SIMPLE METHOD FOR SYNCHRONIZATION OF EVENT CODES WITH ELECTROENCEPHALOGRAPHY (EEG) RAW DATA IN VISUAL EVENT RELATED POTENTIAL EXPERIMENTS

KEHINDE SIMBIAT LAWAL

(Under the Direction of Fred Beyette)

ABSTRACT

Electroencephalography (EEG) is the study of the electrical activity of the human brain. Event-Related Potentials (ERPs) are potentials in the EEG that are generated in response to sensory stimuli (e.g., visual, auditory, olfactory, or tactile stimuli). ERPs are time-locked to a stimulus onset so that changes in the brain's response are associated with changes in the evoking stimuli. As a result, it is important to accurately control the time at which the stimulus appears on the screen and synchronize the event stimulus time with the EEG data associated with the brain response to the stimuli. This thesis presents a cost-effective photodetector circuit to accurately synchronize the visual stimuli onset timing and EEG data corresponding to the brain's reaction to the stimuli. To demonstrate the utility of the synchronization method, a visual stimulus is presented on a laptop screen following a simple oddball paradigm experimental method for collection of ERP data.

INDEX WORDS: Electroencephalography (EEG), Event-Related Potentials (ERP), Stimuli, Oddball Paradigm, Photoresistor, P300.

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by

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DEDICATION

To God for the breath, knowledge, wisdom, and opportunity to do this work. To my dear husband and best friend Taiwo Akinyemi for your love and support, my very adorable son, Erioluwa-Joshua, for the exceeding joy you bring, my parents Abiodun and Taiwo Lawal for your love, prayers and support, and my siblings Malik, Zainab, and Taiwo Lawal for always being so supportive of me.

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CHAPTER 1

PROBLEM STATEMENT

1.1 Overview

Research on Event Related Potentials (ERPs) is derived from Electroencephalography (EEG) techniques where electromagnetic waves are generated by neural activity in the brain in response to internal or external stimuli that are time locked to the beginning of a stimulus associated with the experimental conditions. In research where external stimuli (ex. sounds, images, touch etc.) are used to elicit ERP components, accurately synchronizing these external events with raw EEG data collected during the experiment is one of the most important aspects of ERP research. To effectively synchronize events and data, one of the aspects to consider is the temporal factors associated with presentation of the stimuli to the test subject.

In the past, researchers presented visual stimuli for very short periods of time using devices like tachistoscopes (a mechanical shuttered device used for presenting visual images to a test subject for short time intervals). The tachistoscope was used in ERP research to display visual images to the human eye for a specific time interval. However, as things progressed and ERP study became more advanced, computers became essential tools for providing both visual and auditory stimuli. Presentation of stimuli to participants and recording their responses to the stimuli can now be done using computers with millisecond precision. In addition to improved timing precision, computers provide convenience, effectiveness, and simplicity of use making it possible for uses without significant technical background to conduct ERP research.

In a typical ERP study, the visual stimuli may be presented by flashing, flipping, moving, changing to famous faces, or superimposing the stimuli on moving objects [6-10]. To measure a person's neurologic response to visual stimuli, it is necessary to know the precise stimulus onset time (the time at which a stimulus becomes visible on the screen). In the conventional EEG recording setting, the event codes from the display screen and the brain's neurological response to the displayed stimuli are sent separately to the digitization computer to digitize the data as shown in Figure 1.1. As a result, event-marking and synchronization are more challenging because more than one system is involved. Furthermore, there is the need of synchronization between the devices involved. This is because incorrect synchronization increases the probability of a variable latency between the recorded stimulus display and the actual onset. The reason for this latency is due to technical factors like the operating system, processing time, and software configuration of the computer systems involved and can significantly affect the timing accuracy of the stimuli by about 11 ms [11, 12]. One of the factors that causes stimulus timing inaccuracy is the practice of synchronizing of the stimuli using GPIO pin from the computer generating the stimulus images.

