# Towards Multimodal Neuroimaging

## Ubiquitous EEG Headset


Interactive Qualifying Project

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# 1. Introduction

With the recent advent and success of low cost electroencephalography (EEG) solutions in parallel with the recent larger scale of adoptions of functional near-infrared spectroscopy (fNIRS) research and building of interfaces we saw that there could be a need for lower cost EEG with a multi modal approach. This is an avenue that is unexplored both academically and commercially but has definitely been spoken about as a new path for future brain measurement devices. We are trying to develop a low sensor phase that sets up the backbone for future groups to build upon. We had to cover multiple facets of familiarizing ourselves with the field. Therefore, we researched and compared devices currently on the market, while also finding possible solutions that the current market has failed to fulfill but recent research says that a solution is possible. We give a summary of how the brain and nervous system work, how the EEG and fNIRS technology work and exactly what and how they measure, along with how the gathered information is reported. Next is providing information on the testing kit, in our case the BioSignalsPlux, as well as sensor placements that gave us interpretable data (PLUX Wireless Biosignals, 2018). Finally, the next step for future groups to follow is to design a prototype and test it using analysis tools developed for our low sensor count device.

# 2. Neuroscience Background

## 2.1 Brain and nervous system

The brain is a very complex part of the human body as it controls every aspect of human life. This complex organ consists of multiple parts, the main ones being the cerebellum, brain stem, and cerebrum. Within the cerebrum there are six regions, four of which are externally seen and the other two being found internally. The four regions are the frontal, occipital, parietal, and temporal lobes that each have their own purposes as they make up specific parts of the brain. The frontal cortex, composed mainly of the frontal lobe, is studied when researching cognitive functions such as decision making. The middle of the brain, composed of the parietal lobe, is known for studying motor processing and coordination (touching and moving). The occipital cortex contains the occipital lobes and is used in vision aspects. The temporal lobes make up the temporal cortex which is mainly used in speech and emotion expression (the left side being specifically known for speech comprehension and production). Lastly, within the brain there are various regions within the limbic and insular lobes that are responsible for many things such as memory processing and action selection (Farnsworth, 2020).

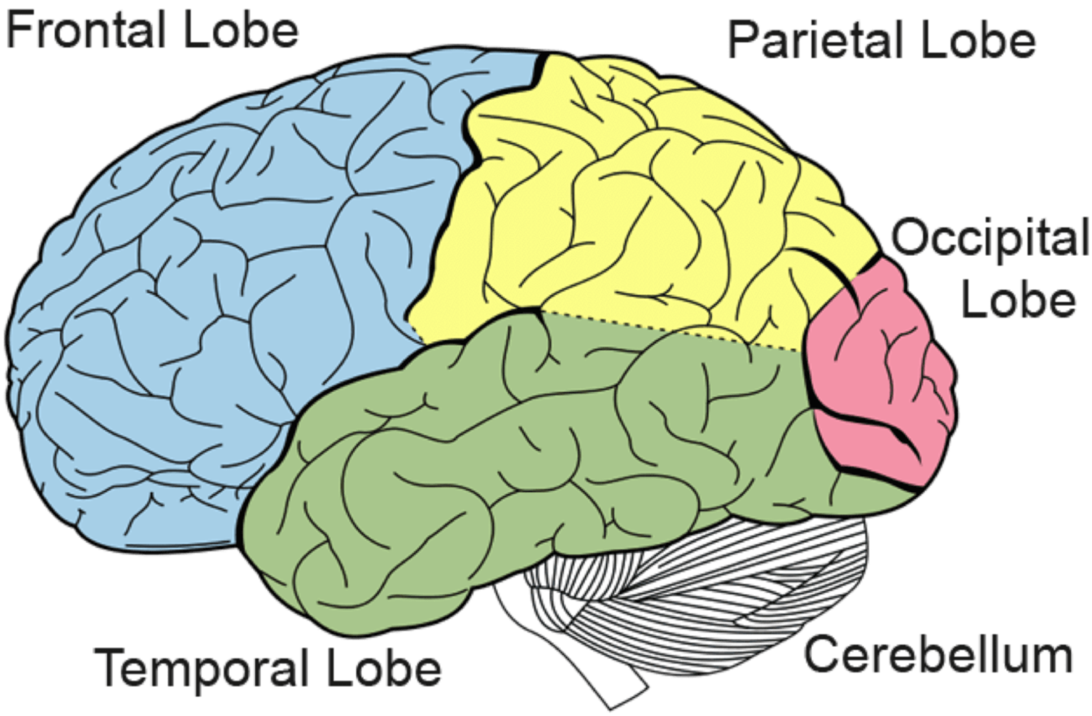


**Figure 1.** Diagram of the brain showing each region/lobe and its location (Farnsworth, 2020).

In order for the brain to function accurately, it must work hand-in-hand with the nervous system. There are two parts to the nervous system, the central nervous system (CNS) and the peripheral nervous system (PNS). The CNS contains the brain and spinal cord while the PNS contains all the nerves that span out from the brain and spinal cord in hopes of connecting the CNS to the body's other organs. However, for these brain signals to be transmitted to the body's organs, the PNS is divided into two systems: the autonomic and somatic nervous systems. The autonomic nervous system is responsible for all involuntary control of the internal organs, smooth and cardiac muscle, and blood vessels. In contrast, the somatic nervous system has voluntary control of the bones, skeletal muscle, joints and skin (Lumen Learning (b)). In order for these signals to be transmitted, neurons are used to help the brain communicate with the rest of the body through these signals. Neurons are made of three main components, the dendrite, axon, and axon terminal. The dendrites extend out from the cell body, which contains the nucleus and other organelles of the neuron, to receive messages from surrounding neurons and pass them to the cell body. The axon passes along the electrical signals from the cell body to the axon terminal. The axon terminal then passes the signal on to other surrounding neurons for the process of transmitting these signals to repeat itself (Lumen Learning (a)).

# 3. Neurotechnology

Neurotechnology is considered a way of measuring and/or analyzing the chemical and electrical activities partaking within the nervous system, specifically the brain and nerves throughout the body, by using technical tools (University of Freiburg, 2022). These technical tools can be used to detect changes within brain activity, which can then be analyzed and connected with different functions of the brain. For instance, electrodes such as those used in electrophotography - explained later on - detect changes in electrical activity within the brain by recording different frequencies present which then relate to specific brain waves and functions (Muller & Rotter, 2017). Another example of neurotechnology is the use of brain-computer interfaces. These interfaces allow interactions to be made between the brain and computers that can then be analyzed to better understand the brain.

## 3.1 Brain-Computer Interfaces

Brain-computer interfaces (BCIs) are used in order for humans to interact with computers through brain activity specifically (Hill & Wolpaw, 2016). BCIs can be inserted directly into the brain through an invasive procedure, or they can be inserted into the skull rather than the brain (semi-invasive), or they can be non-invasive and sit on the scalp. Although non-invasive BCIs record weaker signals due to the presence of the human skull, all these BCI insertion techniques are capable of recording brain activity to be analyzed as other neurological devices can (Gonfalonieri, 2018). In order for BCIs to allow humans to interact with computers, these devices must be able to record, analyze, and translate brain signals into specific commands that the computer can understand and perform what is asked of it by the user. The acquired brain signals however are only produced by the central nervous system (CNS) rather than the peripheral nervous system (PNS) as the PNS pertains more to muscles compared to the CNS, which includes the brain and spinal cord. Therefore, since BCIs are used to allow the human brain to generate a signal that can then be translated and used by the device to perform the task connected to that specific signal, BCIs are linked to the signals produced by the CNS (Krusienski et al., 2012).

# 4. Neuroimaging Techniques

There are many uses and types of imaging used in the field of medicine, such as neuroimaging. Neuroimaging is a type of medical imaging that focuses specifically on the brain and is used to understand how the brain functions, to diagnose any potential diseases, etc. (University of Utah, n.d). There are various techniques to neuroimaging, some of which are simpler than others. Some major and common techniques are computerized tomography (CT Scans), positron emission tomography (PET Scans), magnetic resonance imaging (MRI), functional magnetic resonance imaging (fMRI), electroencephalography (EEG), and functional near-infrared spectroscopy (fNIRS) (Lovering, 2021). All of these techniques are beneficial and allow different aspects of the brain to be studied. Specifically to this project, electroencephalography (EEG) and functional near-infrared spectroscopy (fNIRS) techniques will be studied further in depth.

## 4.1 Computerized Tomography

Computerized tomography (CT) scans can be used to scan not only the brain, but other parts of the body as well. These scans combine various X-ray images that are taken from different angles to then create cross-sectional images of the scanned area through computer processing (Mayo Clinic, 2022). Although very similar to X-rays, CT scans allow more detailed information to be retained from these cross-sectional images that can then be used to detect, monitor, or diagnose anything happening in the scanned area. Focusing on the brain specifically, CT scans are normally ordered by a medical professional when there is a need to assess the brain thoroughly without an invasive procedure taking place (John Hopkins Medicine (a), n.d.).

## 4.2 Positron Emission Tomography

Positron emission tomography (PET) is another type of neuroimaging technique that reveals how the brain is functioning, along with its related tissues, by studying blood flow. Differently from a CT scan, PET scans can be considered an invasive technique as a radioactive material is usually injected into the patient’s veins through an IV (MedlinePlus, 2022). The radioactive material injected is referred to as a tracer which emits a positive electron (positron) that then interacts with an electron within the targeted tissues of the body, in this case within the brain, to convert mass into energy through photons. The camera used in PET scans then detects these photons by using scintillation crystals that are placed around the area. These scintillation crystals record gamma-rays as they absorb the photons detected and produce light that is then converted into electrical signals that can be analyzed. This process of how electrical signals are generated through the emission of a positron is shown through figure 2 below (Berger, 2003).

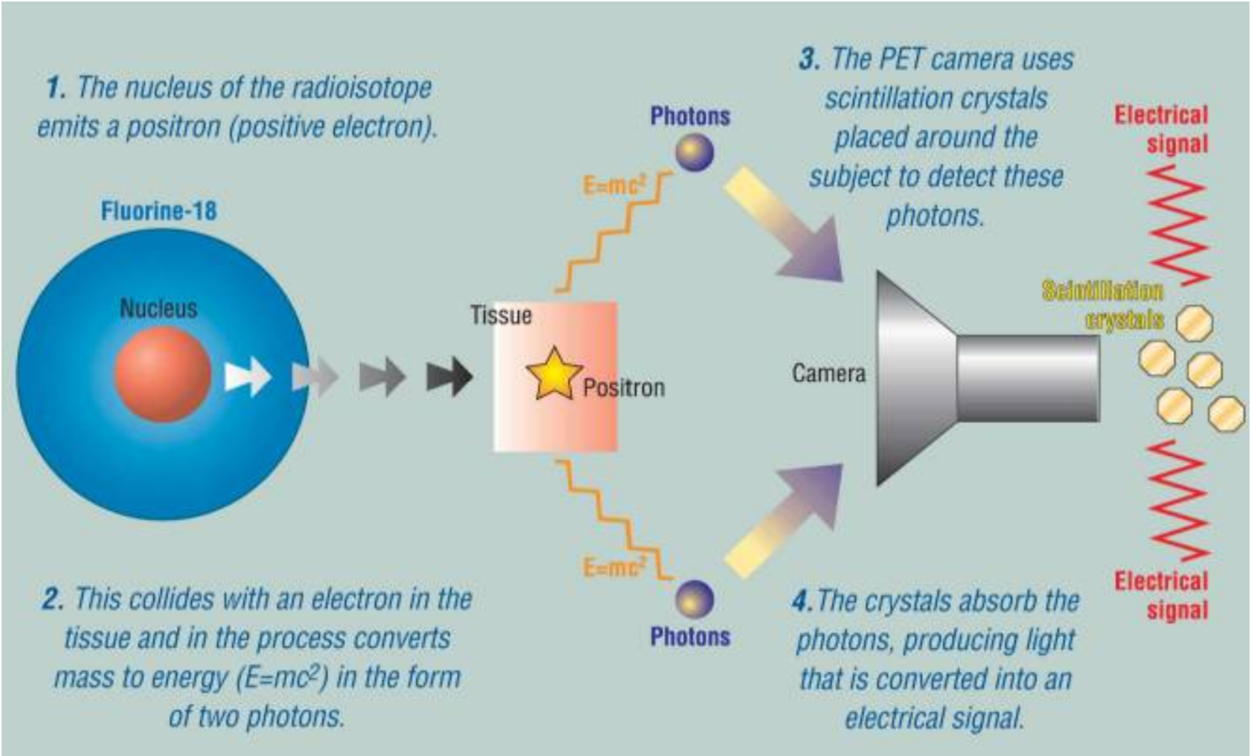


**Figure 2.** Diagram showing how PET scans function in terms of creating an electrical signal that can be recorded and later on analyzed (Berger, 2003).

