Spelling Letters through Brain waves (BCI headset)

Submitted By : Arvin Munkh-Ochir

Supervised By : Tsolmon Yadmaa
Budragchaa Sosorbaram

2024

Acknowledgments

This project was made possible with the invaluable support of Tsolmon Yadmaa and Budragchaa Sosorbaram, engineers from ONDOSPACE. Their contributions to the physical development and software solutions of this brain-computer interface device were game-changing. They provided important guidance on the headset hardware design, its creation, and the other unfindable solutions of microcontroller problems. Additionally, while working on their satellite development mission in Shenzhen, China, they graciously accepted my request to print the required boards and collect essential electronic components from Shenzhen-based electronics companies. I am truly grateful for their expertise, dedication, and the significant impact they have made on the progress of this project for the last four months.

Chapter 1 : Introduction

1.1 Motivation and Future

As technology advances, its impact on humanity continues to expand. Beyond the exceptional results of computation, technology has become a fundamental tool in our daily lives. Among its numerous applications, one of the most transformative yet underexplored areas is human-computer interaction (HCI). From touchscreens and fingerprint authentication to advancements in healthcare, the integration of technology with the human body has paved the way for groundbreaking innovations.

This paper aims to explore a fundamental aspect of HCI within the field of brain-computer interfaces (BCIs). There were different types of technological methods, starting from its category of non-invasive and invasive. Deepening into the non-invasive category there were three methods: Electroencephalogram (EEG), electrooculography (EOG), electromyography (EMG). In this paper it has used Electroencephalogram (EEG), and tried to detect letter by brain brain waves In Mongolia, research and projects involving BCIs are exceptionally rare. While institutions such as the Brain Science Institute of Mongolia focus on studying the brain in-depth, there has been little effort to connect brain signals with technology.

Thus, this study represents an introductory exploration of BCIs, utilizing an EEG device to identify letters through brain signals. Although this is an elementary study, it marks my beginning of future developments in BCIs in Mongolia.

1.2 Distinct features

The device utilized an OpenBCI headset, but it was not purchased directly from the store. Instead, the headset was manufactured in Ulaanbaatar, Mongolia, at ONDOSPACE using open-source files from GitHub provided by OpenBCI. The casing was 3D printed, while the specified microcontroller was produced in Shenzhen, China. The circuit board was created by a board manufacturing company in Shenzhen. The EEG sensors and ear clip electrodes were ordered from the OpenBCI shop through FedEx. Additionally, instead of using the OpenBCI graphical user interface, the headset utilized the OpenViBE software to process the signals.

Chapter 2 : Electroencephalogram (EEG) technology

2.1 Postsynaptic Potential

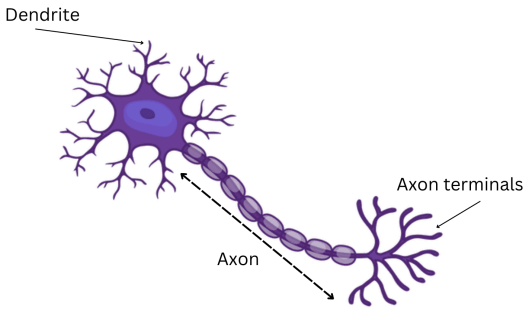


Figure 1.

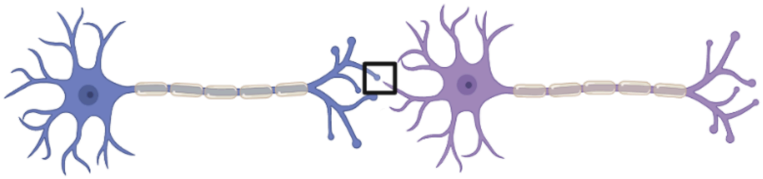


Figure 2.

In the brain, nerve cells (neurons) transmit signals to one another. There are approximately 86 billion neurons in the brain. As shown in *Figure 1*, the parts of a neuron are labeled: dendrite, axon, and axon terminals. Neurons transmit information by sending chemical signals from their axon terminals to the dendrites of other neurons. This transmission process is shown in *Figure 2*.

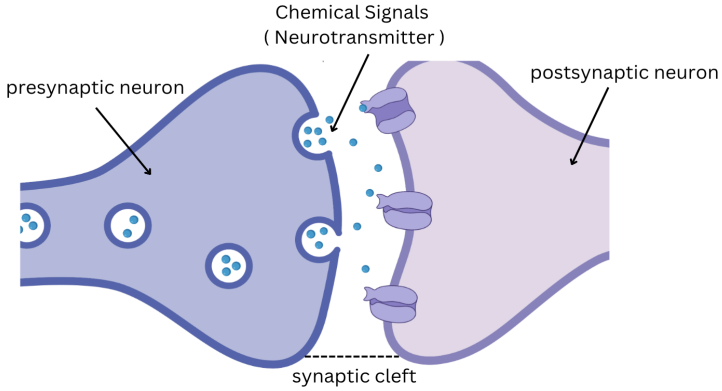
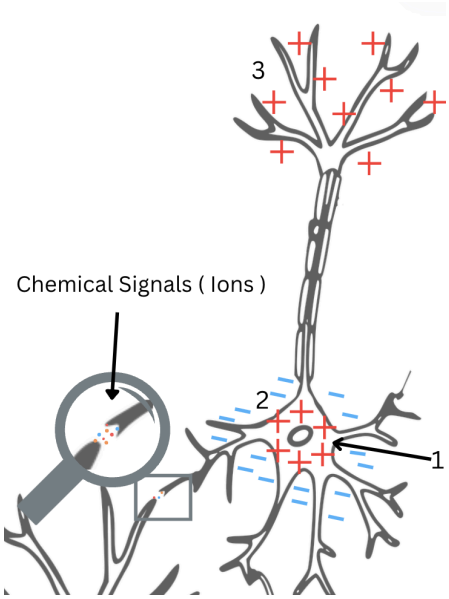


Figure 3.

