engineers also focus on noise reduction, computer scientists are also needed for preprocessing to further reduce this noise. The data processing is mainly a computer scientist task, although knowledge from neuroscience can be very helpful in this step as well as insight on the flaws of the hardware. The final component, where effective actions are performed, can relate to a wide variety of sciences once again. For example, the robotic arm proposed before requires computer vision knowledge for grasp detection, engineering knowledge to make the arm and general computer science knowledge to create an intuitive link between classification labels and action controls. Because of this, it is often the case that research focuses mainly on improving one of these three components rather than the whole system. 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 and shows thorough knowledge as it proposes a very affordable custom system. However, the classification algorithms used and the user interface proposed could benefit from future extensions to make the complete BCI system even better.

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 will leaving room for improvement in other aspects. Likewise, many papers on the data processing and classification algorithms for EEG data are from computer scientists. Those papers often don't even include the final component where effective actions are taken, or the proposed system is limited to simulations because the development of robotics falls outside the scope of their discipline. This interdisciplinary of the BCI field is part of what makes it so fascinating yet also sophisticated. Commercial institutions that can hire many of the required professions will likely accelerate the creation of true complete BCI systems with state-of-the-art in each component of the system.

1.4.6   Difficulties with repeatability and reproducibility of experiments

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1.4.7   Complex data variability and user-training

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1.5   Ethical challenges for BCIs

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1.5.1 The return of the Luddites

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1.5.2 Advertisements based on your thoughts

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1.5.3 Hacking BCI systems

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1.5.4 Changing peoples personal identities

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1.5.5 Painfully confronting users with their brain

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1.5.6 E-waste inside your skull

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1.5.7 The risk of sloppy science due to time-pressured researchers

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1.6 Chapter conclusions and proposing a three-signal system for basic controls

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

As discussed, this master' thesis focuses on providing a great foundation for the knowledge required for working in the BCI field as a computer scientist. The exhaustive literature review

from this chapter should provide a great general introduction to the field and current state-of-the-art as well as challenges and promises of the field. As touched upon in Section 1.4.2 and further discussed in Chapter 3 many different pipelines and approaches exists for the data processing component of a BCI system. Whilst some of the libraries available which make use of deep learning (DL) allow for raw EEG input, the author of this paper believes it to be of importance to know the nature of this EEG data to some extend. For this, an introduction to biosignals and how they can be measured is given in the next chapter. This deeper understanding of the data source ultimately leads to better design decisions in the data processing component.

In part 2 of this thesis, a focus is put on how BCI systems can be development. To accomplish this, an offline BCI that classifies EEG data is discussed in Chapter 4. Chapter 5 extends on this offline BCI pipeline by proposing a three-signal system for live control. Part 3 of this thesis consists of Chapter 6 and 7 which aim to evaluate this three-signal system, taking into account the lack of generalized evaluation strategies as discussed earlier in Section 1.4.4

For this reason, this thesis focuses on providing a solid foundation to the BCI field, a POC application to demonstrate how a working system can be implemented and a thorough viability discussion of these systems in their current state.

Chapter 2

Origin and acquisition of biomedical signals

2.1 Introduction to this chapter

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2.2 Origins of biosignals

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2.2.1   Electrical biosignals

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2.2.2   Non-electrical biosignals

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2.3   Biosignals from the 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   Measurable brain-activity

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Motor imagery (MI) is the process in which a person generates brain-activity in the motor cortex merely by imagining motor movements. MI-based brain-computer interfaces (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 electroencephalography (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, of-

ten 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 then 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   Motivation for using non-invasive EEG

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2.4.3   Standards for EEG measuring systems

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2.4.4   Comparison of available EEG measuring equipment

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2.4.5   Common EEG artefacts

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2.5 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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3.2.3 Windowing

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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 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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3.5.2 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 an EEG-based brain-computer interface that classifies motor imagery tasks

Chapter 4

EEG-based offline classification system for motor imagery tasks

TODO

Chapter 5

Moving from an offline classification system towards an online BCI system

TODO

Part III

Reflection on the results of this thesis

Chapter 6

Using the system and verifying the results

TODO

Chapter 7

Self-reflection and conclusions

TODO

List of abbreviations and acronyms

Symbols

μV microvolts.

A

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.

biosignal biomedical signal.

biosignal control biological signal control.

BMI brain-machine interface.

BPNN back propagation neural network.

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 digitial signal processor.

E

ECG electrocardiography.

ECoG electrocorticography.

EEG electroencephalography.

EMG electromyography.

ERD event-related desynchronization.

ERP event-related potential.

ESI scout EEG source imaging.

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.

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.

U

UI user interface.

UX user experience.

V

VR virtual reality.

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