## 4.3 Magnetic Resonance Imaging

Magnetic resonance imaging (MRI) is another non-invasive neuroimaging technique by taking two-dimensional pictures of the targeted portion of the body. MRI produces a magnetic field using magnets to force the protons found in the targeted area to align with the magnetic field produced. The MRI also contains radiofrequency coils that force radiofrequency currents to pulsate through the patient's body. These currents stimulate the found protons, forcing them to leave their state of equilibrium and leave the magnetic field they're aligned with. Once the radiofrequency currents are no longer flowing through the patient's body, the protons are capable of realigning with the magnetic field, however, how long it takes the protons to realign is what makes up the MRI image. Meaning that the speed at which these protons realign with the magnetic field determines how visible the obtained image will be (National Institute of Biomedical Imaging, n.d). When scanning the brain, different regions can be seen through MRI images that can assist in studying and/or treating these regions. The MRI images are also used for detecting any tumors or injury to the brain resulting in bleeding or fluid being found in the brain, as well as for diagnosing any other conditions or abnormalities (Johns Hopkins Medicine (b), n.d).

## 4.4 Functional Magnetic Resonance Imaging

Functional magnetic resonance imaging (fMRI) is very similar to MRI but only focuses on the brain, specifically active portions of the brain. fMRI is used to study the function of the brain through changes in blood flow and oxygen occurring in the active portion of the brain being studied (RadiologyInfo, 2020). The fMRI procedure is almost identical to the MRI procedure as the same magnetic field concept is used, however, when performing fMRI scans the patient is asked to perform silent brain tasks while remaining still. While performing these brain tasks, activity spikes in specific areas of the brain causing an increase in blood flow within them as well as oxygen present. This increase in blood flow causes active areas of the brain to light up in the scans, allowing readers to see which specific parts are being used and during which tasks (Yale Medicine, 2022).

## 4.5 Electroencephalography

Similar to the heart, the brain produces electrical activity through neurons that can be recorded and analyzed using electroencephalography (EEG). To do so, electrodes are placed on the surface of the scalp to measure the brain's electrical activity and are then connected to a device that records the data to later be analyzed. Within this brain activity, there are five major and different types of brain waves that can be detected. There are other signals that can be recorded by measuring electrical activity in the brain, however, these five brain wave types each have their own frequency ranges that are connected to specific functions of the brain. The first being the delta waves. Delta waves have a frequency range of 1-4Hz and are mainly used to assess deep sleeping in subjects. Theta waves, ranging from 4-7Hz, are associated with cognitive processing found in memory encoding and more. Alpha waves, similar to delta waves, are found when subjects enter a calm state with frequencies ranging from 7-12Hz. To find these alpha waves, subjects are often asked to lay back and close their eyes, putting them in a relaxing state of mind. In contrast, beta waves range from a frequency of 12Hz and can reach up to 30Hz with movement. These waves are also known for increasing when the testing subject is observing another person moving around in any way. Lastly, gamma waves typically have a frequency of 40Hz as they are found active in sensory processing and attentive focusing (Farnsworth, 2021). The frequencies produced by each of these wave types are recorded through the placed electrodes and then analyzed for various reasons. EEGs are mainly used for diagnosing specific medical conditions such as epilepsy, sleeping disorders, strokes, and other types of brain damage, but EEGs can also be used for purposes such as seeing how focused students are in class or other brain-oriented experiments (Mayo Clinic, 2020).

### 4.5.1 EEG Components

In electroencephalography (EEG) machines there are three important components: electrodes, amplifiers, and the computer/display device. EEG or other types of biosignal processing like EKG or EMG, the human body is considered one large part of the circuit. If a light bulb and a battery, the simplest example of a circuit, the human body in this case is the battery producing the voltages that are transferred to the light bulb, or in this case the EEG machine. Since we cannot simply plug wires into our bodies, the electrodes act as the direct collectors of these voltages. Electrodes are the metal parts that interact with the non-metal parts of a circuit. There are many different kinds of electrodes which can be divided into two groups: dry and wet. Wet electrodes usually consist of a silver/silver chloride (Ag/AgCl) material with some type of conductive adhesive medium that conducts the voltages between the skin and the electrode and helps keep the electrode in contact with the skin, typically electrolytic gel. Dry electrodes, on the other hand, consist of a single sheet of metal (usually stainless steel) placed between the skin and the electrode to act as a conductor without the use of an adhesive gel. In order to be useful, these signals need to go through much more processing which is conducted by the rest of the EEG machine. Since in most cases signals are not being directly collected from the brain, they are diffused through the skull and skin and as thus are very small, no greater than 10μV. Therefore, in order to be usable for processing, the signal is typically amplified by a device known as an operational amplifier or op-amp (Cionek, 2020).

Based on when this amplification occurs, electrodes can also be further broken down into two groups known as active and passive electrodes. Active electrodes involve a pre-amplification module that the signal is passed through directly from the electrode (ZETO, 2021). Passive electrodes lack this module and simply conduct the unaltered signal to a device that captures and processes the signal itself. Active electrodes are typically used in situations such as when extremely minimal noise is desired or when there is a large amount of electromagnetic noise in the environment or a large distance between the electrodes and capturing device (ZETO, 2021). By amplifying the signal before it is transferred to the machine it reduces the chance of amplifying any noise that is added during said transfer.

### 4.5.2 EEG Placement

To collect the proper EEG signals, the electrodes being used should follow the standardized 10-20 system. This system is used internationally to ensure that electrode placement will be the same throughout any EEG recordings. The placements span the patient’s entire head, covering all the brain regions while also maintaining equal spacing between the electrodes. Sixteen channels, excluding reference, ground, etc., make up the 10-20 system each with their own specific coding. As all brain regions (figure 3) are covered, each region is described as its first letter, for example the frontal region is coded as F, the temporal region is T, etc. For the numbering system that follows each letter, odd numbers represent the left side, even numbers represent the right side, and regions followed by “z” are placed on the midline. Starting at the forehead, there are channels Fp1 and Fp2, then back a little further is F7, F3, Fz, F4, and F8 (left to right). Next is the middle of the scalp, in line with the ears, starting with M1, T3, C3, Cz, C4, T4, and M2. Lastly, towards the back of the head there is a row of channels starting with T5, P3, Pz, P4, and T6, and then the last two, O1 and O2, at the end. When applying the 10-20 placement system to one’s head, always start with finding Cz as this is the overall midpoint. From there, the middle row of electrodes starting from M1 to M2 (or the pre-auricular points) can be placed horizontally with Cz being in the middle. The next set of electrodes (Fz and Pz) can be placed vertically along the midline, directly above and below Cz. Then the other left side electrodes (Fp1, F7, T3, T5, and O1) can be placed around the left side of the head, and the same can happen on the right side of the head with Fp2, F8, T4, T6, and O2. Lastly, places F3, F4, P3, and P4 can be placed as midpoints to the surrounding places (Hill et al., 2016).

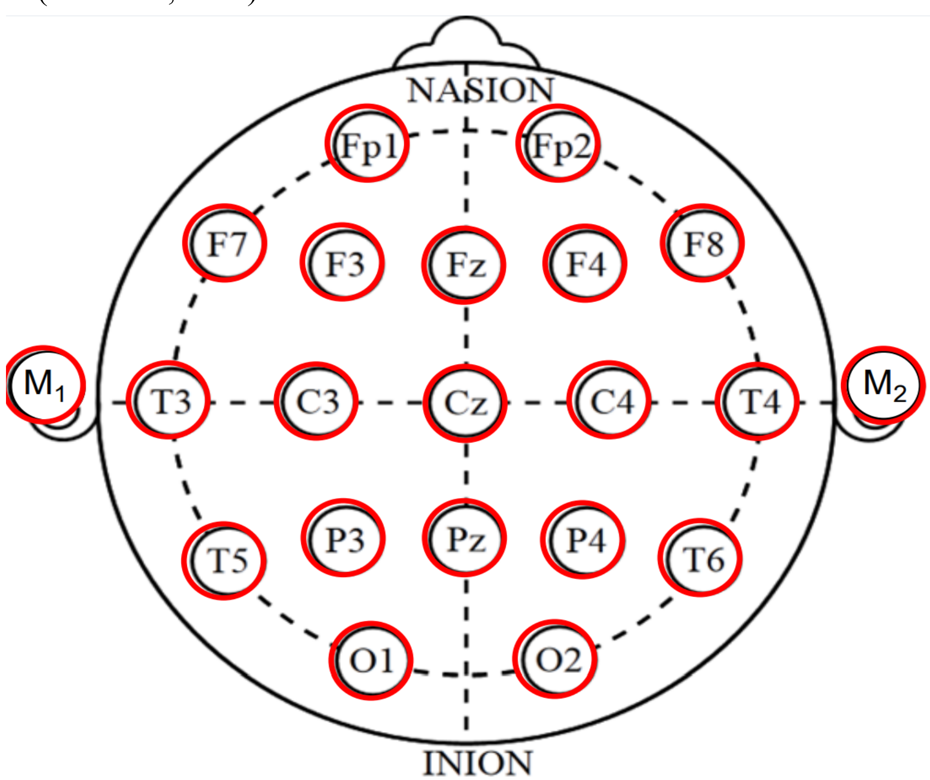


**Figure 3.** Diagram displaying 10-20 system for EEG placement (Hill et al., 2016).

Each of these positions provided by the 10-20 system described above can be used for specific testing experiments as each brain region is known for different things. For instance, positions relative to Fp1 or F3 are reading neural activity from the prefrontal cortex (or frontal lobes) of the human brain when performing cognitive tasks involving decision making, attention, or problem solving. Another example could be regarding positions O1/O2 which are used in reading neural activity from the occipital cortex/lobes of the brain that are mainly responsible for interpreting what we see, in terms of vision. Therefore, each of these positions labeled in the 10-20 system have a purpose when studying different regions of the brain through various types of experiments when looking to study specific topics (Farnsworth, 2020).

## 4.6 Functional Near-Infrared Spectroscopy

In connection with electroencephalography (EEG), functional near-infrared spectroscopy devices (fNIRS) are used for neuroimaging. These devices are non-invasive sensors placed on the scalp, similar to the electrodes talked about previously, to record changes in blood oxygen levels within the brain by emitting near-infrared and visible red light through the skull. The reflectance of this light by the brain tissue can be measured and used to estimate the blood oxygen levels present at the time of testing (PLUX Wireless Biosignals, 2020). By being able to record this data, these devices are often used in experiments where the participating subjects are asked to perform simple tasks like breathing or playing a video game. Depending where the device is placed during testing, the light will shine through the skull and about 5-8mm deep into the brain's tissue where it will then be reflected back to the photodiode found on the other half of the device. The amount of light that is reflected to the photodiode has been found to be directly proportional to the amount of light absorbed by the tissue, which on average a light with a wavelength ranging from 650-900 nm can travel up to 0.1mm before dispersing throughout the brain's tissues. However, when a portion of the brain is involved in a specific task, the blood oxygen levels will change along with the amount of light absorbed due to the amount of oxygen being present in that area through the blood (Beluk et al., 2012).

### 4.6.1 fNIRS Components

fNIRS are made up of six main components: microcontroller(s), LED(s), a photodiode, a current to voltage converter, an amplifier and an analog-to-digital converter (ADC). One or more microcontrollers are used to control the LED(s) as well as read the value provided from the ADC. Some devices also use a different microcontroller to control the LED(s) than the one used to read the value from the ADC. fNIRS devices use LEDs to produce a spectrum of near-infrared to red light with the most common configuration being two LEDs per channel to detect the ratio between oxygenated hemoglobin (HbO) and deoxygenated hemoglobin (HbR). The photodiode then converts the light that leaves the scalp to a current, which is converted to a voltage by the current to voltage converter. This voltage is then amplified by the amplifier, usually an instrumentation grade op-amp, and subsequently converted to a digital value by the ADC. Once converted to a digital value it is read by a microcontroller and transmitted/logged, sometimes using a separate microcontroller for logging/transmitting data presumably to allow the use of cheaper microcontrollers while maintaining temporal resolution.

### 4.6.2 fNIRS Placement

fNIRS placement commonly follows more dense versions of the 10-20 placement system, namely the 10-10 and 10-5 systems named for their 10% and 10% or 5% spacing of the electrodes upon the scalp. The 10-10 halves the distance between the electrodes compared to the 10-20 system, greatly increasing the total number of positions. These positions are labeled in a way similar to the 10-20 system, however, it expands the letter codes to accommodate the increase in the number of rows (figure 4). The added letter codes normally are labeled by their adjacent regions, e.g. FT is between the frontal and temporal lobe positions from the 10-20 system, the only exception to this being the AF code used to label the region between Fp and F. The 10-5 system further reduces the distance between the electrodes resulting in a large number of positions which allows the system to be easily used for multimodal measurements. Similar to how the 10-10 system labels the regions between the 10-20 systems, the 10-5 system labels the regions between those from the 10-10 system by adding a third letter to their code e.g. AFFp. These denser placement systems are better for fNIRS because they have better spatial resolution than EEGs. Additionally, due to how light travels through the brain and is absorbed/reflected, fNIRS emitters need to be placed relatively close to their detectors, generally around 3 to 5 centimeters to maintain a good signal to noise ratio (Balardin et al., 2018).