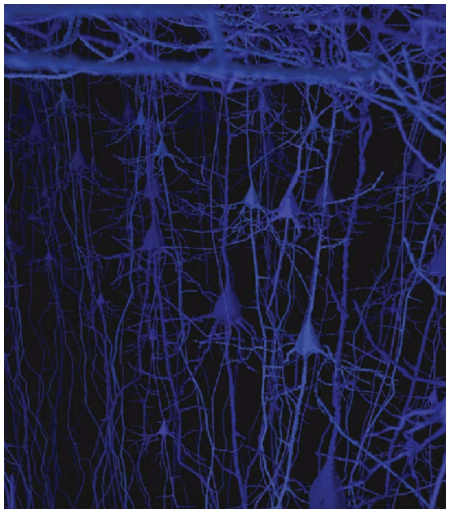
The small gap between the axon terminal and the dendrite is called the *synaptic cleft*, as shown in *Figure 3*. Within this gap, chemical signals consisting of ions such as sodium, chloride, and potassium are transmitted. The neuron sending the signal is referred to as the *presynaptic neuron*, while the neuron receiving the signal is called the *postsynaptic neuron*.

Figure 4.



Through the synaptic cleft, ions are transmitted between neurons, as illustrated in *Figure 4*. This ion movement causes the dendrite of the *postsynaptic neuron* to become positively charged, as indicated in process No. 1 in the figure. Subsequently, the surrounding extracellular region becomes negatively charged due to the redistribution of electric forces between ions, as labeled as process No. 2. This change in the local charge distribution can influence the axon terminals of the postsynaptic neuron, contributing to the generation of a positive charge known as an *Excitatory Postsynaptic Potential*. The other one which makes axon terminals negative is called Inhibitory Postsynaptic Potential.

Figure 5.



In the cerebral cortex, the outer layer of the brain from which EEG technology detects signals, there are numerous neurons creating postsynaptic potentials. The EEG electrodes measure the combined potential activity of these groups of neurons, detecting the resulting electrical potentials (charges).

2.2 Electrodes

The EEG sensors used are made of silver chloride and are shaped like a comb, specifically designed to be placed on the hairy scalp. They serve as electrodes, forming a connection between the microcontroller and the human body. These sensors rely on the electrode–electrolyte interaction, with the human body, particularly the scalp acting as the electrolyte. Notably, these comb-like EEG sensors are dry electrodes, meaning they do not require gel to function.

The human body contains electrolyte-rich fluids, such as sodium, potassium, calcium, and chloride ions, which are essential for regulating nerve and muscle functions. The AgCl electrode behaves like an RC circuit electronically when sensing those electrolytes in the liquids as shown in Figure 6.B. Additionally, on a chemical level, redox reactions occur at the electrode interface, facilitating signal detection as shown in Figure 6.C.