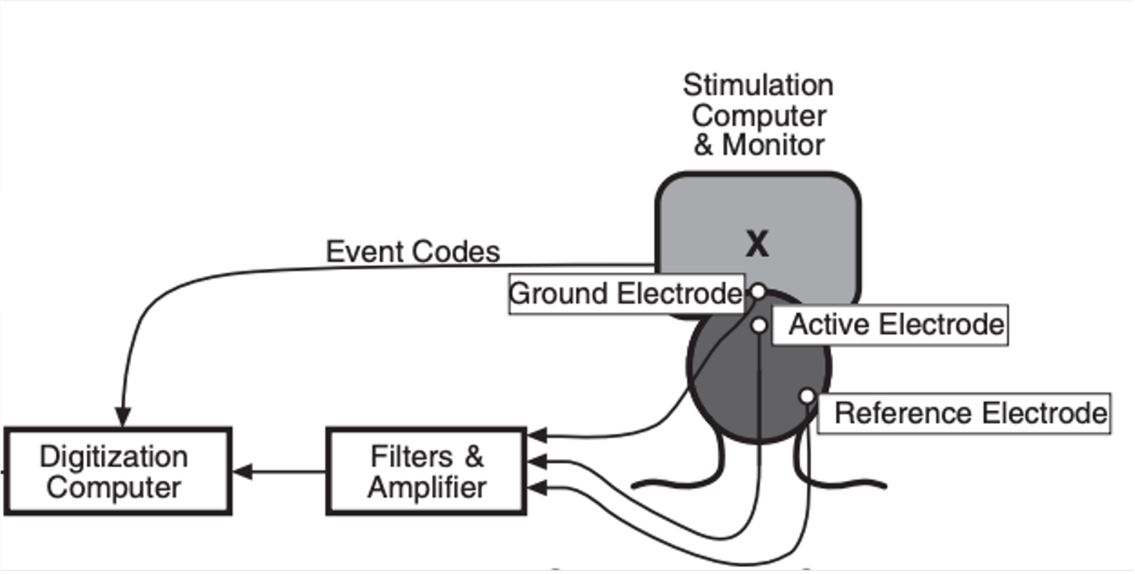


Figure 1.1. Conventional synchronization approach with the event codes sent directly to the digitation computer with the EEG data. [This figure is adapted from [3]].

Tobii provides a detailed explanation regarding time delay in using a PC to display visual stimuli [13]. To display the image, the graphics card in the CPU obtains data about the stimulus to be presented and then sends the image to the monitor screen. Before the image is displayed on the screen, it is initially stored and buffered by the screen's controller card. Due to these processes, there is the possibility of a delay between the time the CPU sends the image data and the time the image finally appears on the screen. This lag introduces timing errors in the stimulus timing.

A 2006 paper by Stewart describes the development and evaluation of a C program running on a Linux environment computer to display visual stimuli on a CRT monitor in a study to measure a person's reaction time with milliseconds precision. Included in this work is an algorithm to measure the exact stimulus onset time with limited error [14]. In a study by Wiens et al., they compared different visual technologies for displaying stimuli. For their experiment, both liquid crystal displays (LCD) and thin-film transistor (TFT) panel were considered. The monitors were connected to each other with an analog cable and a target image was displayed on both monitors using the Presentation® software on an IBM ThinkPad. When the target image is presented, a marker pulse is simultaneously sent to the parallel port. A photodiode was placed in the middle of the monitor to measure light intensity changes. An MP 100 data-acquisition unit and an AcqKnowledge 3.7.1 software were used to record the light changes and marker signal. On analyzing their data, they observed that the LCD and TFT panel are not effective in displaying pictures with short durations compared to other display technologies [15]. This was because both LCD and TFT were not able to display images at all at duration less than 12 ms and had large variability in image display at durations less than 47 ms.

1.2 Research status and problem identification

This section focuses on describing the major technical problem associated with methods reported in the literature for presenting visual stimulation and recording the time of visual stimulation onset.

