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Why, What and How to Start

A first journey in DIY brain computer interfaces, part 1

Fig 1. Designed by rawpixel.com / Freepik

> *In the summer of 2022, I started a new series of blog posts with updated, more advanced information, and way better results than achieved in this series of blog posts. Click here to go to part 1 of that series.*

Imagine paralyzed patients typing text messages using only your thoughts. Imagine people moving their hands again after a spinal cord injury, using only their thoughts connected to a robotic arm. Imagine people walking again, using their thoughts to command an exoskeleton.

Stop imagining. Researchers are currently turning these projects into reality!

For example, recent research achieved a typing speed for a paralyzed patient comparable to able-bodied participants by decoding the brain signals of imagining hand-writing characters (while the patient was not able to move their hands)! Although we're not nearly there yet, the future is exciting.

How do they achieve this?

With Brain Computer Interfaces (BCIs): brain signals are captured with a device which measures brain signals, which are then send to a computer, where the signals are processed and decoded with machine learning techniques, from which the output is determined.

The field of BCIs is fascinating, but can be a bit scary to step in at first.

Surely you need a lot of knowledge of neuroscience, be an expert programmer, and have enough funds to buy the expensive BCI hardware…

Well, actually that's not true.

With this series of blog posts, I hope to introduce you into the field of BCIs and try to convince you that you can build your own projects and experiments, in a beginner friendly, cheap manner, by taking you with me on my journey of building my very first hobbyist BCI project!

Structure of this series

> **Disclaimer:** *This series of blog posts is written to make myself aware of the details and concepts in the field of BCIs and neuroscience, as I go through my very first own BCI project. Right now, I really have no idea how this project will turn out.*
>
> *Therefore, note that this series of blog posts should not be used as a definitive guide for your own journey. Rather, I hope you will take inspiration from my first journey, and maybe not make the same mistakes as I might do ;)*

This series of blog posts will be divided into 5 parts, released once per week, covering:

- Part 1, introduction: What are BCIs, which device to use, and some neuroscience fundamentals

- Part 2, collecting data: which data will we collect and how, and our experiment design
- Part 3, pre-processing: noise filtering, outlier detection, feature engineering
- Part 4, machine learning: experimenting with machine learning models, and choosing the best model
- Part 5, applying the model: trying to use the model for real-time predictions, and an outlook for future projects!

What you need to know to start

- Basic programming (I use Python for my project, but any language can be used of course)
- Some knowledge of data analysis / machine learning

Part 1

Let's get started with part 1! Here, I introduce the field of BCIs and the specific BCI I will use for my project. Lastly, I will give a short overview of the fundamentals of neuroscience needed (don't worry, it isn't much!) to start your own project.

What are BCIs?

Brain-computer interfaces exist for a couple of decades now. With a BCI, one can interact with computers by means of brain-activity. Only recently however, due to advancements in machine learning and hardware, significant steps are made to improve the decoding of brain signals for useful applications. Also, major players in the tech industry have announced their involvement in the field - Elon Musk announced Neuralink in 2017, and several weeks later Facebook also announced to work on a BCI.

A BCI starts with measuring brain activity. What is meant by brain activity differs from method to method, which will be explained below. The methods used can be grossly classified in two categories: invasive and non-invasive.

With invasive methods, electrodes can be applied at the surface of the brain (for example ECoG), or implanted directly into the tissue of the brain (for example sEEG). All these methods measure brain activity in forms of electrical activity (voltage fluctuations). How and why the brain produces these electrical signals will be explained in the neuroscience section below.

> ***ECoG:*** *Electrocorticography. As visible in figure 2, electrodes are placed directly on the exposed surface of the brain. This allows for great precision, but a low amount of brain area can be covered.*
>
> ***sEEG:*** *Stereoelectroencephalography. This is a minimally invasive method. Whereas for ECoG, the skull has to be opened for a large part, for sEEG only make 10 to 20 small incisions with electrodes which go into the brain, as visible in figure 2.*