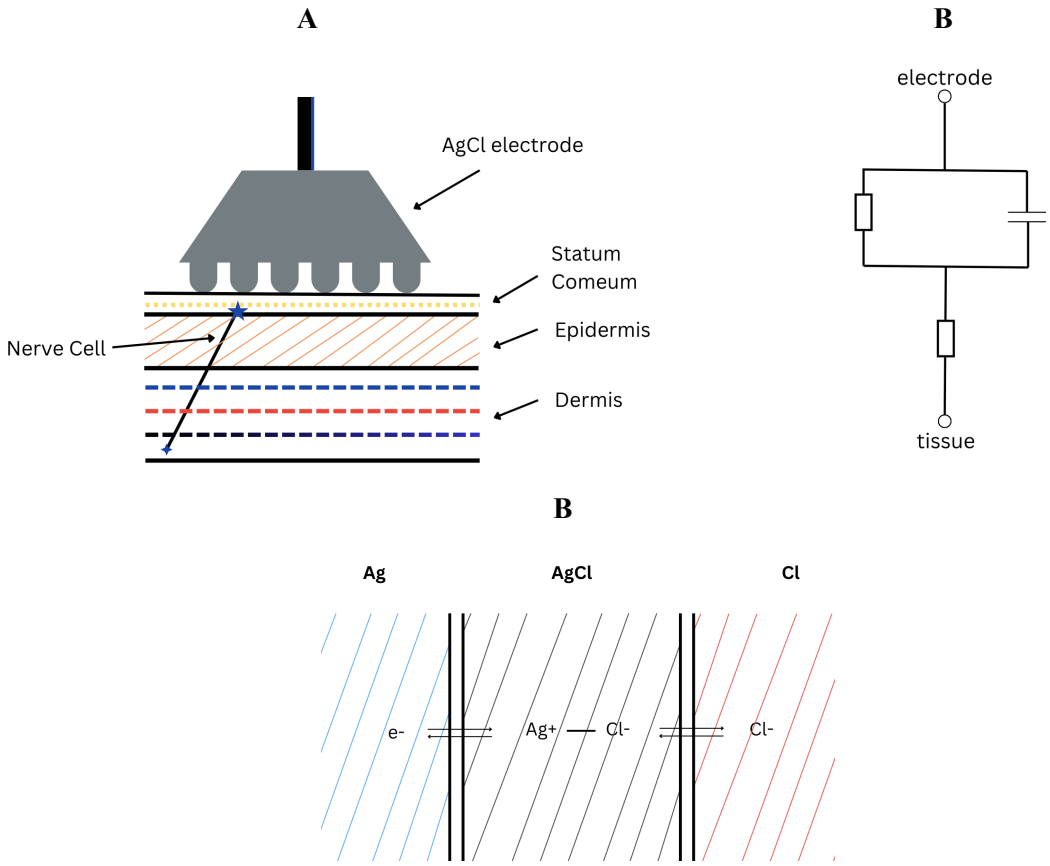


Figure 6. Electrode Explanation: **A)** Simplified illustration of electrode placement on the scalp surface, **B)** Equivalent representation as an electronic component, **C)** Chemical reactions occurring at the Ag/AgCl electrode interface.

Chapter 3 : Electric Components

3.1 OPENBCI headset

There are numerous types of electroencephalogram (EEG) devices available worldwide, including Emotiv, NeuroSky, Muse, OpenBCI, and others. Among these manufacturers, only OpenBCI provides open-source software. This means that anyone globally can access their open source files related to EEG headsets. The open-source folder contains all the necessary resources, such as 3D design files for the headset, the bill of materials (BOM) for the board, firmware for controller and other essential components' list. Consequently, this brain-computer interface (BCI) was developed using OpenBCI's open–source software.

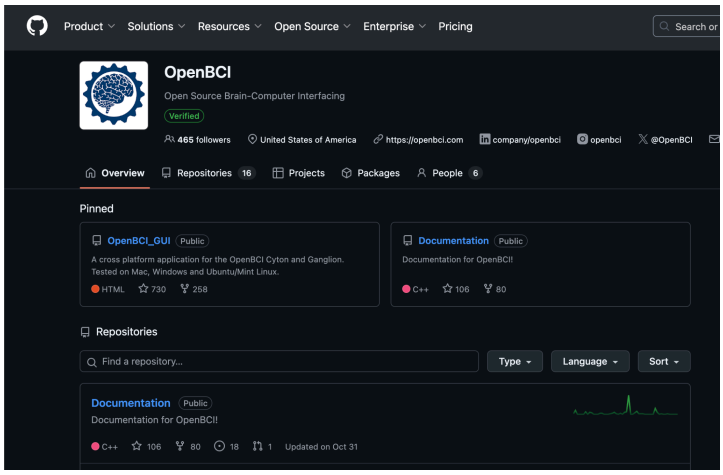


Figure 7. Github of OpenBCI

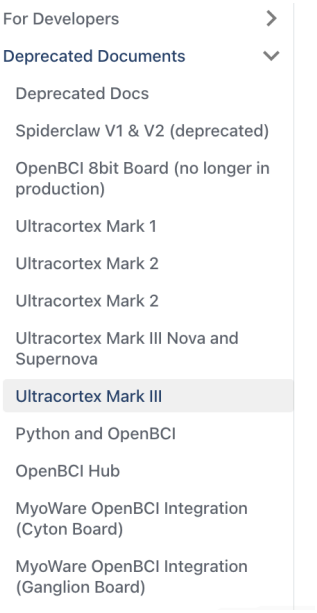


Figure 8. Ultracortex Mark 3

By accessing the OpenBCI GitHub repository and locating the UltraCortex Mark 3 files, we were able to obtain all the necessary board and headset files for our project. To ensure everything was open-source, we selected a headset design from deprecated documents. Although labeled as "deprecated," meaning there are no ongoing updates or active support, the design proved sufficient for capturing the required signals effectively.

3.1.1 3D-printed Headset

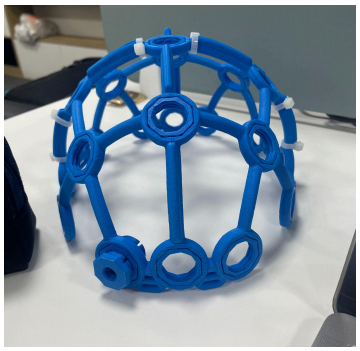


Figure 9. Printed Headset

Figure 10. During the process

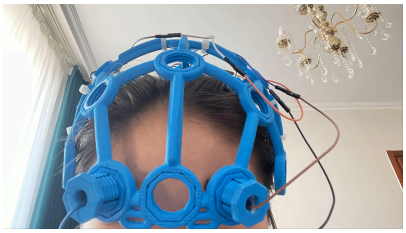


Figure 11. During the process

The electrode case and the brain-holding case were printed separately. These components, along with the sensors, were assembled to create a single integrated headset. The headset design included 21 sensor placement holes, but in this project, only 8 of these were utilized. This limitation was due to the microcontroller board, which supports only 8 channels.