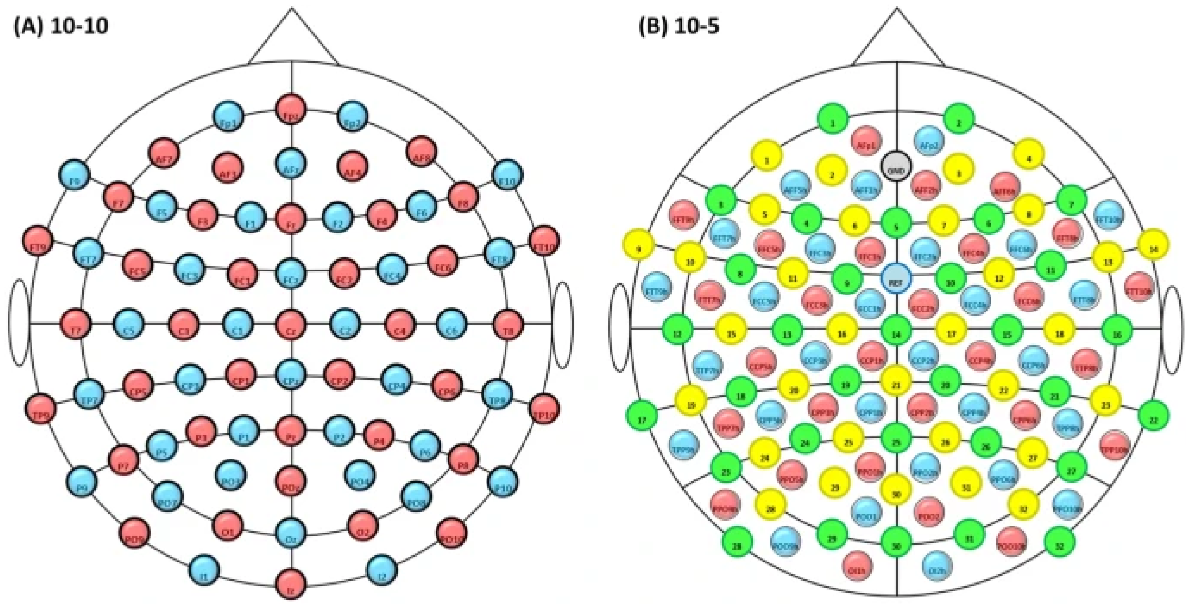


**Figure 4.** Diagram displaying the 10-10 and 10-5 systems for fNIRS and multi-modal placement (Balardin et al., 2018).

# 5. Applications

In the world of neuroscience, there are many different ways of using neurological devices, such as those including EEG and fNIRS sensors, to test different regions of the human brain. There are many different needs for testing different brain regions, as well as, many different applications for doing so as the data collected can be very useful in different fields. As studying neurological behavior can be useful in the medical or psychological field in terms of different disorders involving diseases or anxiety, it can also be used in the field of education and finding ways of engaging students specifically. In this section, some important applications of studying neurological behavior through EEG and fNIRS devices will be described in both the importance and what scientifically can be studied (i.e. different brain waves) through the neural activity collected from different experimentations.

## 5.1 Mood, Color, and Music

There are many different experimental applications for EEG headsets as the main goal is to receive some sort of neurological feedback. This feedback consists mainly of changes within the active brain waves such as alpha, beta, delta, etc. as each wave corresponds to different body responses. For example, changing the color of a room or the music playing are two ways of altering one's mood, which can be detected by using EEG recording devices. When present in a red colored room or listening to some heavy metal music, the person may feel some sort of anger, meaning that their alpha waves will not be as high as their beta waves will be. In contrast, if the person was in a blue colored room or listening to very light classical music, the opposite would occur as the alpha waves were increasing and the beta waves would decrease as relaxation occurs (Ashtaputre-Sisode, 2016).

## 5.2 Stress and Anxiety

Similar to detecting the changes in mood through high beta or alpha waves, EEG or fNIRS can be used in different experiments to measure stress levels. When feeling stressed or anxious, the main goal is to find a way to reduce that stress or anxiety that one is feeling before it becomes unbearable. In terms of the brain activities, stress and anxiety is connected with low alpha waves and high beta waves. Alpha waves induce relaxation, therefore when feeling stressed, increasing these alpha waves will put the person in a calming state of mind and reduce their stressful feelings. Similar to alpha waves, low theta waves are also associated with anxiety and stress as they are capable of putting the brain into a deep relaxation point too. Therefore, activating these waves may also be beneficial when detecting stress or anxiety levels through EEG and/or fNIRS. Lastly, these waves are also found responsible for producing GABA, which is known as a "peacemaker" chemical within the brain in order to calm the brain and person together (NeuroScience, 2020).

## 5.3 Education

Measuring the electrical activity within the brain through EEG recording devices can be used within the education field. By having students wear EEG devices, teachers could be able to measure whether students are focused or engaged in the lesson as a whole class or individual students. Specifically, the students' beta waves could be monitored in an environment like this as these waves respond to a focused mental state. These devices could also be used to study how the students interact with other students in the class through brain-to-brain synchrony, which could help with future student pairings (Atteveldt et al., 2020).

## 5.4 Medical

As the brain is a very complex organ itself, it is constantly being studied in various ways. In a medical sense, a common use of EEG and fNIRS are found in stroke detection. fNIRS can detect the changes in blood flow occurring in the brain that could potentially lead to cells becoming deprived of oxygen, failing, and causing a stroke to happen (Chowdhury et al., 2019). By being able to detect this before the stroke occurs, many patients could be saved as medical procedures can take place once aware that the brain is at risk of failing. Another medical application to using an EEG headset is for ADHD. By having an ADHD patient wear an EEG headset, their elevated theta waves and/or slowed beta waves can be detected and studied in ADHD research (Lenartowicz & Loo, 2014). Also, in terms of personal use for these particular patients, wearing the headset and knowing when the specific waves are increasing or decreasing, they will be aware of when their ADHD may act up the most and already begin to find ways to cope before it gets worse. For instance, analyzing the theta/beta ratio along with the current ADHD diagnostic criteria, it has been found through preliminary research that using EEG to diagnose ADHD is very promising. In a study done by a group of investigators, doctors had a jump from 61% to 88% in accuracy of correctly diagnosing ADHD in 275 children and adolescents when using EEG (Hornig et al., 2015).This study and the gathered data entertains the idea of creating a product for on site medical diagnosis, such as for ADHD.

## 5.5 Sleep

Sleep can be broken down into several stages contingent on the different types of brain wave activity which are also then separated into rapid eye movement (REM) and non-rapid eye movement sleep (NREM) sleep phases. The first four stages are a part of the NREM phase while the final stage is the REM phase. The first stage involves both alpha and theta waves as the person enters a state of relaxation yet they are not fully asleep yet. In the second stage the low-frequency theta waves begin to dominate the brain activity yet they are interrupted by short bursts of high-frequency and high-amplitude waves known as sleep spindles. These spindles are thought to be important to learning and memory. K-complexes, which are occasional very high-amplitude waves that appear in response to outside stimuli, also appear in this stage. The third and fourth stages are the deep sleep stages where the lowest frequency delta brain waves become dominant. Finally the person enters REM sleep in which their brain waves resemble those of someone who is awake (Lumen Learning (c)). Since the final three stages are considered the most important for feeling rested, EEG could be used to automatically recognize and analyze the duration in which these stages take place and report the quality of sleep based on the total time sleeping.

### 5.5.1 Sleep Spindles

The stages of sleep are phenomena denoted by the dominant brain waves shown in EEG readings. The second stage of sleep is the period in which low frequency (4-8Hz) theta waves become the most present; however, they are also accompanied by a phenomenon known as sleep spindles (Lumen Learning (c)). These spindles are very high frequency (10-16Hz) and occur for very short periods of time, only about 0.5-2 seconds (Andrillon et al., 2011). There are two types of spindles differentiated by their spatial occurrence and their range of frequency: fast (13-15Hz) centroparietal spindles and slow (9-12Hz) frontal spindles. Frontal spindles also lag behind centroparietal spindles by approximately 200 milliseconds (Andrillon et al., 2011). The placement of an EEG system is heavily influenced by this application as there are two areas in which the source density is maximized: Brodmann areas (BA) 7 and 10 (Alfonsi et al., 2019). Utilizing the 10-20 system for EEG electrode placement, the areas of focus would be P3, P4 areas for collection of the BA7 and the Fp1, Fp2 areas for BA10. The purpose of sleep spindles is not definitively known; however currently they are associated with sleep-related functions like memory consolidation and cortical development (Andrillon et al., 2011) therefore the lack of this phenomenon is a major concern in the analysis of mental conditions, most notably autism and schizophrenia. There are also prospective correlations to the amount of spindles with respect to chronotype, that is, whether an individual is a morning or night person, age, and genetics (Cade et al., 2017). With age, there is a decrease in spindle density (number of spindles per minute) and a slight increase in individual spindle frequency (Cade et al., 2017).

### 5.5.2. Autism and Sleep Spindles

Autism is known as a spectrum disorder usually found in children after twelve months of age. The symptoms of this disorder vary from patient to patient and are usually combinations of difficulty communicating/interacting, repetitive behavior/movements, upset at changes in daily routines, unusual responses to certain situations, etc. The combinations of these symptoms can range from mild to severe cases, causing patients to be mildly or severely sensitive to certain things like touch, noise, temperature, and more. These sensitivities are usually what lead to “meltdowns” that the patients experience, and it can be very difficult to avoid and stop these meltdowns. As these symptoms can be seen as early as twelve months, they are usually detected as the child shows no signs of babbling or pointing by this age, which often leads to diagnosis of autism. However, some patients develop normal language and social skills and as time goes on these skills begin to regress causing “regressive autism”. Currently there is no reason, prevention, or cure to autism, but it has been found that behavioral and speech therapy can help repress the disorder (Iowa Department of Education Early Childhood Services Bureau, 2010).

Along with the discovery of therapy being a step in the right direction of finding a treatment for this disorder, studies have proven that those with autism have fewer sleep spindles present in the second stage of NREM sleep when compared to the average person (Berthiaume et al., 2005). Also within these studies, it has been found that these sleep spindles are correlated with procedural memory (long term memory associated with performing different skills), which is something that those with autism tend to lack (Denckla et al., 2000). Therefore, this lack in sleep spindles found in autistic patients can be identified as a biological marker that can be detected using EEG and/or fNIRS during NREM2.

### 5.5.3 Schizophrenia and Sleep Spindles

Schizophrenia is a chronic brain disorder that can produce a lifetime of disability and emotional distress to those affected. Contrary to autism, symptoms of schizophrenia are found within patients between twenty and thirty years of age as signs of delusions, hallucinations, disorganized speech, trouble thinking, and lack of motivation are noticed (Torres, 2020). There also is no cure for schizophrenia, however, these symptoms can be diminished through constant therapy sessions. Development of schizophrenia has been connected to genetics as it has been found that first-degree relatives of those with the disorder are at greater risk of also developing the disorder when compared to second-degree relatives. Also, focusing on twins, identical or monozygotic twins are at greater risk for developing schizophrenia rather than fraternal or dizygotic twins. The children of identical twins are also at high risk, regardless of whether the actual parent has the disorder or the parent's twin has it (Levitt & Lewis, 2002).

Similar to autisic patients, those with schizophrenia also have fewer sleep spindles compared to the average person. As sleep spindles are generated within the thalamic reticular nucleus through thalamocortical and corticothalamic connections, the lack in sleep spindles may indicate that there is some sort of malfunction within this nucleus and the corresponding connections. In relation to diagnosis of schizophrenia, this malfunction could be a very significant biological marker of this disorder that, with more research and use of EEG and fNIRS to detect changes in both electrical activity and oxygenated blood flow through the brain, could potentially allow this disorder to be diagnosed and treated early on (Bria et al., 2007).

# 6. Market Comparison

When looking to design a product that is capable of doing the same things as already existing devices, it is important to look into those existing devices and see how they differ. Also while looking at those devices, different criteria can be selected and scored in terms of value to the new device being designed. In this case, various EEG and fNIRS devices were researched in terms of what features they consist of and what they're capable of. While looking at these features, specific criteria such as battery life, comfortability, and modality were considered to be some of the most important and crucial factors to creating a new device that would stand apart from the devices currently on the market. In this section, each criteria that was pulled from the devices described in the following section will be described and scored in a table format to organize the importance of the criteria.

## 6.1 Value Analysis

### 6.1.1 Comfortability

The comfortability metric that we have come up with has to do with how long the device can be worn comfortably while collecting data. As we want our device to be comfortable for the user, we decided on making our comfortability metric very high. When using a wearable device to record data over long periods of time, making the device comfortable to the user should be one of the main priorities; especially considering comfortability is one of the areas that current devices are struggling in. In terms of recording neural activity for different applications, being able to wear such a device for 24 hours or more would be ideal as the neural activity recorded from the targeted brain regions could be done so during one's everyday routine.

### 6.1.2 Battery Life

Another important criteria for creating a wearable recording device is it's battery life. Based on the comfortability section above, if this device can record data for more than a day, it's battery life needs to be more than sufficient in comparison to these other devices. However, this could be difficult when looking to design a device that not only records but stores data from potentially two or more sensors. Currently, the biggest problem with batteries in a situation like this is finding the right one to fit the needs of the device and making the battery life last as long as possible while performing all the necessary functions.