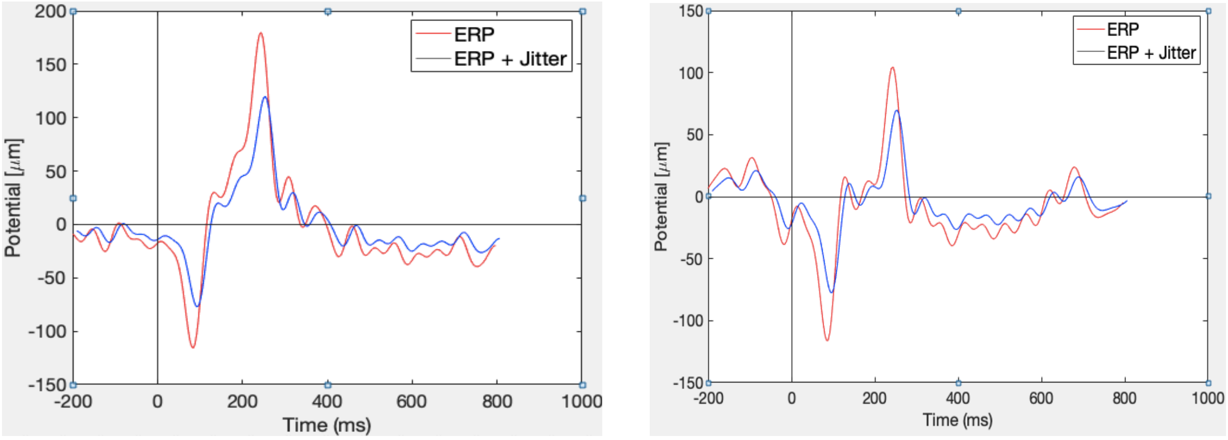
Some of the software that have been developed for visual stimuli presentation and synchronization in ERP experiments include but are not limited to PsychoPy, VIEWPixx, OpenSesame, jsPsych, Labsjs, Eprime, and Testable [16]. PsychoPy is a popular tool programmed with Python and has a set of libraries for visually related ERP experiments. Its performance, however, is dependent on timing intervals. Experiments with short stimulus time intervals negatively affected the operation of this tool and the test results [11]. VIEWPixx commercial toolbox can be directly controlled through a programming language to generate and present the visual stimuli and recording the response time. Eprime is another software tool for visual stimulus presentation and has a feature for detecting and measuring the scanner trigger. It is particularly designed for Functional Magnetic Resonance Imaging (fMRI) research. Forster solved timing inaccuracies by proposing a DMDX software [17].

Studies that address synchronization problem and timing errors involved the conventional approach where event codes are recorded separately from the EEG data already exist. McKinney et al. addressed timing errors by accurately measuring response time using stimulus onset detection approach. In their study, the visual stimuli were presented on a PC operating on Microsoft’s Windows. Before the stimulus appeared on the screen, the PC sent a start signal via one of its input-output ports. The time interval between the start signals and the display of the initial stimulus character was measured with a phototransistor placed on the computer screen. Between the time that the start signal is sent and the exact time the stimulus appears on the screen, there is a substantial time delay caused by the computer hardware and display software. This time delay significantly affected the neurologic response to the visual stimuli. A phototransistor was connected to an LED driven by a pulse generator and an oscilloscope was then used to measure the difference in duration between the start signal and the signal applied to the oscilloscope. It was further observed that the comparator threshold affected the response time. Therefore, to address the delay time to less than 100 μsec, the threshold was adjusted [18].This approach was also corroborated by De Clercq et al. For their study, they used two PCs, a SlavePC that runs a program that detects signal changes from the serial port and a MasterPC that controls the SlavePC. Pulses were generated with a pulse generator card. A photocell connected to an amplifier was placed in front of the monitor running the software presenting the visual stimuli and the SlavePC's printer port. In one of the tests conducted when pictures were used as the target stimulus, there was a 1.4 ms deviation from when the stimuli were sent from the PC and when it appeared on the screen [18, 19]. The solution proposed by McKinney et al. and De Clercq et al. had a high cost-to-benefit ratio because it required additional expensive hardware. They designed a custom-built system, named the Airmarker, that was connected to a wireless EEG system to detect stimulus onset as pulses [20]. The pulses were recorded with the EEG signal and the onset of each of the pulses were used in processing the stimuli timing. The challenge with this approach in this study two of the EEG channels had to be removed and additional processing had to be done to ensure proper synchronization. Some of these studies are listed in Table 1.1.

A major challenge in neurological research is inaccuracy in associating brain activity with external stimuli activities. In situations where correct synchronization between the event codes and EEG data is not properly done, the timing widow of the extracted ERPs are affected.

Table 1.1 Comparison between the time delay of the photodetector and other approaches.