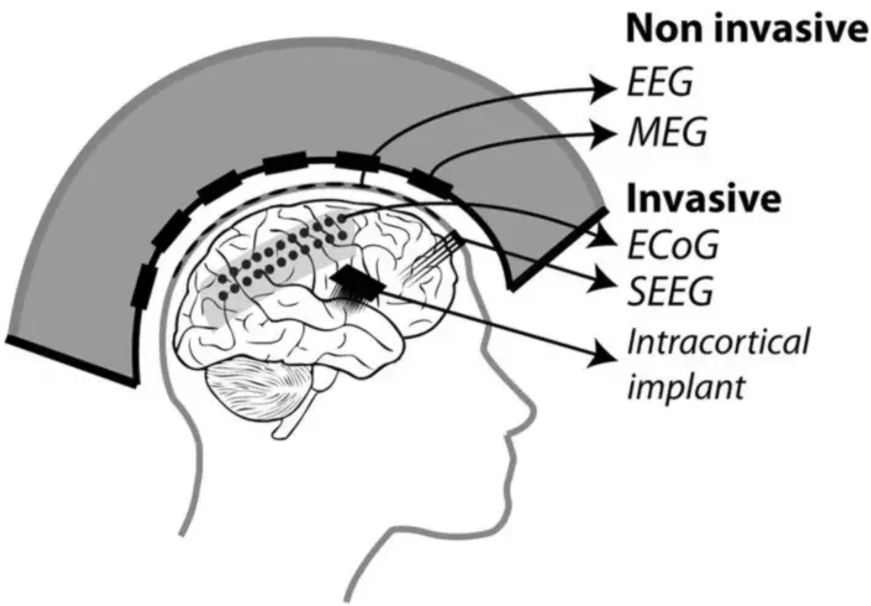

Fig 2. Different methods to measure brain activity. Copied from this research.

Invasive methods are quite complex to implement, and come with risks such as the body rejecting the device, or damage to the brain.

With non-invasive methods, the device will be place on top of the skin of the person, without the need to penetrate the skull of skin of the patient. You can imagine these methods being far less impactful for the patient, as there is no need for operation. However, the amount of undesired background noise that comes with the actual signal (the signal-to-noise ratio) is lower for non-invasive measurements when compared to the invasive methods, making it less accurate. Fortunately, a lot of effort has been done in removing noise and decoding the actual signal from these devices. Examples of non-invasive methods are EEG and fNIRS.

> ***EEG:*** *Electroencephalography. By far the most popular method for more low cost research and experimenting. As with sEEG, voltage fluctuations are measured at different parts on the skull by electrodes. Due to the large distance to the neurons, EEG measures more so the large group of*

> *active neurons, and not individual neurons, whereas sEEG does zoom in a bit more, and ECoG even more.*
>
> ***fNIRS:*** *Functional near-infrared spectroscopy. This method measures changes of hemoglobin in blood moving through the brain using infrared light, where more hemoglobin basically indicates more activity. The same method is used with your smart watch to measure heart rate on the wrist. An upcoming company using this technique is Kernel.*

Currently, EEG is probably the most popular method. In recent years, devices have been made which are easy to wear, and reasonably cheap, making it the best choice as BCI device for the home hobbyist.

So, let’s focus on EEG. Which EEG device should you choose?

Choosing your EEG device

Fig 3. Brain Products ActiCHamp EEG headset, with 32 up till 160 channels.

Chances are you have seen an EEG device as the one in figure 3, using a 32, 64 or 128-channel electrode system. The price of a device like this is can be staggering (above $25.000!). Next to this, these devices often have cables linked to machines. Not really suitable for a hobby project, huh?!

Luckily, also cheaper, and wireless, options are on the market, which still give good results for our purposes. OpenBCI offers packages with 8-channel EEG devices for around $1200. Emotiv also offers devices ranging from $300 to $850. One of the first customer EEG devices was NeuroSky, and this device is also the cheapest, priced around $200. However, only 1 channel is used for this device, which is quite low.

The device I ended up buying is the Muse 2. For $270, this device has 5 electrodes, easy start up, easy data transfer to my computer with the Mind Monitor mobile application, and still is reasonably cheap to buy. Let’s explain the Muse device some more.

Fig 4. The Muse 2 EEG headset.

The Muse 2 headset has 5 dry electrodes. Dry electrodes consist of a single metal that acts as a conductor between the skin and the electrode. A small amount of sweat between skin and electrode helps with the connection. Also wet electrodes exist, which use an electrolytic gel material as a conductor between the skin and the electrode. Dry electrodes are simpler to use, as they don't require the gel. The electrodes of the Muse 2 device are placed at TP9 and TP10, AF7 and AF8, and FpZ (which is the reference electrode), see figure 5.

The names of the placements come from the 10–20 system, which is a system invented for standardized testing methods to compare results of EEG across different subjects. Basically, we start with drawing a vertical line from nasion (above your nose) to the inion, at the back of the skull. Also a horizontal line from ear to ear is drawn. Then, all points are divided into 10% or 20% distances across those lines and between these points, additional points are added with the same ruleset.

The points are then coded based on the function of the underlying brain structure: pre-frontal (Fp), frontal (F), temporal (T), parietal (P), occipital (O), and central (C), which we will discuss below. The left part of the brain then gets odd numbers, and the right part even numbers. The middle part has a Z, for 'zero'.