### 6.1.3 Durability

The durability of the device is also another important factor. This new device should be easily worn while a person is in a non-contact environment and must also stick to their head, even with prolonged exposure to a surface and sweat. That being said, the adhesive of the wearable device must be strong enough to withstand exposure to sweat, water, etc. as it will be designed to be worn for extensive time periods. Along with the adhesive, the material of the device itself should also be durable to withstand any potential contact, especially if the device is designed to be worn overnight, etc. These device components may also affect the installation of the device as the stiffness can make a device harder to install or the flexibility of the device can make installation easier.

### 6.1.4 Data Storage

For data storage, using onboard storage as well as streaming would be beneficial in heavy data recording devices. Streaming the data allows the device to be completely enclosed while also removing the need for any external ports. Whereas the use of onboard storage allows the recording of data without the use of streaming. This means that the device would be capable of operating even when a stable connection cannot be made. However, the amount of storage needed would be determined after determining how to store the data along with how much data is being recorded and stored within the device.

### 6.1.5 Data Resolution

In terms of data resolution, approximately 512Hz would be enough for sampling with both fNIRS and EEG sensors. By looking through the sampling rates of currently marketed devices, having a value of 512Hz as a sampling rate would be high enough to collect functional data while also consuming the least amount of power during recording. That being said, this sampling rate would be considered the happy medium for both the resolution of data being collected and the overall battery life of the device.

### 6.1.6 Modality

Most of the BCI devices currently on the market only operate on one modality, or use one type of sensor to collect data. Majority of the time, that one sensor is an EEG, which means that these devices tend to get really good temporal data but poor spatial data. Receiving good temporal data is one benefit of using EEG sensors, whereas receiving poor spatial data is not. Other types of sensors that could be paired with these BCI devices are EOG, which measure eye movement, and fNIRS that measure the levels of oxygenated hemoglobin in a targeted area. Creating and using a multimodal device is significantly beneficial in comparison to using an unimodal device as multimodality allows for more than one aspect of the brain, in this case, to be recorded and eventually analyzed.

### 6.1.7 Modularity

The modularity of these devices could be said to be situational based as it depends on what the device was made to measure. For instance, if measuring means of sleep, the device would want to mainly be placed towards the back of the head as that is where the most reliable data would be collected. But, if measuring attention or focus, the device should be placed on or near the forehead as the best data would be retrieved from the prefrontal and frontal cortices.

Therefore, when creating a new device that may also be multimodal, the modularity of it may be different compared to current standard modularity cases.

**Table 1**. Value analysis table where each of the design goals described above are scored on their importance to the device design on a scale of 1 to 10.

| Design Goal | Value/Score |
|---|---|
| Comfortability | 9 |
| Battery Life | 10 |
| Durability | 7 |
| Data Storage | 7 |
| Data Resolution | 7 |
| Modality | 9 |
| Modularity | 5** |
| **TOTAL:** | |

*appearance as well - considered sub-goal to these goals*
**Modularity depends on the specific device design and purpose.

The value analysis table shown above (Table 1) lists each of the design criteria chosen from current devices on the market and described above. Each criteria is listed as a "design goal" and is scored based on it's individual value or importance to a new device design. For instance, battery life is scored the highest as any device used for recording neural activity for an extended period of time must be able to withstand that time period, meaning the battery needs to last as long as possible for extensive recording to occur. In contrast, the modularity of the device is scored the lowest. As this specific goal depends on the device itself and what it's intended purpose is, the modularity can only be scored with a specific device or design in mind. In terms of the durability, data storage, and data resolution of the device are all scored the same as these three goals are equally important, but they're just not as important when compared to battery life or comfortability. Collecting data is certainly important but how it is stored and seen through the device can be overlooked as having the data is the most essential part. Also, in terms of durability, the device should be durable (especially if being worn for extensive time periods) but make the device comfortable to wear and multimodal would be more beneficial when designing a new device that differs from those already on the market.

## 6.2 Existing devices

There are many existing EEG and fNIRS based devices currently on the market ranging from low to high resolution consumer models or to expensive models that are more targeted towards research. One of the cheapest consumer available EEG devices is the toy Mindflex. While being relatively cheap and using dry electrodes, it requires a physical connection to the user's ear to serve as a reference and there are also questions about the validity of EEG data it's capable of collecting. A portable solution called Muse utilizes EEG with several dry electrodes to record data from the front of the head. However, this is non-multimodal and only utilizes EEG sensors to do so. Additionally, it has a relatively small form factor but yet it is still significantly larger than a patchable solution. The company DSI offers a portable EEG and fNIRS based device that transmits data over Bluetooth. However, this device collects data from several regions on the head using large, uncomfortable sensor pucks that contain both the fNIRS and EEG sensors. Also, due to its large number of sensors it only has a battery life of approximately four hours. Lastly, the company Artinis offers several different fNIRS based headsets, including a portable one that measures activity at the front of the head. Unfortunately, their multimodal devices use the cap form factor making them bulky and non-portable. From this subset of available devices, there seems to be an apparent gap in the BCI market for portable, multimodal devices that utilize a small form factor. The market also proves that both fNIRS and EEG can both be utilized together in a small portable form factor. This gap could potentially be filled by creating a multimodal, patchable device.

### 6.2.1 Muse Headset

An EEG headset created by the company Muse, records electrical activity primarily from the prefrontal cortex of the subject. This headset consists of six sensors arranged on a band that wraps around the forehead and hooks behind the ears. Although not the most appealing device to society, this headset has been said to be comfortable enough to wear up to two hours per day while its battery can last up to five hours when used continuously. In terms of application, this device is specifically known for mediation and sleep as it provides real-time neurofeedback. Once this data is collected at a resolution of 256Hz, it can then be stored in channels (10Hz each) and then transferred via bluetooth (MUSE, 2021a and 2021b).

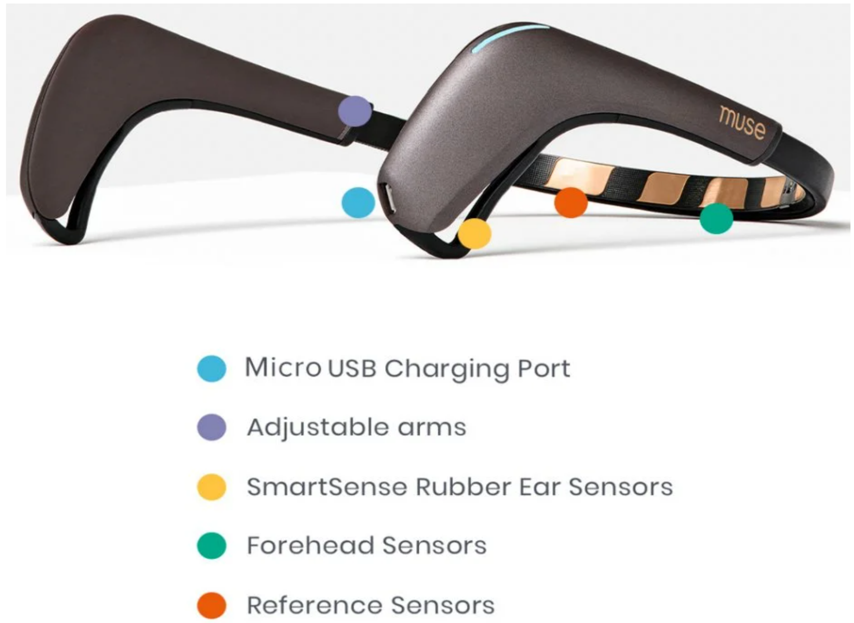


**Figure 5.** Diagram displaying the Muse Headset along with its sensors and other components (MUSE, 2021a).

### 6.2.2 AttentivU Glasses

Another group of researchers out of MIT created a socially acceptable pair of glasses that reads both the EEG and EOG of the particular subject. This device is considered multimodal as it consists of recording both EEG and EOG through the motor and somatosensory cortices. To do so, the device has two EEG sensors and two EOG sensors that are used to measure cognitive load, fatigue, engagement, and focus of the subject in real time. Also, as this device was created to resemble a pair of glasses that most wear daily, this device is comfortable enough to wear for extended periods of time, allowing neural activity to be captured for longer times compared to other devices. With that, the longevity of the AttentivU device is about fifteen hours, which allows data to be collected for more than half the day as the device is powered by a Lithium Polymer (LiPo) battery. Lastly, in terms of data, all data collected can be stored and transferred via Bluetooth at a currently unknown resolution (Kosmyna et al., 2020).

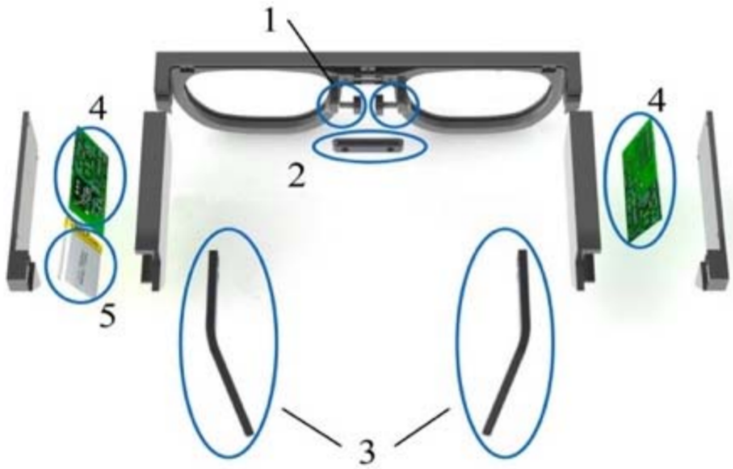


**Figure 6.** Diagram displaying the AttentivU Glasses along with its components; (1) EOG electrodes, (2) EEG reference electrode, (3) EEG electrodes, (4) PCBs, and (5) integrated battery (Kosmyna et al., 2020)

### 6.2.3 Emotiv Insight Headset

The Emotiv Insight is an EEG headset that rests above the ear and has five electrodes protruding from it, two on the forehead, one on either side of the head and one near the back of the head. It uses three pronged saline based electrodes to get signals without the use of gel, additionally the prongs allow it to collect measurements from regions of the scalp that have hair. According to the company the headset is comfortable to wear, however there is no specified amount of time it can be comfortably worn for. The Emotiv Insight has a battery life of four hours when sending data over bluetooth or eight hours when being used in a wired configuration. It collects data at 128Hz with a resolution of 0.51μV/LSB which can be streamed to a device via bluetooth or through a data cable (EMOTIV, 2021).


**Figure 7.** Diagram displaying the Emotiv Insight Headset (EMOTIV, 2021).

### 6.2.4 Neurable Headphones

Neurable, a neurotechnology company located in Boston, has created a device that resembles headphones. The Neurable Headphones contain sixteen sensors, eight around each ear, to mainly record activity from the auditory, primary somatosensory, and primary motor cortices using EEG specifically. As there are sensors around each ear, this data is recorded from both hemispheres, rather than just one. However, the only downside to having this many sensors is the comfortability aspect as these headphones have been used for about forty minutes before becoming uncomfortable to the user. Even though uncomfortable, this device can be charged rapidly and has an "all-day battery life", which is very beneficial when hoping to record neural activity throughout a whole day. Similar to the AttentivU glasses above, the Neurable Headphones were primarily created for focus tracking as the device gives scores at different times while being used to tell the user/researcher how focused the user is when performing certain tasks. These scores are determined by the neural activity captured and stored at a resolution of 500Hz and then eventually transferred via Bluetooth (Alcaide et al., 2021).

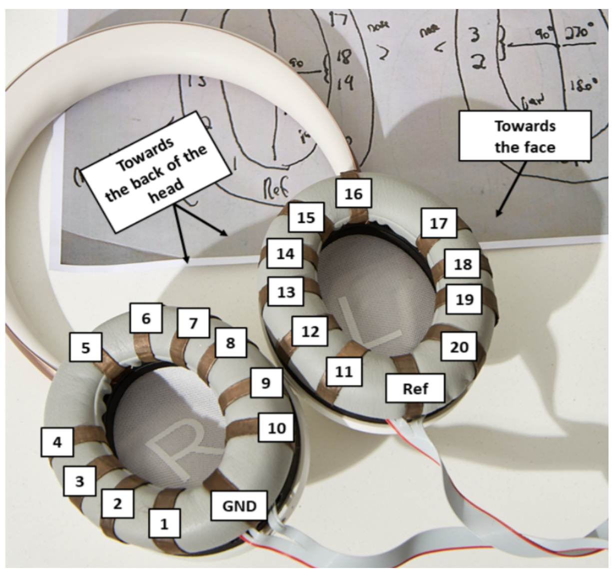


**Figure 8.** Diagram displaying the Neurable Headphones with the locations of all recording sensors. (Alcaide et al., 2021)

### 6.2.5 Ear-EEG

As most EEG devices are known for recording data either from being placed on the forehead or behind the ear, neural interfaces placed inside the ear (also known as ear-EEG) actually collect data from the ear canal. The ear-EEG consists of electrodes placed both in the ear canal and concha. This is usually done by using a device similar to ear plugs with electrodes embedded within them. As this approach is more discreet compared to a headphone styled device as the device is placed directly inside the ear, it is also said to be more comfortable compared to other scalp devices. The embedded electrodes both recording data from within the ear canal and concha are coded in conductive gel, while also connected to a g.tec USBamp amplifier. From there, the data is collected using the g.Recorder software that works hand-in-hand with the g.tec amplifier. Lastly, in terms of design, when using this ear-EEG concept the device is customly made to fit each individual performing tests. These custom devices have mainly been created through 3D-printing by using ear imprints from each patient (Kappel et al., 2015).