Authors	Method	Delay	Reference
McKinney et al.	Used the traditional approach of synchronizing two different computer systems presenting the stimuli and recording the EEG data. A start signal indicating stimulus onset is sent via an I/O port of one of the computers thereby introducing some jitter to the data.	100 µs	[18]
DeClerq et al.	Connected a single photocell to an amplifier and placed in the middle of the computer running the software generating the visual stimuli and synchronized the events with EEG signal.	1.4 ms	[19]
Ohyanagi & Sengoku	Designed a SMART system using photodiode connected to a kit that consists of a USB dongle and expansion card. The hardware system was designed to function with a specific firmware developed using PSoC software.	< 2 ms	[21]
Plong et al.	Developed a software package to display stimuli. The timing of the stimulus displayed on a windows operating system was measured using two system functions.	2 ms	[22]
Wang et al.	Customized a photosensitive gel phantom by using a solar cell and compared timing of the generated event with EEG signal. In this approach, the stimulus image generated the synchronization instead of the traditional software	0.5 ms	[23]
Wang et al.	Conducted their study using both the hardware and software synchronization approach. In designing the hardware, a single light diode resistor comparator circuit (LDRCC) recorded stimuli onset. Then they compared their result of the triggers generated by their designed hardware with software generated triggers.	2.5 ms	[24]
Krigolson et al.	A DataPixx stimulus unit was used to send pulses based on stimulus timing generated by MATLAB to the auxiliary port of the EEG device. The time delay was majorly due to transmission time of the generated pulses to and from the device.	40 ms	[25]



a) b)

Figure 1.2. The effects of 28 ms jitter on a P300 ERP waveform for a) oddball stimulus and b) common stimulus.

Specifically, jitter in the synchronization of external stimulus events to the EEG raw data collection can compromise overall results of the research by significantly impacting the shape/timing of peaks in the averaged ERP results. The occurrence of jitters in an stimuli timing can be challenging to correct because it varies from trial to trial.

Two primary sources of jitter are inconsistency of the device generating and/or displaying the stimuli and variability of the hardware or software recording the stimuli onset. This might be due to the internal data processing, sampling rate, and communication protocol in wireless and wired systems through which signals are transmitted. A Bluetooth device, which is a wireless device can generate a jitter of about 5 ms [26]. The presence of jitters in an EEG data distorts the averaged waveform and makes it difficult to view the ERP components. To demonstrate the effects of jitter in an averaged ERP waveform, a 28 ms jitter was introduced to the stimulus onset time for design validation data collected as a part of this thesis work. The ERP waveform generated by both oddball and common stimuli were compared in both jittered and non-jittered conditions. Figure 1.3 a) and b) show that the 28 ms jitter changes the timing window and reduced the amplitude of the averaged ERP waveform. This result is corroborated in research by Hairston where the effect of jitter on an ERP waveform was studied [27]. On adding a 55ms jitter to an event timing, the amplitude of the ERP also decreased substantially. In another study by Williams et al., three different experiments were conducted to examine the accuracy and precision of timing in the event-marking device, Emotiv [28]. They introduced jitter to their data to test ERP's tolerance and plotted the ERP waveform for each jitter level. Their result showed that the distribution of peak of the plotted waveforms varied at each level of jitter. Overall, it can be concluded that jitter attenuates the original ERP waveform depending on the amount of jitter.

In addition to timing challenges suggested in the previous work, system cost and ease of use can be additional factors that limit acceptance of solutions to the stimulus event synchronizations issue. The cost of the hardware and software packages involved in the traditional approach of accurately capturing and synchronizing stimulus events is often very expensive. Examples include the TRIGbox, Stimrack, Blackbook Toolkit listed in Table 1.2. For comparison the anticipated system add-on costs (i.e., the potential cost of a synchronization component that can be added on to an existing EEG data capture system) should be on the order of $50.

Table 1.2. Comparison between the designed photodetector and some pre-existing commercial synchronization approaches.

Name	Type of Synchronization	Price	Reference
TRIGbox	Hardware	$3,300	[29]
Stimrack	Hardware	$1,500	[29]
Eprime	Software	$995	[29]
Blackbox Toolkit	Hardware	$3,900	[12]
Photodetector (This work)	**Hardware**	**$50**	

Aside from the high cost, some of these conventional commercial devices can be difficult to use. Software like OpenSesame and PsychoPy used in event timing experiments can be complex and as such may not be preferred by the ERP user community who are predominantly non-engineers [30]. Most ERP experimentalists are cognitive psychologists with little technical training associated with the setup and maintenance of complex data capture systems. Thus, the user community would prefer a stimulus synchronization system stimulus synchronization system that is easy to use and does not require the need for extra setup, maintenance, or system programming beyond what is required for a commercial off-the-shelf (COTS) laptop system running either a Windows or Mac OS operating system.