3.1.2 8 channel Cyton Board

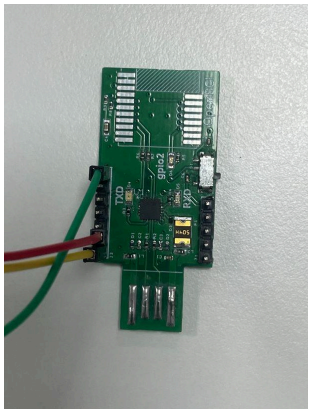


Figure 12. USB Dongle

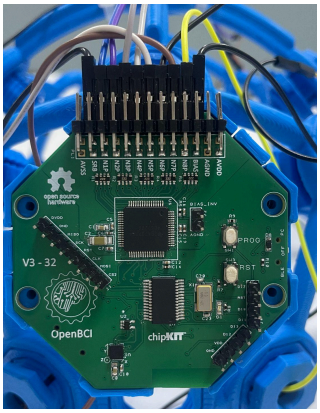
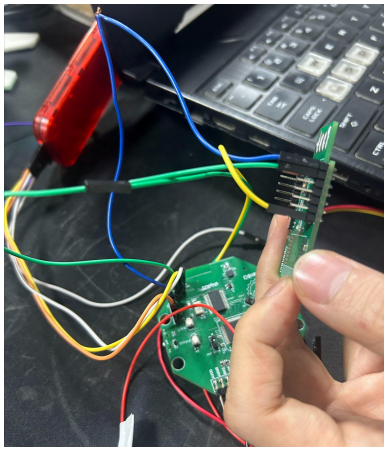


Figure 13. Cyton Board

Instead of purchasing components directly from the OpenBCI shop, the microcontroller, board and other required parts were manufactured in Shenzhen, China. The electronic components were collected from U.S. online shops such as Mouser and some of them were also bought from Shenzhen. After returning to Ulaanbaatar, Mongolia, the necessary components were soldered together. However, during the project timeline, the Bluetooth module connecting the USB dongle to the headsetboard became obsolete. As a result, ONDOSPACE's professional engineer recommended wiring a USB dongle directly to the EEG headset using UART (Rx/Tx) wires to transmit data between the components. This modification disabled the wireless feature of the OpenBCI headset, which originally supported wireless data transmission. But still, these UART protocols have been used in this project great enough.

Figure 14. PickIt and Cyton Board



Furthermore, to enable the OpenBCI firmware, which processes data from 8 channels and transmits it to the computer using a USB dongle via the UART protocol, the microcontroller needed to be programmed. Custom firmware required to bypass the Bluetooth module and transmit EEG sensor data directly to the USB dongle required additional configuration and that was carried out with guidance from ONDOSPACE engineers. The microcontroller for Cyton board is PIC32MX250F128B, which was programmed using a PICkit programmer to load the necessary firmware with MPLAB IPE v6.10.

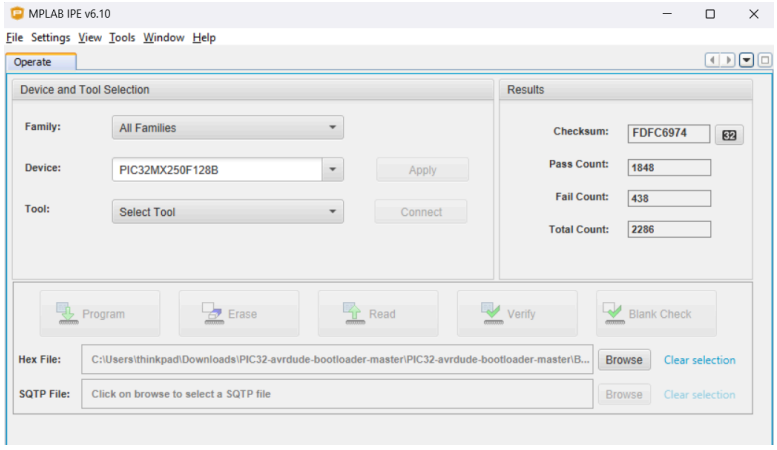


Figure 15. MPLAB IPE v6.10

Figure 15. ADS1299IPAG (8 channel Analog-to-Digital converting chip)

The **ADS1299IPAG** chip is embedded in our board to read EEG sensor data from the 8 channels it supports. Each of these channels connects to the EEG comb sensors, which are mounted at the its intended positions on the headset. The chip processes the signals from these sensors, allowing for the acquisition of high resolution EEG signal data needed for further training.