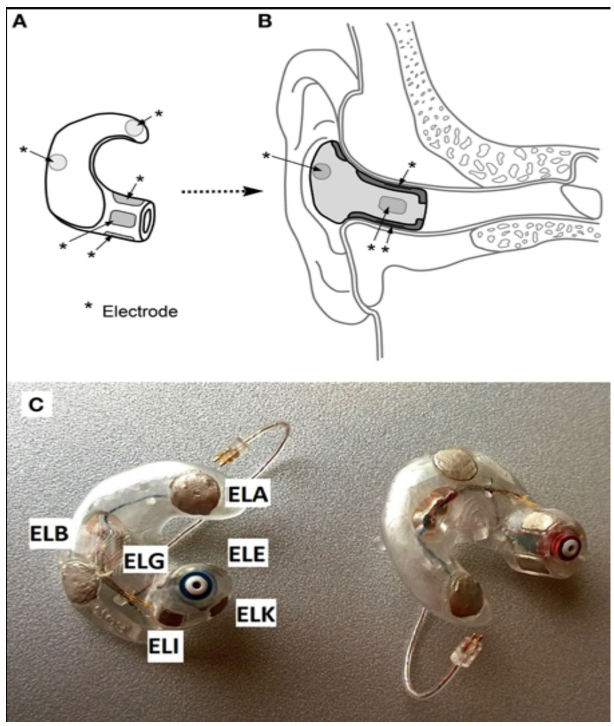


**Figure 9.** The top diagram shows the positioning of the device within the ear canal and concha, along with where the electrodes are embedded (shown by little stars). The bottom diagram shows a custom made ear-EEG where ELG is at the posterior surface of the ear canal and ELE is at the superior surface of the canal (Kappel et al., 2015).

### 6.2.6 Humm Patch

Humm is a patch-based tACS device that is attached to the forehead with a temporary adhesive. Unlike an EEG or fNIRS headset it does not collect data from the brain but instead attempts to stimulate it through the application of current to the scalp. Because of its light weight, flexibility and form factor it is comfortable to wear. The Humm patch proves that a patchable device can be made to allow comfortable contact to the scalp with electrodes (HUMM, 2021).


**Figure 10.** Diagram displaying both sides of the HUMM Patch (HUMM, 2021).

### 6.2.7 mBrainTrain Smartfones

Similar to Neurable, mBrainTrain has also created an EEG headphone device that decodes the user's attention from their neural activity as music is played. This device consists of eleven semi-dry electrodes, four around each ear and the remaining three within the band spanning the top of the head. This allows the device to collect activity from the auditory, primary, and primary somatosensory cortices as well as the auditory association. Although very similar in design to the Neurable Headphones, this device seems to be more comfortable as users have been able to wear it for a couple hours rather than forty minutes. This device also has a better data resolution of up to 1000Hz as the data is stored and transferred using SMARTING streamer and android apps. However, the Neurable Headphones do have a better battery life/longevity compared to this device that can only withstand up to five hours of usage (mBrainTrain, 2012).


**Figure 11.** Diagram displaying the mBrainTrain Smartfones along with its three central electrodes, four other electrodes surrounding each ear, and some other device facts. (mBrainTrain, 2012)

### 6.2.8 Flow Headset

Another headset device created by Flow has a little different approach compared to the other devices previously described. This headset goes over the midline of the head and has two electric stimulating nodes that are placed on the forehead. This placement allows the device to stimulate the frontal cortex by electrical stimulation. Electrical stimulation of the frontal cortex is used in depression treatment through tDCS neuromodulation through the use of this device. Similar to the other devices, the Flow Headset is controlled via Bluetooth and can be used for up to five hours. However, this device is not as comfortable as others as users claim to use it for thirty to sixty minutes before being uncomfortable (Flow, 2020).

**Figure 12.** Diagram displaying the Flow Headset (Flow, 2020).

### 6.2.9 Sens.ai Headphones

The Sens.ai headphones utilize EEG in a headphone-based form factor that also attempts to stimulate the brain using LEDs. The EEG portion of the headphones has three gel free electrodes placed along the midline of the scalp presumably targeting the Fz, Cz and Pz positions. Its battery can last 8+ hours while connected to an iPhone using BLE, however it is recommended to use the device for around ten minutes. The device's manufacturers claim to be able to read brain waves up to and above 50Hz including gamma waves. They do not make any claims about the rate or resolution that they collect data at (Sens.ai, 2021).

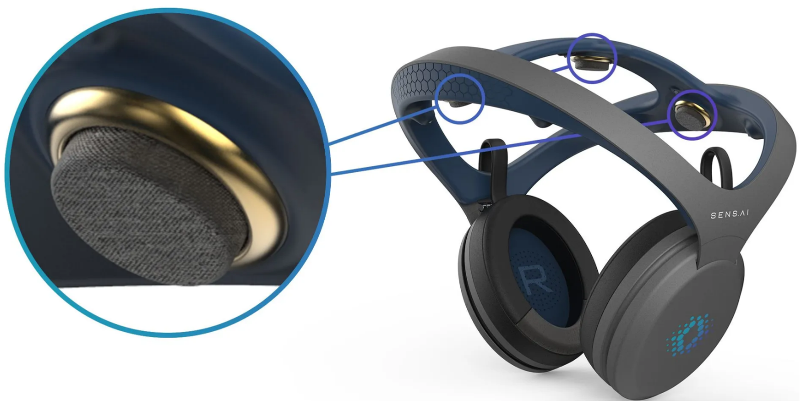


**Figure 13.** Diagram displaying the Sens.ai Headphones along with a close up photo of the gamma-grade sensors used (Sens.ai, 2021).

### 6.2.10 NeuroSky MindWave Mobile 2

Another EEG recording device with a more modern design is the NeuroSky MindWave Mobile 2. This device resembles a headband but with an adjustable arm extending to the forehead specifically above the left eye. The headband stays in place with the help of a small clip that attaches to the left ear. There is one EEG electrode placed at the FP1 position and a ground/reference electrode within the ear clip. This device is known to measure, track, and even improve attention, meditation, and focus of the user for up to eight hours. The recorded data is stored through a proprietary software and transferred to a device within 10m via Bluetooth after being collected at a resolution of 512Hz.


**Figure 14.** Diagram displaying the NeuroSky MindWave Mobile 2 device (NeuroSky, 2015).

### 6.2.11 Epilog Patch

Lastly, the Epilog patch has been created by Epitel specifically for seizure detection. This EEG patch consist of two electrodes within one small patch that has been designed to wear near one's hairline in order to record data from the prefrontal cortex. This device is capable of being worn/used for seven days as its single lithium watch battery supports continuous EEG recording over this time period without being replaced or charged. This data can then be transmitted through the connected app using Bluetooth. Also, when Bluetooth is disconnected, the device is capable of storing ten days worth of recorded EEG data. The powering and recording components of the patch are packaged in a medical-grade silicone with a hypoallergenic conductive hydrogel and adhesive hydrocolloid applied in ordnationaler for the patch to stick to one's forehead. For the best results, four patches are applied in positions F7, F8, T5, T6 following the 10-20 system in hopes to capture all aspects of where the seizure(s) will most likely occur (National Library of Medicine (U.S.), 2018).

**Figure 15.** Diagram displaying the Epilog Patch and its EEG sensors/electrode (Drees et al., 2021).

## 6.4 Pugh Analysis

Pugh analysis used in this scenario compares the features of devices currently on market with what we consider to be the gold standard for EEG devices. Our gold standards are based on the BiosignalsPlux Hub EEG sensors that were used for testing in this project. These listed features are considered relative metrics when designing a device to what criteria we deem to be of importance. Focusing on the comfort metric, we decided that if the user could wear the device for longer than a hour without feeling any type of discomfort, it performs better than the gold standard. If the device has a battery life of over 10 hours and a data resolution greater than 512 Hz then it performs well in these categories. A device that includes a modality other than EEG is considered better than the gold standard. Using each of these relative metrics, devices that perform better than the gold standard are given a 1, those that perform equally as well are given a 0, and those that perform worse are given a -1. These values are then weighted and summed to give each device a value. Those with higher values perform better overall in the desired criteria.

The most important conclusion to draw from this pugh analysis is that the majority of current products on the market do not provide multimodal approaches to their goals, meaning that these devices focus solely on the utilization of EEG signals. Our proposed design is novel in that it utilizes both EGG and fNIRS signals to bring multiple perspectives to the previously discussed applications.

**Table 2**. Pugh analysis chart comparing current solutions against the BiosignalsPlux Hub.

| | Weight | Gold Standard | Muse | AttentivU | Emotiv | Neurable HP | Humm | mBrainTrain | Flow | Sens.ai HP | Epilog Patch |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Comfort** | 2 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | -1 | 1 |
| **Battery Life** | 4 | 0 | -1 | 1 | -1 | 1 | -1 | -1 | -1 | -1 | 1 |
| **Data Resolution** | 2 | 0 | 0 | 0 | -1 | 0 | 0 | 1 | 0 | 1 | 0 |
| **Modality** | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | -1 |
| **Modularity** | 1 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| **Sensor Reliability** | 5 | 0 | 1 | 0 | 1 | 1 | -1 | 1 | 0 | 1 | 0 |
| **Totals** | | 0 | 3 | 8 | 1 | 12 | -7 | 5 | -2 | 1 | 5 |

# 7. BioSignals Plux

BioSignalsPlux is a biosignal acquisition company that creates specific devices that can be used in researching different kinds of biosignaling. For this project, we will be using the BioSignalsPlux hub, EEG sensor (to study electrical activity within the brain), and fNIRS sensor (to detect changes in oxygenated blood flow in the brain) while conduct numerous experiments to study how this activity differs between various regions of the brain. All the data collected using the hub and two connectable sensors is done so by using the OpenSignals software, which works hand-in-hand with the BioSignalsPlux devices. As this company does not produce medical devices just yet, these devices and their components can be used in various other ways such as in biomedical or life science research, human-computer interaction, robotics, physiology, psychophysiology, neurophysiology, sleep studies, neurofeedback, and many more.

## 7.1 Four Channel Hub

The main BioSignalsPlux device is the hub. The hub has four analog ports, with which it can acquire data through various connected sensors simultaneously at a sampling rate of 3kHz per channel. Along with the analog ports, the hub also has an auxiliary port, known as the ground channel. The hub has a battery life of about ten hours when used for streaming as it is powered by a 700mA 3.7V Lithium Polymer (LiPo) rechargeable battery. The hub also communicates and transfers the collected data by Bluetooth Class 2 (PLUX Wireless Biosignals, 2018).


**Figure 16.** BioSignalsPlux four channel hub used to record data through various sensors that can be connected through the hub's four analog ports (PLUX Wireless Biosignals, 2018).

## 7.2 EEG Sensor

There are many different types of sensors that could be connected with the BioSignalsPlux hub described previously that can each read specific kinds of data. As for the EEG sensor, it allows users to monitor electrical activity within the brain by simply being placed and held on the scalp rather than performing any invasive procedures to gather EEG data. This single-channel differential sensor is ready to use from its packaging as it has both a medical-grade raw and pre-conditioned analog outputs, high signal-to-noise ratio, and a miniaturized form-factor. In terms of specifications, this particular EEG sensor has a gain of 47.8 with a range of 37.5mV (when VCC = 3V) and bandwidth of 0.8-48.2Hz. The sensor also has an input impedance over 100GOhm and a common mode rejection ratio (CMRR) of 100dB. Lastly, the sensor has a male connector type of UC-E6 that allows it to connect with the hub and collect data (PLUX Wireless Biosignals, 2015).

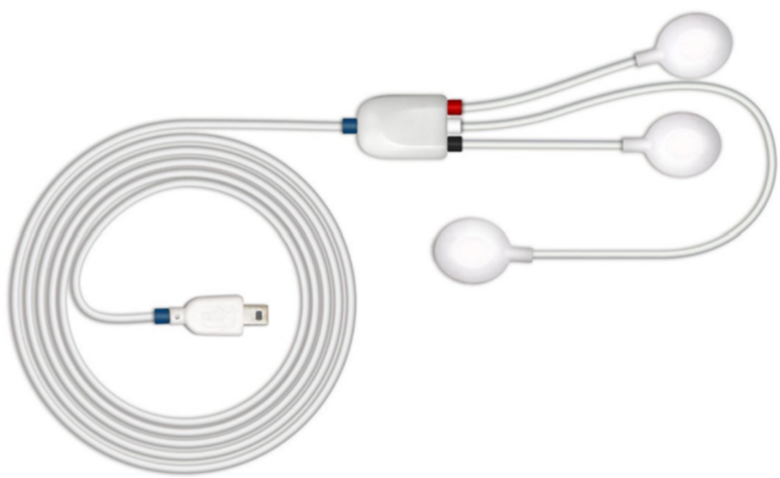

**Figure 17.** BioSignalsPlux EEG sensor connected to the hub to record electrical activity within specific regions of the brain (PLUX Wireless Biosignals, 2018).