While the focus in this section has been on approaches that enable synchronization between system components that provide external stimulus and the data acquisition hardware used to acquire the raw EEG data, it is worth noting that the last decade has seen significant advancements in the core components required to implement and ERP system. On the stimulus presentation side, the continuing refinement of computing hardware has led to laptop computing systems that are well suited to the implementation of external stimulus generation. Specifically, high performance LCD display technologies now enable the presentation of high-resolution color images with minimum stimulus presentation times that are well below the few hundred millisecond stimulus durations times that are typical of ERP experiments.

Similarly, on the EEG data acquisition side, advances in integrated circuit technologies have enabled the COTS availability of analog front-end integrated circuits that provide analog signal amplification, signal conditioning, filtering, and digitalization for multiple analog input channels in a single integrated circuit package. The emergence of these high performance analog front-end integrated circuits has enabled the development of low cost, ambulatory EEG systems such as the OpenBCI Cyton board [31] that provide wireless connectivity between the battery powered EEG data acquisition hardware and a laptop computer. Further, these low-cost ambulatory EEG systems support 24-bit sampling resolutions, 250 Hz sample rates, and wireless data transmission rates that support continuous EEG collection from 8 channels over several hours. While these low-cost ambulatory EEG systems are not medical grade EEG systems, their performance is more than sufficient for ERP research and Brain-Computer Interface applications [32].

1.3 Research objectives

As detailed in the previous section, the component parts of an ERP system are readily available. The challenge faced by existing systems is to provide accurate event synchronization between the stimulus presentation laptop and the EEG data acquisition system. Further, it is important that this synchronization minimize jitter while maintaining a simple to use ERP system that can easily be run by a non-engineering trained ERP researcher using COTS laptops running on either Windows or Mac OS operating systems. Finally, the ideal event synchronization methods would be inexpensive and work as a modular add on to low-cost ambulatory EEG systems such as the OpenBCI Cyton board [31].

The focus of this thesis work is to design and prototype a modular unit for synchronization of visual stimuli that meets the operating use case detailed above. For demonstration purposes, this project assumes that the modular synchronization method developed here will use a Mac OS laptop for stimulus presentation and a windows laptop with an OpenBCI Cyton board connected for EEG raw data acquisition.

Consistent with many of the low-cost ambulatory EEG systems that have recently entered the market, the OpenBCI Cyton board provides 5 GPIO pins that are sampled along with the 8 analog channels used for EEG data acquisition at 24-bits/channel digital resolution. Because the GPIO pins and the analog channels are all sampled using the same system clock on a 250 Hz