Chapter 4 : System Architecture and Coding

4.1 OPENVIBE Software

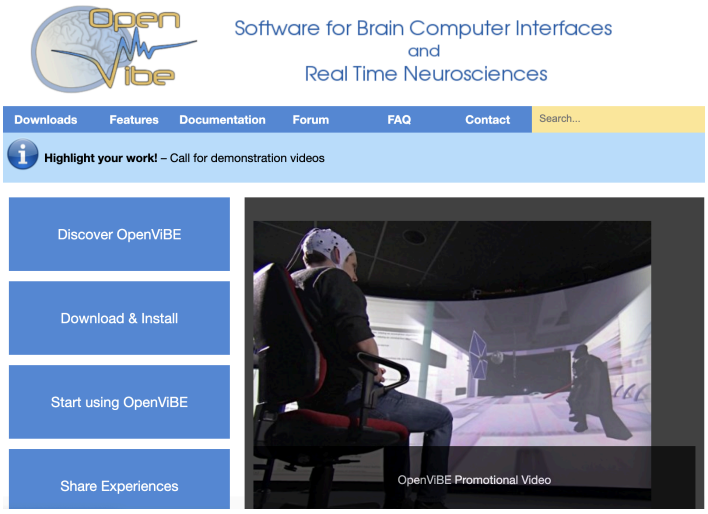


Figure 17. OpenVibe Software

Although both the headset and microcontroller boards used in this project were created by the OPENBCI community, the data streams I got couldn't appear on the OPENBCI GUI (Graphical User Interface). To solve this problem, the OPENVIBE platform was utilized in this project, instead. OPENVIBE provides a variety of pre-built examples for working with EEG headsets, ranging from motor imagery tasks to P300 signal processing, as shown in *Figure 18*. Among these, the p300-speller-xDAWN example was chosen for this project to support the letter-spelling task.

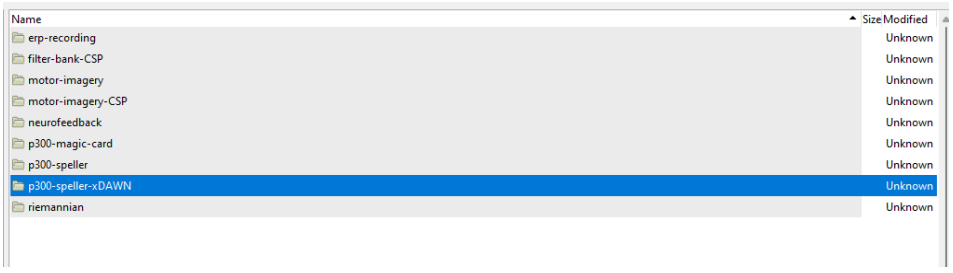
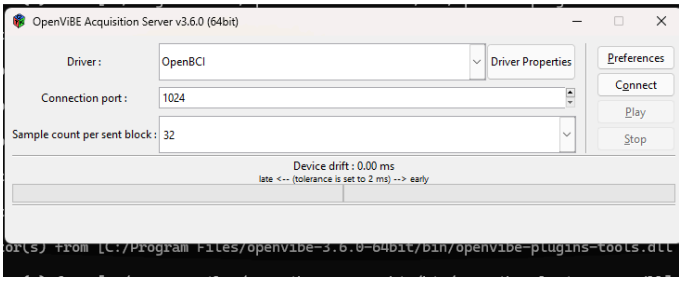


Figure 18. Pre-built Examples

Using the OPENVIBE platform requires running two applications concurrently, as shown in *Figure 19*. The first is the **Acquisition Server**, which connects to the headset device (OPENBCI), and the second is the **Designer Bit** module, which enables users to select and configure functional components (referred to as "boxes") programmed in C++. The Acquisition Server handles data collection from the headset, while the Designer module is used for designing and processing the EEG data pipeline.

A)



B)

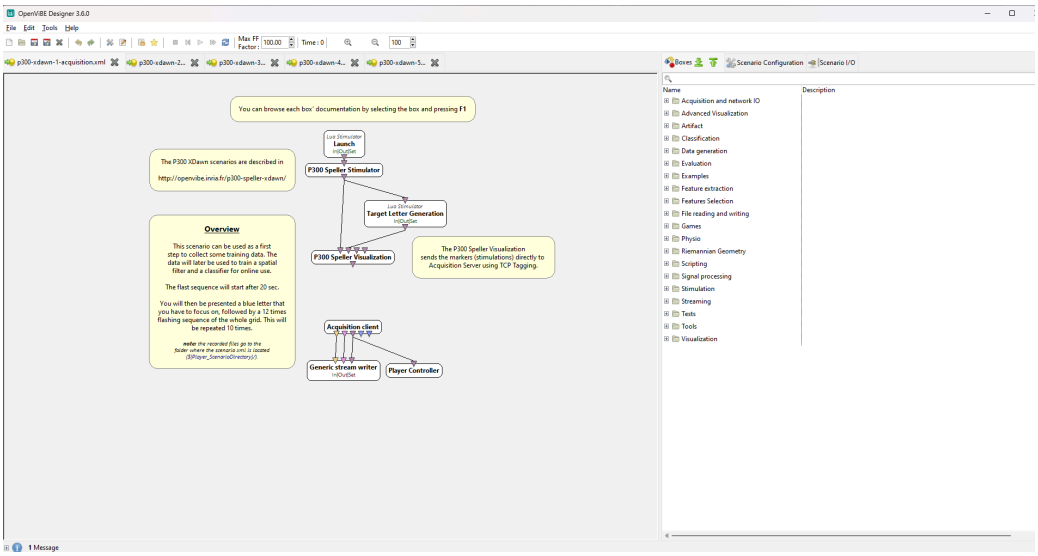


Figure 19. OpenVibe software : A) Acquisition Server, B) Designer Bit

4.2 P300 Speller xDawn Example

For the letter-spelling task, the P300-Speller-xDAWN example was used. This pre-built folder contains five main files, as shown in *Figure 20*.