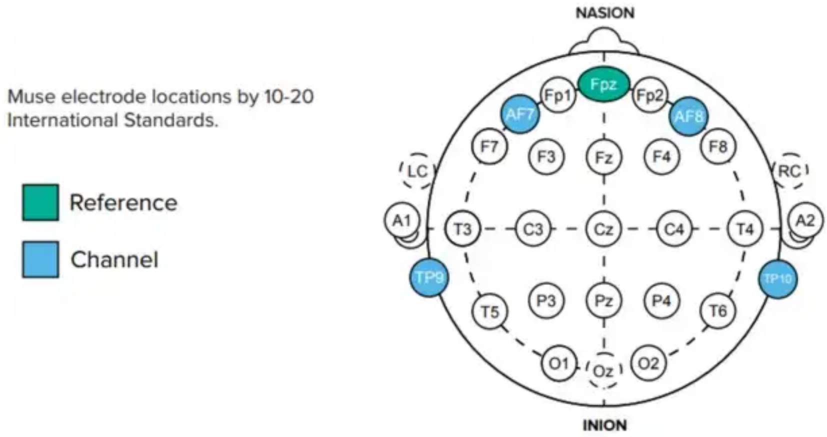

Fig 5. The 10–20 system (from Wikipedia), with colors for placements of the Muse 2 electrodes.

Neuroscience quick overview

Neurons are the building bricks of the brain. These neurons pass on information from all over your body to the brain, and back. A neuron consists of three main components: a cell body with the nucleus, dendrites with receive signals from other neurons, and axons which then send signals to other neurons. How are these signals transmitted?

With the process of the action potential: the change in electrical potential associated with an impulse of an electrically active cell. The action potential is caused by ion flow. Ions are molecules, charged positively or negatively. By altering the flow of these ions, a neuron can generate a current, thereby generating an action potential. This action potential triggers other chemical reactions, potentially causing an ion flow in neighboring neurons.

If enough neighboring neurons trigger the ion flow for one neuron, these flows sum up and a threshold is reached, meaning this neuron will generate an action potential itself. This is the way neurons communicate.

> *Want to learn more about the basics of neuroscience? This video from the BCI guys is a great next step.*

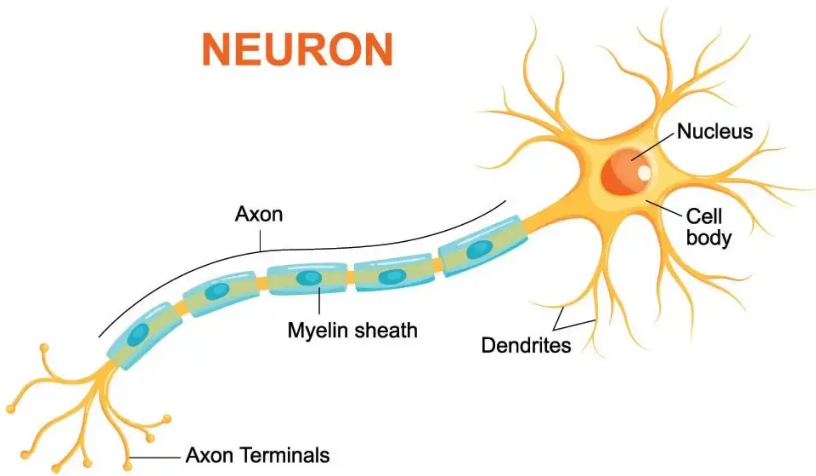

Fig 6. A basic illustration of a neuron. From: VITALII DUMMA/ISTOCK/GETTY IMAGES PLUS

Moving on to the brain structure, we divide the brain areas in some major areas for EEG placement with the

10–20 placement: pre-frontal (Fp), frontal (F), temporal (T), parietal (P), occipital (O), and central (C), which are associated with certain functions.

> ***Pre-frontal:*** *executive functions, such as planning, decision making, short-term memory, personality expression, moderating social behavior and controlling certain aspects of speech and language*
>
> ***Frontal:*** *movement control, reasoning, emotions, speech, problem solving*
>
> ***Temporal:*** *auditory, memory, processing*
>
> ***Parietal:*** *attention, perception of senses*
>
> ***Occipital:*** *visual functions*
>
> ***Central:*** *sensorimotor functions*