## 7.3 fNIRS Sensor

Also used with the BioSignalsPlux hub is the fNIRS sensor, which uses two LEDs and a detector to record changes within the oxygen levels found in the blood flowing through a specific brain region that is being studied. Similarly to the EEG sensor described above, the fNIRS sensor is placed mainly on the forehead, usually Fp1 or Fp2 positions, while the patient is asked to perform tasks as simple as breathing. Overall the sensor has a resolution of 16 bit at a sampling frequency of 500Hz as it communicates with the BioSignalsPlux Hub through a serial peripheral interface (SPI) by sending it's pre-conditioned digital output to the hub after recording. This fNIRS sensor is also capable of adjusting the current for each LED by using application programming interfaces (API). Along with this, the sensor has a high signal-to-noise ratio and a ready-to-use form factor as it is mainly used in life sciences studies, human-computer interaction, biomedical research, and more (PLUX Wireless Biosignals, 2017).

Focusing on the two LEDs, one is an infrared emitter with a peak emission of 860 nm (at a radiant intensity of 750mW/sr) and the other is a red emitter with a peak emission of 660nm (with a power output of 7mW). The infrared emitter has a half intensity beam angle of $\pm$13 degrees while the red emitter has a greater angle of $\pm$18 degrees. In contrast, the infrared emitter has a slightly greater spectral bandwidth of  30 nm when compared to the spectral bandwidth of the red emitter (25 nm). Looking at the detector, it is considered a photodiode that receives the light reflected by one the LEDs previously described  and then converts that absorbed current into a digital value sent to the BioSignalsPlux Hub through SPI. This detector has a sensitivity range of 400-1100nm with a maximum wavelength sensitivity being 850nm. The detector also has a radiant sensitive area of 7mm$^2$, where the area's dimensions are 2.65mm x 2.65mm (PLUX Wireless Biosignals, 2017).


**Figure 18.** BioSignalsPlux fNIRS sensor used to record changes in blood oxygenation levels present in the specific brain regions (PLUX Wireless Biosignals, 2018).

## 7.4 OpenSignals Software

When using the BioSignalsPlux Hub and any of the attachable sensors, such as EEG and fNIRS, the OpenSignals software must also be used when recording data. This software provided by BioSignalsPlux is known as a versatile but easy-to-use software that directly interacts with the devices through Bluetooth connection when recording data. The software not only records the data but it also helps the user visualize and process the data. In terms of data analysis, the OpenSignals software also has features that can be added on to help analyze the data directly without having to do any additional coding unlike other software (PLUX Wireless Biosignals, 2020).

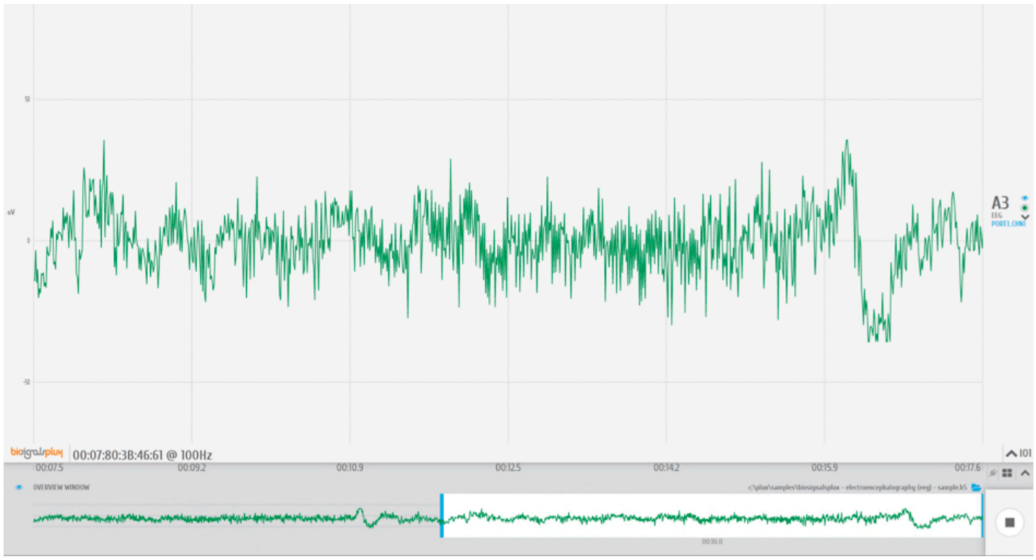


**Figure 19.** EEG sample recording from BioSignalsPlux User Manual (PLUX Wireless Biosignals, 2018).

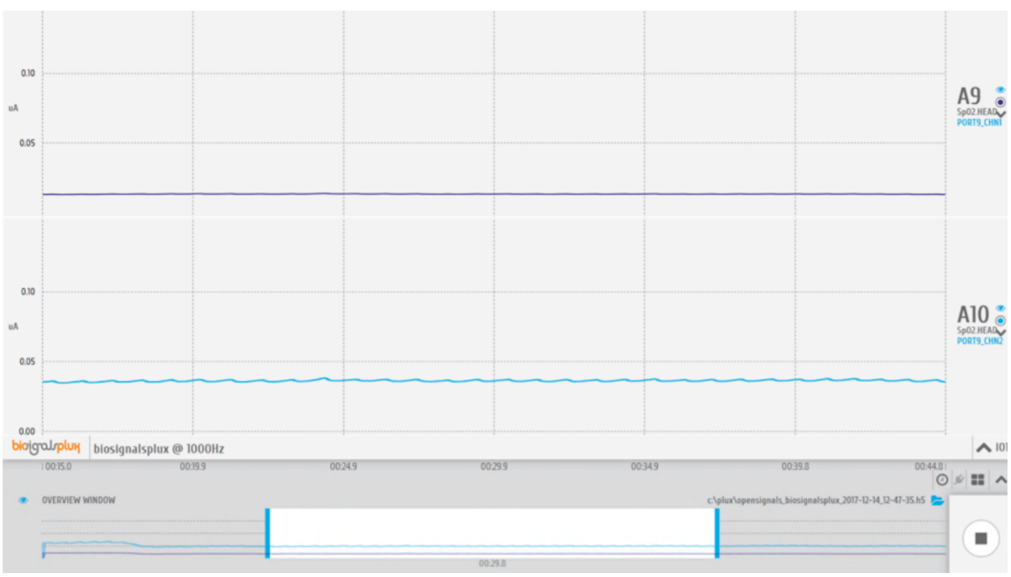


**Figure 20.** fNIRS sample recording from BioSignalsPlux User Manual (PLUX Wireless Biosignals, 2018).

# 8. Design

## 8.1 Electrical Design

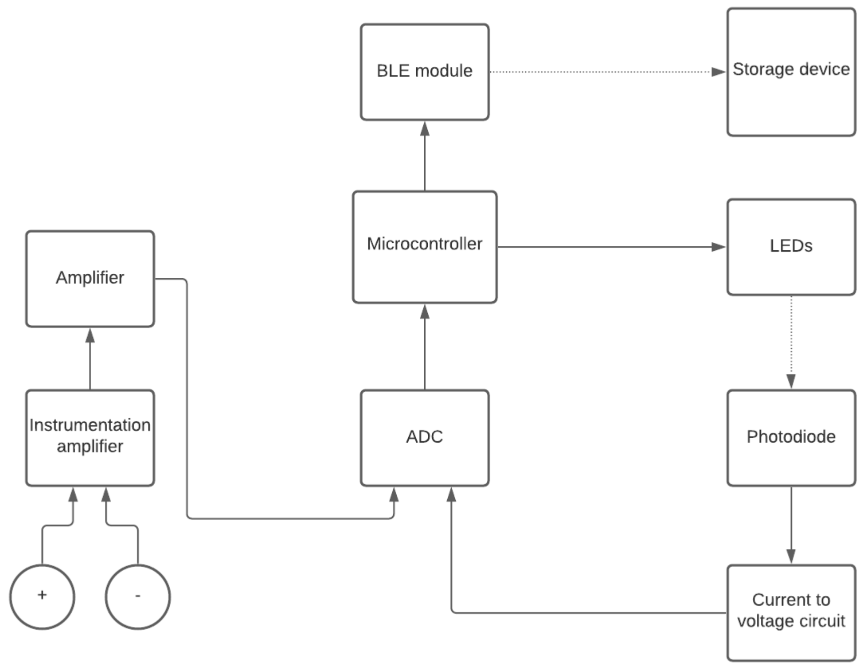


**Figure 21.** Block diagram of necessary systems for both EEG and fNIRS sensors created by using Lucidchart (Lucidchart, 2021).

A combined fNIRS and EEG device requires a similar set of systems as the individual devices share some similarities with how they function. Additionally, the number of components could be reduced by utilizing an IC with multiple operational amplifiers for the second stage of the EEG amplification as well as for the voltage to current circuit. Further details on the components required for EEG and fNIRS can be found in the Neuroscience Background section.

## 8.2 Pairwise Analysis

Pairwise analysis used in this scenario compares the device features that are considered relative metrics when designing a device to each other. This compares the importance of a feature in the left column to a feature in the top column. The left column is assigned a relative value of importance when compared to the top column; 0 being less important, ½ being equally important, and 1 being of greater importance. This causes each row to be summed together to get the relative importance of what should be prioritized when designing a device. For example, based on the pairwise analysis table shown below (Table 3), the battery life or power consumption of the device should be the most important component when designing the device. Whereas, the modularity and durability of the device is not a crucial component in creating a new design as both features rank the lowest.

**Table 3**. Pairwise analysis chart comparing each design goal listed in our value analysis against each other.

| **Pairwise Analysis** | Comfort | Battery Life | Durability | Data Storage | Data Resolution | Multimodal | Modularity | Total |
|---|---|---|---|---|---|---|---|---|
| Comfort | X | 0 | 1 | 0 | 0 | 0 | 1 | 2 |
| Battery Life/power consumption | | X | 1 | 1/2 | 1/2 | 1 | 1 | 4 |
| Durability | | | X | 0 | 0 | 0 | 1/2 | 0.5 |
| Data Storage | | | | X | 1/2 | 1 | 1 | 2.5 |
| Data Resolution | | | | | X | 1 | 1 | 2 |
| Modality | | | | | | X | 1 | 1 |
| Modularity | | | | | | | X | 0 |

0- less important
½- equally important
1- more important

### 8.3 Design Goals

Based on both criteria analysis, the main goal of the proposed device is to provide longer remote duration than what is on market, factoring in both battery life and subject comfort, as well as novel scope by providing both EEG and fNIRS modalities in one device design. This device could ideally be designed as a patch that the subject could easily wear for extensive periods of time to record neural activity while performing everyday tasks. In terms of battery life, this device should be capable of recording data for more than 24 hours using both EEG and fNIRS sensors. Using two different types of sensors to record data alone may drain the battery of the device over a short period of time. Therefore, finding a battery that can withstand these conditions is very important to efficiently collect data. This patchable device must also be durable, if being worn throughout the day. For example, if the patch is worn when the subject is sleeping, the patch must remain adhered to the skin throughout the night regardless of any tossing and turning the subject may do when sleeping. The components, i.e. the sensors, should be enclosed as well to avoid any potential damage due to movement or contact. As for the collection of data, the data should be stored on the device itself and also be capable of streaming. The device should have a sampling frequency around 512Hz as this would provide readable data without draining the device's battery. Lastly, based on the testing done using both the EEG and fNIRS sensors together as in a multimodal device design, the ideal placement would be the side of the head (specifically positions F8 and T4 for EEG and Fpz for fNIRS).

# 9. Baseline Testing and Analysis

## 9.1 Baseline Testing

For signal testing using the BioSignalsPlux EEG sensors, we systematically went through various placements on the scalp using the 10-20 system and ran various tests on different subjects. One of the tests performed with the EEG sensors placed in various places following the 10-20 system was having the subject open and close their eyes every 30-60 seconds (known as the eyes open, eyes closed test). This test was used as a baseline to detect whether alpha brain waves were detectable by the device as they are expected to appear strongly during the eyes-closed sections.