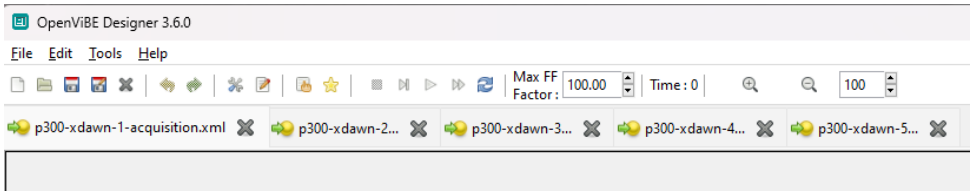


Figure 20. P300-xdawn 5 files

4.2.1 p300 waves :

For example, when a person is concentrating on an image of a bear, as shown in *Figure 21*, and it suddenly changes to a star, the visual stimulus triggers a response in the brain. This change in the target generates a P300 wave, which is a spike in brain activity occurring approximately 300 milliseconds after the stimulus is detected by our eyes.

Figure 21. Oddball paradigm

4.2.2 p300 example letters :

To utilize P300 waves for detecting letters, this example implements a 6x6 grid of letters, as shown in Figure 20. The target letter is highlighted in blue. During the process, the rows and columns of the grid flash sequentially a total of 12 times, with each flash lasting 0.2 seconds. When the target letter is flashed, it briefly stands out, creating a noticeable change in the visual stimulus (our eyes). This change is detected by the user's eyes and processed in the brain, generating P300 waves. By associating the P300 waves triggered by the flashes of the target letter with their corresponding positions on the grid, the system trains a model to recognize the brain's response patterns and map them to the intended letter.

4.2.3 p300 folder's essential files :

1. **P300-xdawn-1-acquisition.xml**:
   This file handles the flashing of letters and records the corresponding EEG signal data in the Openvibe (ov) format. These signals include brain responses to the visual stimuli, such as the P300 wave.

2. **P300-xdawn-2-train-xDAWN.xml**:
   This file processes the acquired signal data, from the previous file, using the xDAWN algorithm. The trained spatial filter configurations are then saved in a Spatial Filter configuration (cfg) file for later use.

3. **P300-xdawn-3-train-classifier.xml**:
   In this step, the signal data in ov format, created by the first file, is further processed using the Linear Discriminant Analysis algorithm. The output updates the previously generated Spatial Filter configuration (cfg) file by integrating both spatial filtering and classification for optimized detection.

4. **P300-xdawn-4-online.xml**:
   This file is designed for real-time operation. While it also has the ability to enhance the Spatial Filter configuration (cfg) file, its primary function is to use the trained one from the earlier steps to detect letters in real time based on the user's brain signals.

4.2.4 Checking our Headset :

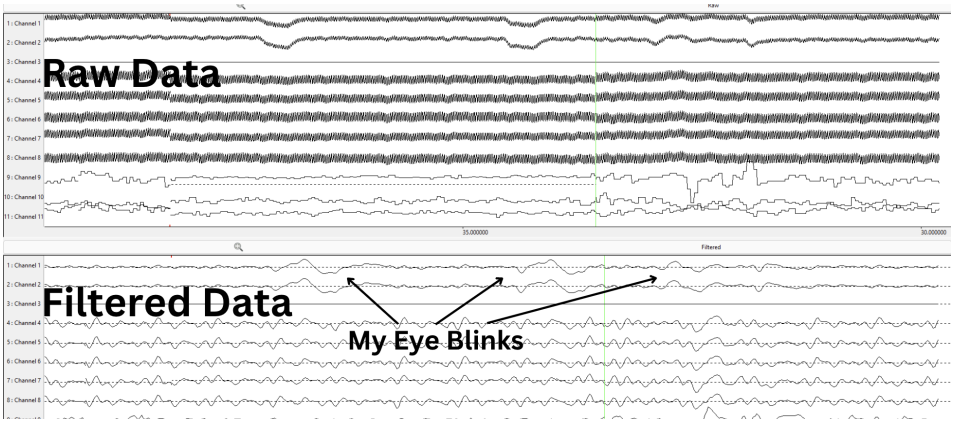


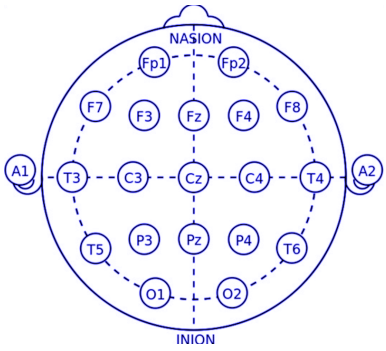
Figure 22. Signal display: Raw data on top, Filtered data below

Before using the pre-built examples, there are initial headset calibration files. These files check whether the channels are receiving accurate data by prompting the user to perform simple actions, such as blinking our eyes or clenching our jaw. Result is shown in *Figure 22.*

Chapter 5 : Testing and Conclusion

5.1 Headset and Channels

Figure 23. Putting on the head



- Channel 1(N1P) - Fp1
- Channel 2(N2P) - Fp2
- Channel 3(N3P) - C3
- Channel 4(N4P) - C4
- Channel 5(N5P) - P7
- Channel 6(N6P) - P8
- Channel 7(N7P) - O1
- Channel 8(N8P) - O2