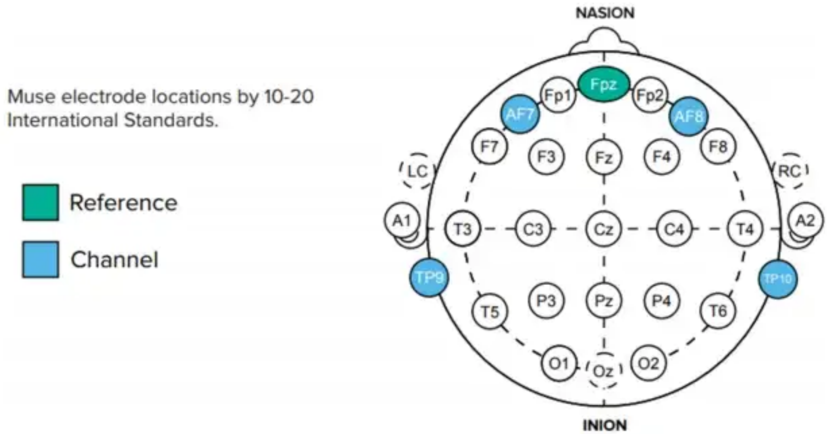

Fig 7. The 10–20 system (from Wikipedia), with colors for placements of the Muse 2 electrodes.

Coming back to the placement of the Muse sensors, we have TP9 (left ear), TP10 (right ear), AF7 (left forehead), AF8 (right forehead) for average sized heads, and the reference electrode in Muse is Fpz. It does not capture brain signals, but measures the potential differences (voltage) between the active electrodes and Fpz. So, Muse essentially measures voltage fluctuations in the temporal/parietal lobe (TP), and the frontal lobe (AF).

To explain a bit more what Muse measures, we try to explain which signals the Muse captures.

Neurons that wire together, fire together. What this means, it that a neurons often fire in groups. A larger group of neurons firing together results in a higher amplitude in our EEG signals. It was observed that large groups of neurons tend to fire together once in a while, while smaller groups more occasionally fire together. So, brain waves with lower frequency had higher amplitudes and vice versa.

Later, these signals were combined with the brain function at that moment. It was observed that for certain tasks and mental states, the brain waves waves in specific frequency intervals were predominant over the other frequency intervals. This resulted in the distinction presented in figure 8 below.

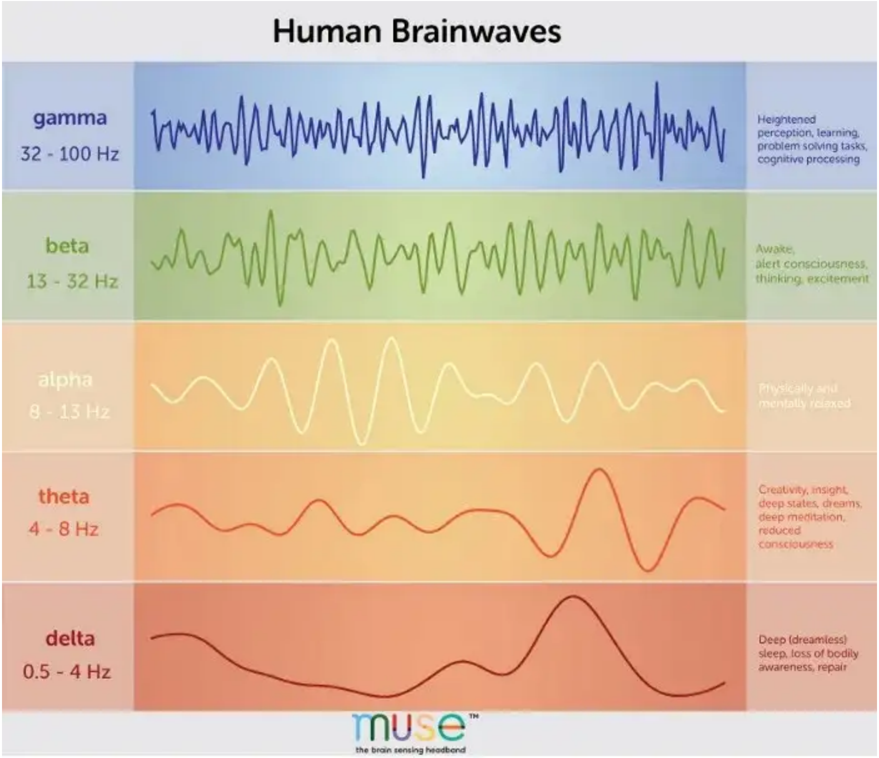

Fig 8. Brainwaves are classified in 5 categories with corresponding mental states. Image copied from Muse.

Based on this distinction in brain waves, we can try a lot of interesting experiments! Let’s see which in part 2 of this series. Thank you for reading this blog post.

> *Now that the theoreticals are out of the way, we can really start! Part 2 is available here. In part 2, I will proceed to choose my very own project, collect data and start to do some coding!*

> *PS. interested in learning more fundamentals of neurotechnology? Check out this Foundations of Neurotechnology YouTube series made by the BCI guys! Want to learn more about neuroscience in general? Check out this Neuroscience Crashcourse!*
>
> *Also, any feedback for this project and blog post is welcome!*

Brain Computer Interface   Neuroscience   Muse

Machine Learning   Python Programming