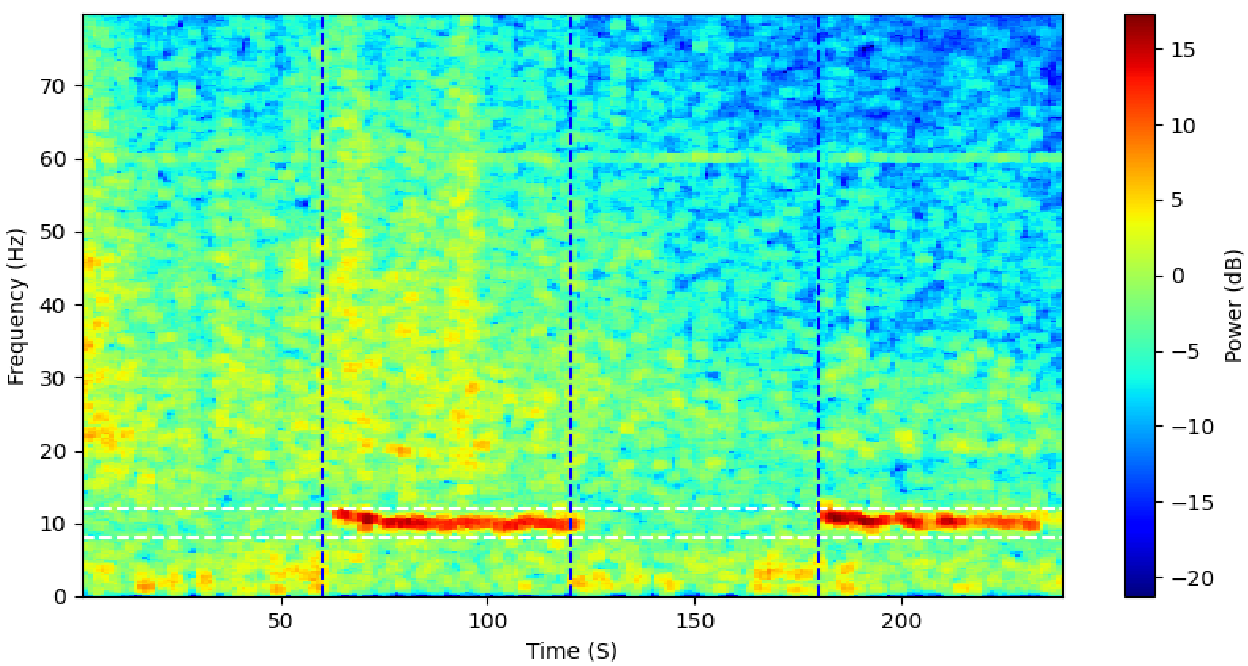


**Figure 22:** Multitaper spectrogram EEG signal from eyes open, eyes closed test over 4 minutes (240 seconds). The blue dotted lines mark 60 second intervals, approximately when the subject swapped between having their eyes open or closed. The dark red regions show increased activity in the alpha band when their eyes are closed, the alpha band is shown with horizontal dotted white lines.

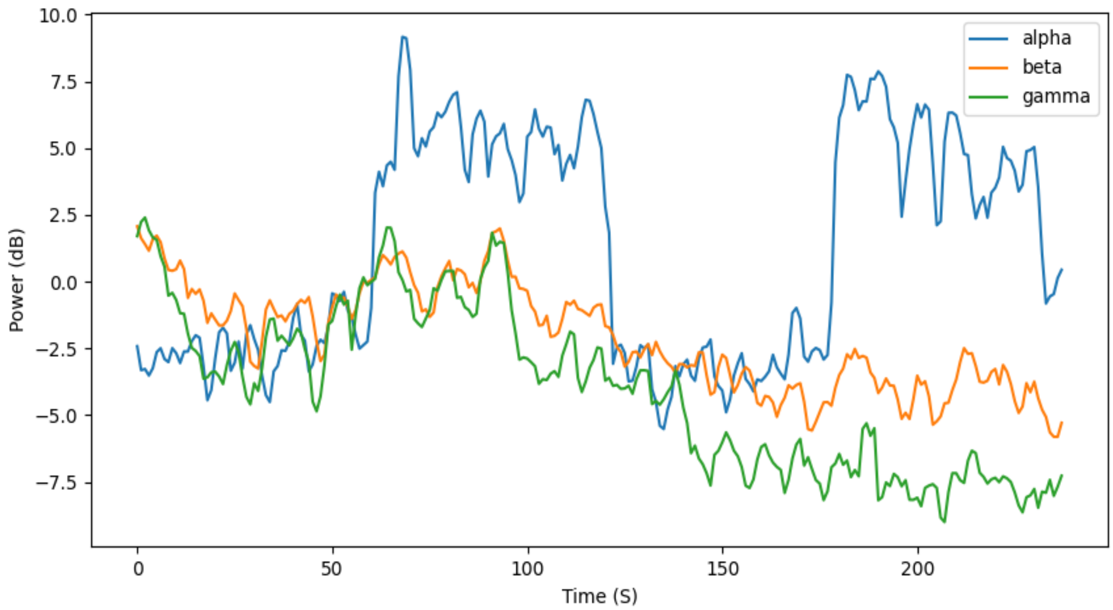


**Figure 23:** EEG wavelet energy for each waveband of alpha, beta, and gamma that shows the intensity over time as the average power in decibels over each band. This graph shows the power of recorded brain activity over the alpha, beta, and gamma bands from the same recording as the previous figure. It shows a noticeable increase in intensity in the alpha band both times the subject closed their eyes, at 60 and 120 seconds.

As shown in the spectrogram, figure 22, strong bands matching alpha wave frequencies, that is 8-12Hz, can be seen at the 60s and 180s timestamps both lasting 60s. This can be seen in a different format in the wavelet energy graph, figure 23, as the power of alpha increases during the eyes-closed sections and returns to normal as the subject opens their eyes. A notable feature in this data is that the subject's overall activity of beta and gamma decreased by 2.5db through the duration of the experiment while alpha stayed constant. Based on this baseline, we could conclude that the device was functioning as intended and that the position the sensors were collecting from were successfully creating an EEG channel we could collect data from reliably. Another simple experiment conducted using the EEG sensors, sustained attention reaction test (SART), was used to test the sensors' capability in capturing beta and gamma waves. The subject utilizes a virtual reality (VR) game where they are positioned in an office-like setting facing a monitor that flashes numbers on the screen for about five minutes. The subject then has about one second to respond to the number shown. For example, when the screen shows any number that is not "3", the subject must click the trigger given to them. While playing this VR game, a background program tracks the subject's reaction time and whether or not their response was correct. Then on the preprocessing end, the average reaction time is displayed over time (in seconds) to be used in comparison to the amount of beta and gamma activity found during the experiment. The hypothesized result is to see a decline over time in a subject's focus indicated by both a decline in beta and gamma activity as well as reaction time.

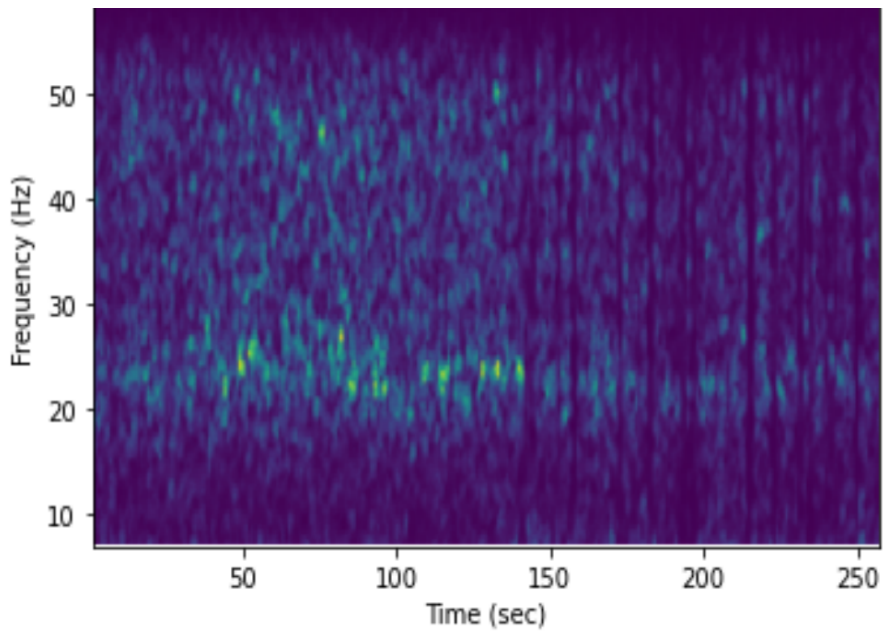


**Figure 24:** Multitaper spectrogram EEG signal from first project group for SART experiments. This specific spectrogram shows that there was gamma activity within the subject's brain during the experiment.

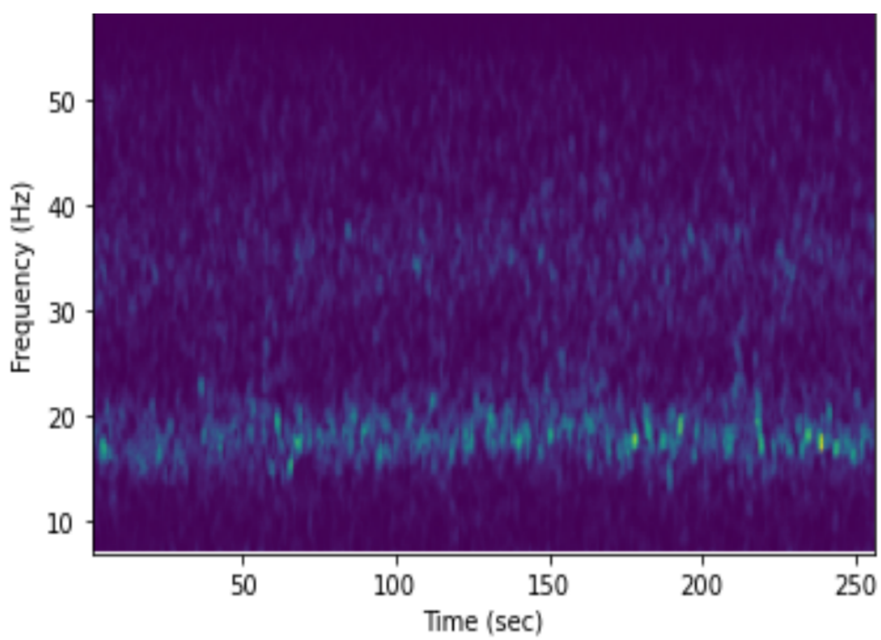


**Figure 25:** Multitaper spectrogram EEG signal from first project group for SART experiments. This specific spectrogram shows that there was beta activity within the subject's brain during the experiment.

As a baseline test for the fNIRS sensors, a simple apnea experiment was performed by asking the subject to hold their breath as long as possible. The expected outcome is a drop in $SpO_2$ concentration as the subject holds their breath. As seen in figure 26, the $SpO_2$ concentration slowly declines between the 20-30 second mark until the subject catches their breath and the concentration swiftly returns to the level seen initially.

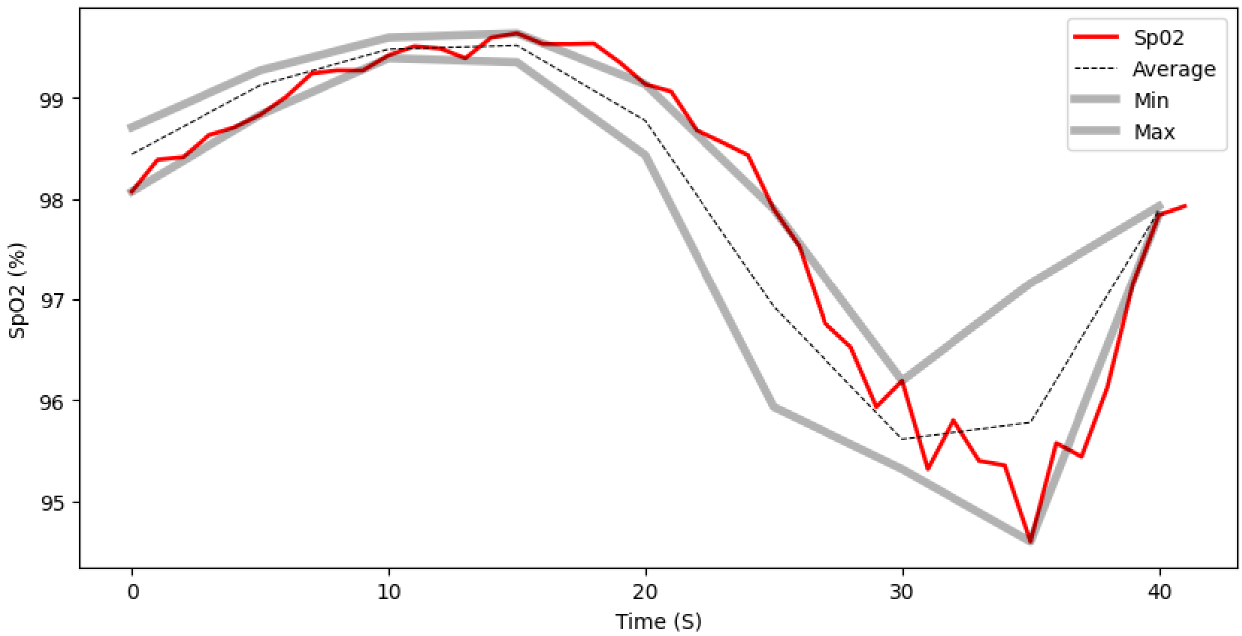


**Figure 26:** Filtered and smoothed waveform for the SpO2 concentrations from the data collected from the fNIRS sensors from an apnea test. While this test is ongoing about ten seconds into the recording they hold their breath then after the thirty second mark they begin to breathe normally again. This leads to the behavior of the declining sp02 concentration and then its subsequent rise. This is also where you can find the characteristic spo2 being a lagging indicator as it takes about 5 seconds to react to the change in state.