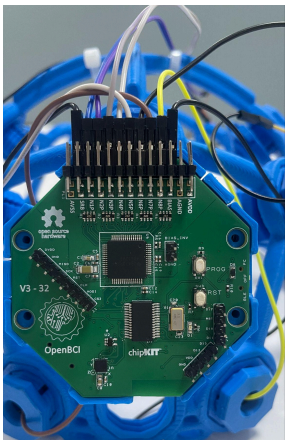


Figure 24. EEG sensor placement **Figure 25.** Cyton Board in the Back of Headset

Our Cyton board features 8 channels, and as shown in *Figure 24*, the EEG sensors are placed at Fp1, Fp2, C3, C4, P7, P8, O1, and O2 positions on the scalp. These placements allow the board to read data from these specific locations.

As shown in *Figure 23,* the user (myself) has securely positioned all the sensors and ensured they are pressed firmly against the scalp, enough to feel their tips. Additionally, as shown in *Figure 25*, the eight wires from the **EEG sensors** are connected to the **Cyton board**, which is placed on the back of the headset.

5.2 p300-speller-xDAWN example

From the acquisition file to the online use file of the P300 module, each step of the process was followed as instructed. Initially, I acquired my EEG data by focusing on the flashing sequences of letters, followed by training the system using the collected data.

During the first few days of training, the results were not enough. The Designer Bit module's terminal reported performance levels ranging from 69% to 80%, with an overall training accuracy of 72%, as shown in *Figure 26*. This level of accuracy was insufficient for reliably detecting letters using P300 waves. As illustrated in *Figure 27,* most of the target letters appeared incorrectly in the resulting letter list.

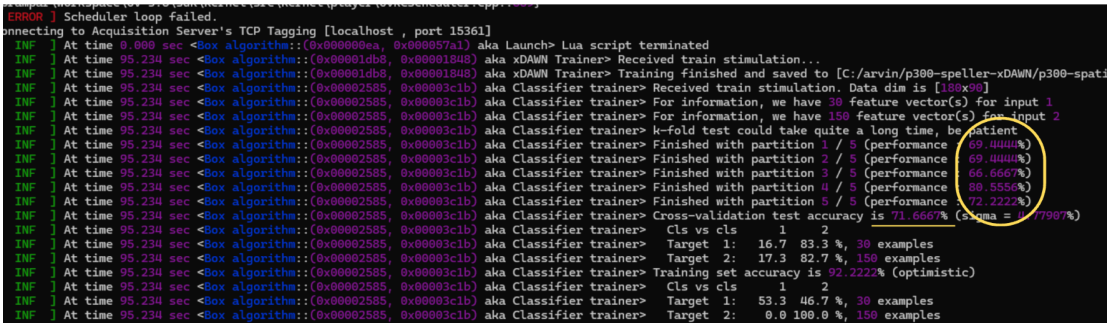


Figure 26. Initial performances (Zoom it to see)

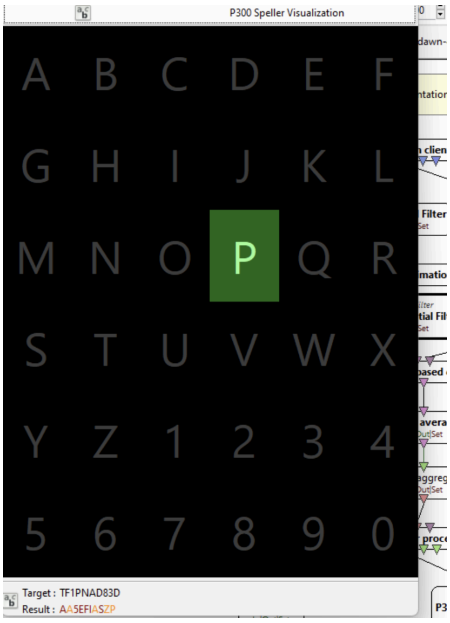


Figure 27. Real time testing file

To improve these performances, I conducted numerous training sessions, refining the system more and more. Through consistent effort, I enhanced the performance to 81.875% as shown in *Figure 28.* When tested with the module's real time testing file (4), the improved spatial filter produced outputs that were much closer to the letters I intended to select.

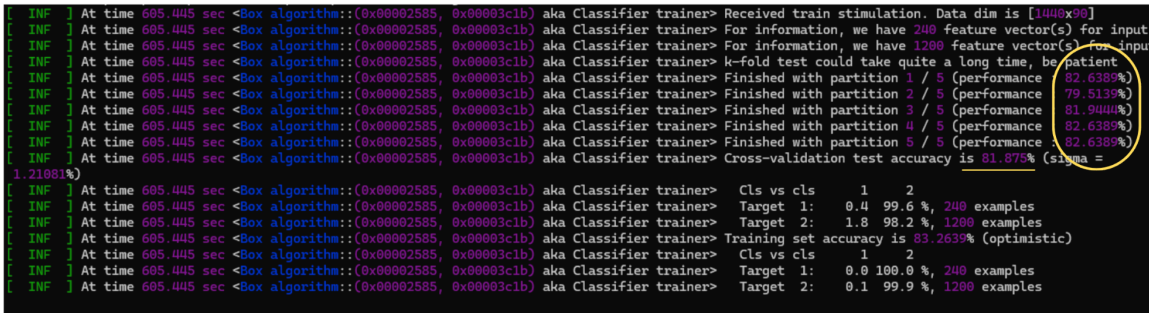


Figure 28. Last few performances (Zoom it to see)

This improvement showed that repeated training sessions and highly concentrated brain activity significantly increased the system's accuracy. By saving and utilizing these updated spatial filter configuration, the system achieved more precise letter detection based on my P300 responses.