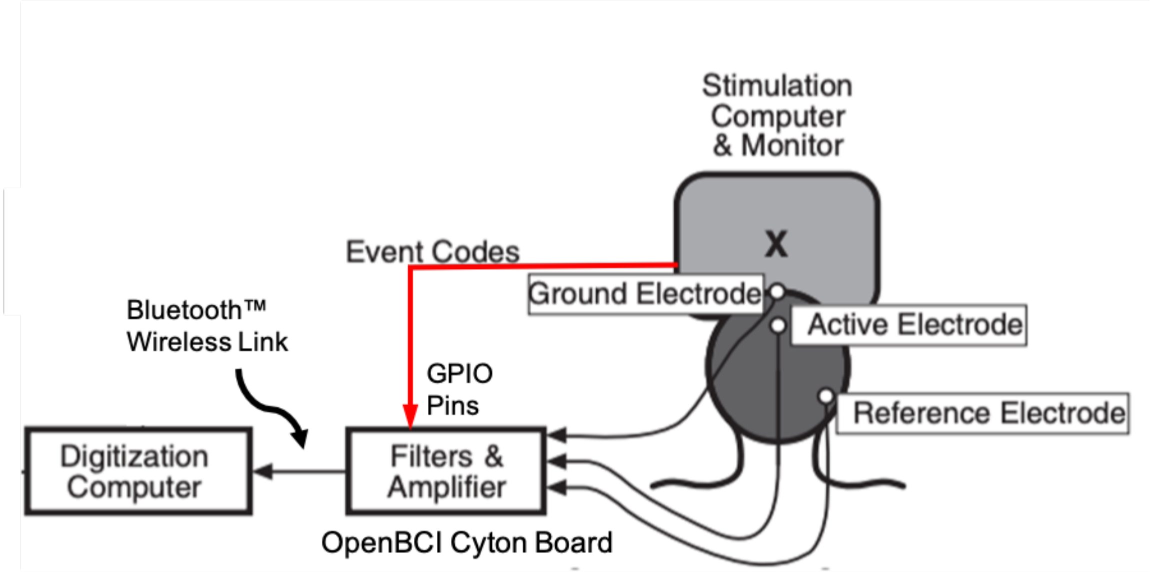


Figure 1.3. Modified synchronization approach with the event codes sent directly to the EEG amplifier. [This figure is adapted from [3]

sampling rate, there is no jitter or latency associated with synchronization between the GPIO signals and the analog signals coming from the EEG electrodes.

As shown in Figure 1.2, this thesis explores the implementation of a modular hardware system that can be used to capture event codes directly from the presentation display of the external stimulus computer and transmit those event codes in the form of digital signals that can be input to the OpenBCI Cyton board on the available GPIO lines. In short, the objective of this thesis is to design and prototype the hardware necessary to implement the red arrow in Figure 1.2.

The external event synchronization module implemented in this thesis is conceptualized as an add-on device that an ERP researcher could purchase to use with an OpenBCI Cyton board (or similar low-cost ambulatory EEG system) to synchronize data collection from external visual stimulus application running on a COTS laptop. Table 1.3 details the design requirements associated with the synchronization module developed in this thesis. Along with the specific design requirement, Table 1.3 provides a brief justification for each design requirement.

Table 1.3: Synchronization Module Design Requirements with Justifications.

Design Requirement	Justification
Provide less than 4 ms of jitter in the event code timing compared to when the stimulus actually appears on the stimulus presentation screen	At a sample rate of 250 Hz, the EEG signals is being sampled every 4 ms. Thus, any jitter less than 4 ms is negligible within the limits of the digitization system.
Provide an event code latency of less than 8 ms	At a monitor frame speed of 60 Hz, the frame refresh rate for the monitor is 16.67 ms. Thus, a latency of 8 ms is less than half of the frame refresh rate which is also a factor of 10 faster than the ERP components that are typically being explored in ERP research which typically occur on 100 ms timeframes.
Computing platform agnostic (no requirement for specific hardware, software, or operating system)	Being computing platform agnostic helps to ensure that the module will work with majority of user systems without requiring the users to have specialized hardware/software expertise
Connect to the stimulus generation laptop without obstructing the center of the screen or limiting interaction with the laptop by the test subject.	The synchronization module cannot disrupt the ability of the test subject to participate in the ERP experiment
Keep anticipated component costs in the final product to less than $5	While prototyping costs may be higher, the goal should be to keep the component costs of the final product below $5 which would likely keep the final product cost below $50. This would make the synchronization module cost on the order of a factor of 10x less than the cost of a low-end ambulatory EEG system.

1.4 Research content

Chapter 1 introduces the importance of accurate stimuli presentation and the precision of stimulus timing in ERP studies. This chapter also provides the research status and identifies the problem that the thesis addresses.

Chapter 2 provides detailed background about electroencephalography (EEG), event related potentials (ERPs), and the basic steps that must be considered when carrying out ERP experiments.

Since a P300 ERP experiment will be used to validate the timing synchronization system developed here, this chapter will also provide a detailed description of the P300 ERP component and how it is evoked using the visual oddball stimuli.

In chapter 3, the design of the oddball paradigm and solution to synchronize the event stimulus time with the raw EEG data is discussed in detail. This chapter also shows how the hardware is built and the materials used..

Chapter 4 discusses the different tests that were carried out to record the EEG data and events based on the presented visual stimuli to test the validity of the designed solution and the performance results.

Finally, the conclusion of this thesis project and future work is presented in Chapter 5.

CHAPTER 2

INTRODUCTION

2.1 History of Electroencephalography (EEG)

Electroencephalogram (EEG) was first recorded in 1924 by Hans Berger, a German psychiatrist. It was not until the year 1929 he reported his discovery by demonstrating how electrical brain activity in humans can be measured [3]. As time progressed, the finding of Gibbs, Davis, Jasper, Carmichael, and Lennox bought about the global acceptance of EEG as an actual occurrence [33]. This marked the year 1964 as the contemporary age of EEG research. The discovery of EEG revolutionized the neurological field and has been used over time in the clinical diagnosis of brain tumors, sleep disorders, seizures, epilepsy, and other brain-related diseases [34].