## 9.2 Analysis and Results

To prepare our fNIRS data for analysis we converted it to discrete filtered points. The first step was to convert the raw data to microAmps to normalize the inputs from the two emitters due to the response curve of the detector. Then filter high frequency noise such as the heartbeats of the user by subtracting the result of a fourth order Butterworth high-pass filter with a critical frequency of 15 hz from the microAmp values. After the values were filtered using an equation from the manufacturer for this device they were converted to SpO2 values, SpO2 referring to the ratio of oxygenated hemoglobin (Hbr) to the total hemoglobin (Hbt) also called the blood oxygen level. The data was further smoothed by taking a rolling average, unwanted fluctuations caused by breathing were removed by using a notch filter at 0.2 hz, and lastly these values were averaged in 30 second windows moved with a step of 2 seconds to collect points to compare to the reaction times.

To prepare our reaction time data for analysis we converted it to discrete points that are synced with the points from the fNIRs data. First the values corresponding to when the user did not supply input were filtered out. Then the timestamps were converted to be relative to the start of the fNIRs recording. Using these points, averages and standard deviations were calculated over windows matching those used for fNIRs data to create points that were synced to their respective fNIRs data.

Using the synced points from the previous steps the reaction time was plotted relative to SpO2 using a scatter plot. Due to large amounts of noise observed at the beginning and ending of the SpO2 values points removed from the ends of the data to keep the noise from masking the data. Using these points the correlation between the two sets of data was calculated as well as the line of best fit. Using these values it was found that there is a weak negative correlation between SpO2 and reaction time variance in our data on average having an R2 value of 0.13, this value might be improved by altering the testing methodology or increasing the trial duration to increase the variance over time of the reaction time and its standard deviation. This relationship means that an increase in SPO2 would indicate an increase in attention, which can be seen as a decrease in reaction time variance. The source code used for the data processing and analysis can be found at https://github.com/Ubiquitous-EEG-IQP/DataViewer.

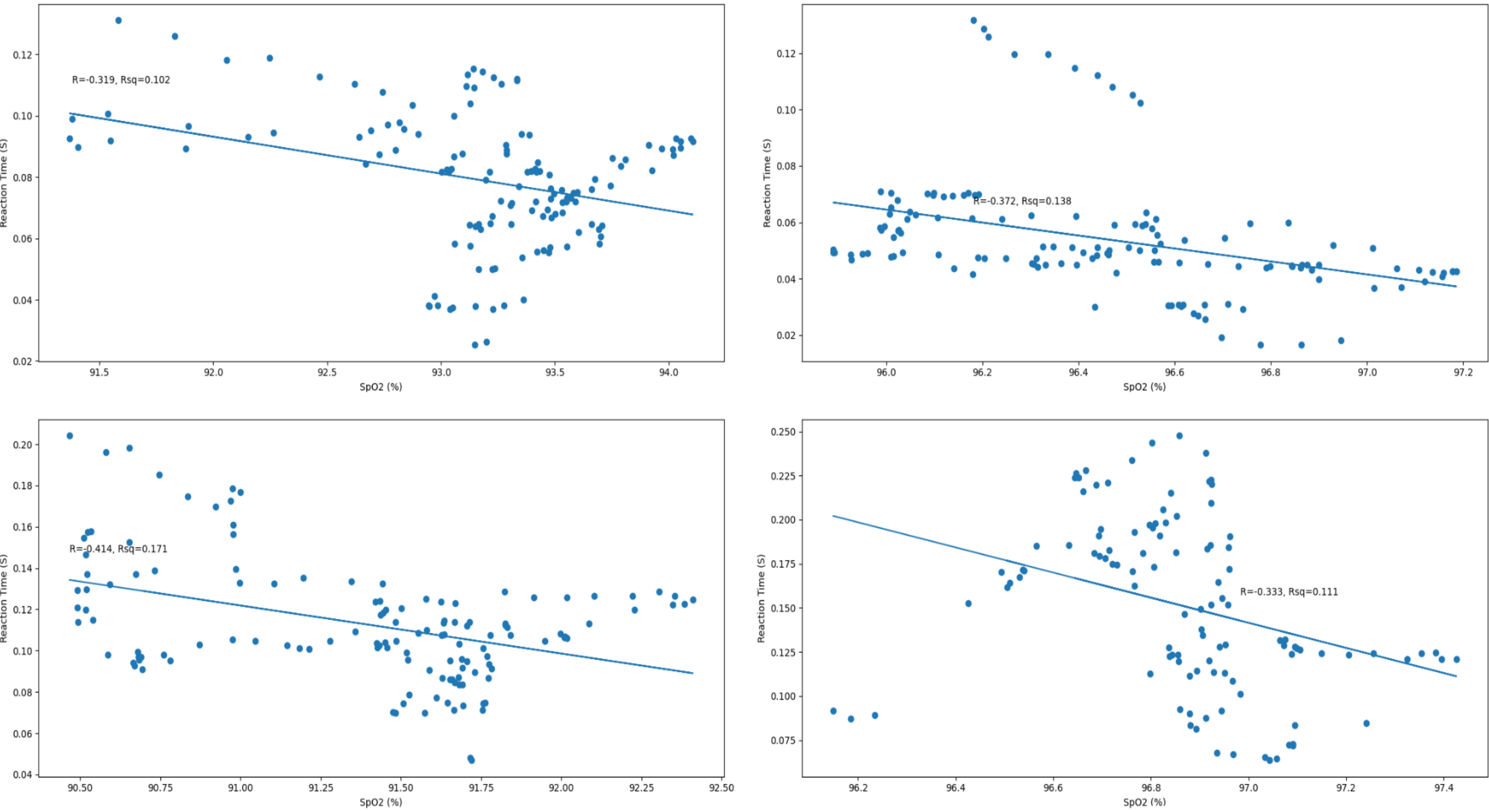


**Figure 27:** The resulting scatter plots are from several SART tests with SpO2 on the x axes and the variance in reaction time on the y axes.

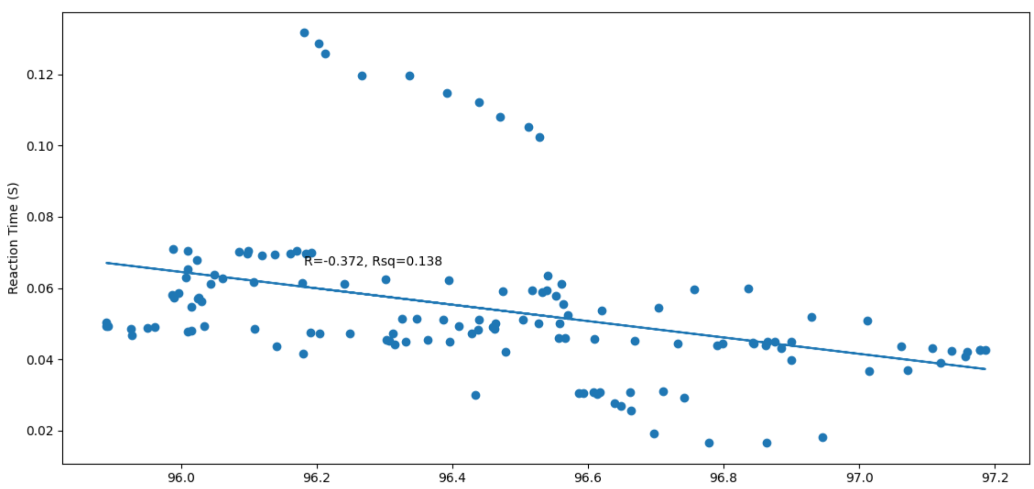


**Figure 28:** The resulting scatter plot from a single SART test showing how SpO2 and variance in reaction time are negatively correlated

# 10. Prototype

While testing, the best neural activity retrieved from using the BioSignals Plux EEG and fNIRS sensors were from positions on the forehead and above the subject's ear. Specifically, the EEG was placed at F8 and T4, when following the 10-20 system, and the fNIRS was placed at Fpz, when following the 10-10 system. When performing the eyes open eyes closed experiment, alpha activity was found through this EEG placement. In this same configuration, beta and gamma activity were found when performing the sustained attention experiment (shown in figures 24 and 25 above). As for fNIRS, the best data has been retrieved from this placement as changes in $SpO_2$ are seen, as shown in figure 26. This makes sense considering the BioSignals Plux fNIRS sensor was made to be used in this configuration compared to others.

When looking at the patch design, it's dimensions are 135mmx40mmx5mm and consist of indentations for both sensors and the wires attached to them. These indentations are all 4mm deep, leaving 1mm of material that will provide both protection and block out any outside light from interfering with the fNIRS. The EEG sensors are placed 30mm away from each other in order to both be placed in their designated positions. The furthermost sensor indentation is 5mm away from the edge of the device itself. The fNIRS are designed to be placed as one whole piece (even though the one used in testing was cut in half and placed edge to edge) with the wires extending from both ends. The sensor itself is 10mm away from the closest edge and 5mm away from the closest EEG sensor. The indentations extending from each sensor indentation are specifically designed to fit the wires extending from each sensor. The dimensions of each wire was taken three times before the average measurement was calculated and used in the design shown below. Although this prototype was only designed and never created, the idea was to 3D print the design and add some sort of adhesive to the flat surfaces surrounding the sensors to accurately test the sensor placement and the design concept of using an adhesive patch before going any further with material decisions.

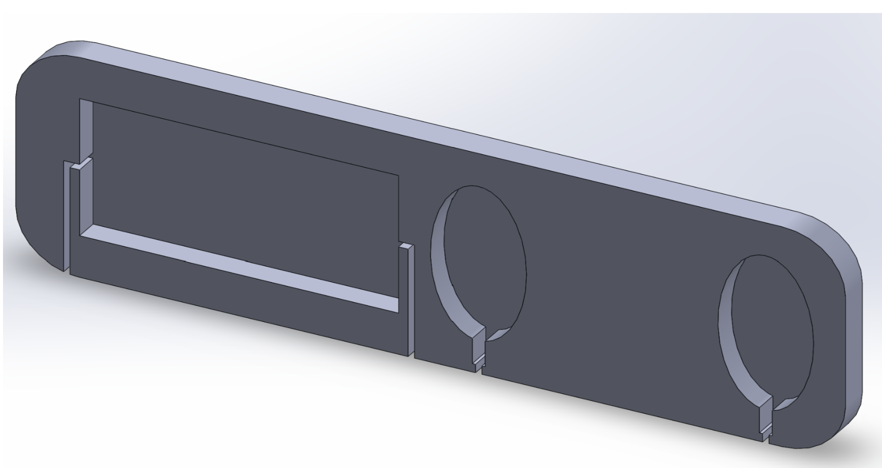

**Figure 29:** Potential design for a patchable device using SOLIDWORKS.

# 11. Future Work

There are several ideas with respect to sensor development and analysis that we would have liked to pursue during the development of this project. One improvement to our current sensors that could be made is the partial removal of the rubber shroud on the fNIRs sensor. By doing this the length of the channel would be reduced which would increase the intensity of the light received, and in doing so improve the signal to noise ratio. This change would also make the layout of the device more closely match the industry standard for emitter detector layout, in which they are closer than the 2cm that the device is currently at due to its rubber shroud.

Additionally it could be fruitful to pursue improving/expanding the designs proposed in this report to further this project. One way this could be done is the use of flexible materials such as silicone or polyurethane (or in its printable form TPU) to construct the proposed patch design from figure 29. By doing this the device would be more compliant removing the need to alter its design in the event that it does not naturally fit on the user. As for the electrical design it could be converted from a block diagram to a schematic by deciding which parts are required and best suited for the construction of each of the subsystems. Additionally by doing this the system could be cost optimized by combining similar systems, for example voltage to current circuits like the one required to collect data from the photodiode are commonly constructed using operational amplifiers, which could be used in the second amplification step of the EEG device; meaning that using an integrated circuit with enough amplifiers, as it is common to have several amplifiers contained within a single chip, it would allow the person designing the device to remove the need for a dedicated chip for the current to voltage circuit.

An improvement that could be made to the analysis that was outside the scope of this project would be implementing Beer Lambert's law to extract both HBo and HBr from our raw data. This is the most common method for extracting meaningful data from the raw intensity data provided by fNIRs sensors. In this case, the method used to extract data is an equation provided by the manufacturer of the device to convert its raw data into SpO2, which measures the ratio of oxygenated hemoglobin(HbO) to the total amount present(HbT) and, because of this it doesn't react to changes in the total amount of hemoglobin present. Additionally, because it divides HbO by HbT, it obfuscates the hemoglobin response of both HbO and deoxygenated hemoglobin (Hb) by adding a layer of complexity on top of them. Using Beer Lambert's law both HbO and Hb can be extracted separately. Because of this the output value is able to change with changes in HbT. Additionally both HbO and Hb have distinct waveforms which opens the possibility of analysis of the two values independently. In short the extraction of HbO and Hb using Beer Lambert's law would allow for the extraction of more and more meaningful data.

## 12. Conclusion

As we reach the end of this project, we've found that there is a market for low cost neuro-diagnostic devices for various mental health problems but, the current market is focusing on the neuromodulation path for the current and near future devices. There is also a current gap in the research on multimodal devices and therefore, our approach is somewhat novel in action. This means such a device is worth continuing to develop as it seems to be a very worthwhile approach for the future. The testing completed, although very basic, has shown promising results that allow for the continuous development of a better analysis platform and to eventually print and test multiple prototypes. Overall, there are many holes in the current market for these devices along with many under explored uses, especially in a non-academic aspect. With continuous testing using our device, we can help improve our results and potentially share something new and beneficial with the world.

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