5.3 Conclusion

Although this project was developed over the duration of four months, it did not fully achieve its main goal of accurately identifying letters based solely on brain waves. However, through the process, I gained a deeper understanding of various Neural Engineering concepts and the complexities involved in developing a brain-computer interface.

Looking ahead, as I continue to expand my professional knowledge, I hope to further enhance this letter-spelling brain-computer interface. Several challenges impacted the progress of this project:

1. **Limited Number of Channels**: In many brain-computer interface examples, systems use 10 to 32 channels for more comprehensive data acquisition. In this project, however, I was limited to an 8-channel Cyton board, which restricted the amount of data available for training and decreased the system’s overall performance.
2. **Non-Original Design**: Due to limitations in Mongolia, it was difficult to obtain all the specific components required for the OPENBCI headset. For instance, the springs needed to

secure the sensors to the headset were hard to find. Thanks to guidance from an ONDOSPACE engineer, we were able to find five springs that were nearly identical to the originals and the remaining three were substituted with less ideal alternatives. This resulted in some sensors to be unstable, when it placed on the scalp.

3. **Lack of Advanced Neuroscience and Engineering Knowledge**: As a high school graduate, I faced challenges in fully understanding the neuroscience theories and engineering principles behind the project. However, with guidance from Mongolian experts and further research, I was able to better understand the concepts. As I gain more knowledge in neuroscience and engineering in the future, I am confident that I can continue to enhance the project.

Despite these obstacles, significant progress has been made. While the project has not yet reached its main goal, the experience has given me the foundation for future improvements and has deepened my understanding of brain-computer interfaces.

Figure 29. Empty Headset (No EEG sensors mounter)

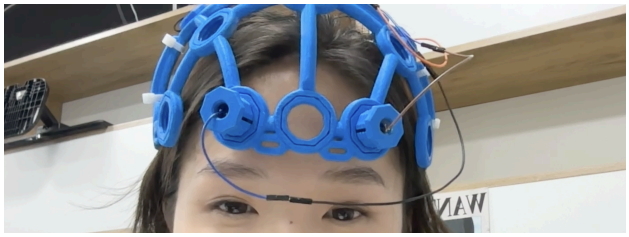


Figure 30. Final Headset

References

[1] Renard, Y., Lotte, F., Gibert, G., Congedo, M., Maby, E., Delannoy, V., Bertrand, O., & Lécuyer, A. (2010). OpenViBE: An open-source software platform to design, test, and use brain-computer interfaces in real and virtual environments. *Presence: Teleoperators and Virtual Environments, 19*(1), 35-53.

[2] OpenBCI. (2019, May 28). *How to use OpenBCI Cyton with the GUI (Graphical User Interface)* [Video]. YouTube. https://www.youtube.com/watch?v=5MK1Suvo4zg

[3] OpenBCI. (2020, August 20). *OpenBCI Mark IV assembly instructions* [Video]. YouTube. https://www.youtube.com/watch?v=CkOlVS7gEpg&t=63s

[4] Cox, C. (n.d.). *EEG Wiki* [PDF]. Rice University. https://www.cmor-faculty.rice.edu/~cox/wrap/eegwiki.pdf

[5] OpenBCI. (2019, September 5). *Understanding EEG and neurofeedback* [Video]. YouTube. https://www.youtube.com/watch?v=GDgInyAn-C8&list=LL&index=13&t=64s

[6] OpenBCI. (2020, January 13). *EEG basics and signal processing* [Video]. YouTube. https://www.youtube.com/watch?v=XMizSSOejg0&list=LL&index=12&t=348s

[7] MSD Manuals. (n.d.). *Overview of electrolytes*. The MSD Manual. https://www.msdmanuals.com/home/hormonal-and-metabolic-disorders/electrolyte-balance/overview-of-electrolytes

[8] BioRender. (n.d.). *Neuroanatomy and physiology templates*. BioRender. https://app.biorender.com/biorender-templates/t-5e3c46d72a90ac00861a558d

[9] Orehek, A. (2020, April 25). *Illustration of neurons in the cerebral cortex*. ResearchGate. https://www.researchgate.net/figure/llustration-of-neurons-blue-as-found-in-the-cerebral-cortex-The-dendrites-top-of-the_fig3_338142006

[10] University of Queensland. (n.d.). *Action potentials and synapses*. Queensland Brain Institute. https://qbi.uq.edu.au/brain-basics/brain/brain-physiology/action-potentials-and-synapses

[11] OpenBCI. (n.d.). *Mark III wiring and connections*. OpenBCI. https://docs.openbci.com/Deprecated/MarkIII/#connect-wiring-to-openbci