The Electroencephalograph (EEG) is an electrophysiological approach for recording the brain's electrical activity by using electrodes connected to the scalp. EEG oscillations are classified into the alpha, beta, theta, delta, and gamma frequency bands and they are regular patterns of neural activities. The alpha oscillations have a range of 8 – 12 Hz in humans and are very small oscillations that are prominent during a restful or idle state [35]. Beta oscillations, with frequency range of 13 – 30 Hz, are present during an alert or active thinking state. Theta oscillations, frequency range of 4 – 7.5 Hz, are present during the transition from awake state to sleep state and is connected to intuition and creativity. Cognitive and memory performances are reported to be due to the presence of both alpha and theta EEG oscillations [36].The frequency range of delta oscillation is 0.5 – 4 Hz and gamma is 30 – 50 Hz [37]. EEG recordings provide information about brain-wave activities in real-time and its sensitivity has proven very effective in exposing abnormalities in neural performances. Despite the great advantages of EEG, a major drawback is its spatial resolution. The simultaneous operation of the inhibitory and excitatory postsynaptic potentials contained in an EEG make it problematic to select an individual neural process; thus, making it challenging to use the data in its raw form. Asides from this, EEG contains a lot of artifacts from neural and non-neural sources that distort the collected recordings. There are two different ways through which EEG can be measured: invasive and noninvasive approaches. In the noninvasive approach, electrodes are simply placed on the head so that they make connection with the scalp as seen in Figure 2.1 while in the invasive approach, sensors are placed surgically beneath the scalp (i.e., in direct contact with neural tissue in the brain).

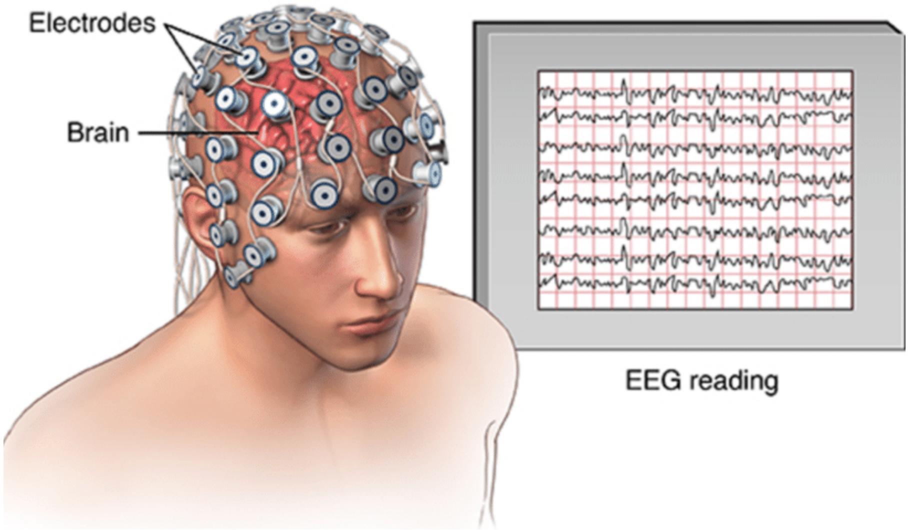


Figure 2.1. Electroencephalography uses the electrodes to record the EEG data. The electrodes are placed on the scalp in a noninvasive way to record the electrical activity of the brain and displays it on a BCI [1].

2.2 Event related potentials (ERPs)

Event related potentials (ERPs) are small electrical voltages embedded within EEG that are evoked in response to sensory (i.e., auditory, visual, and olfactory or tactile) stimuli. ERPs are time-locked to the beginning of a stimulus presentation so that the changes in the brain reaction are connected to changes in the evoking stimuli [38]. ERPs can be extracted from continuous EEG data with either an averaging technique, time-frequency analysis, or support vector machine algorithm [3, 39]. In the averaging technique, many trials are averaged together with a discrete event. In extracting ERPs, the EEG data are segmented into epochs with respect to the stimulus onset after which the epochs are then averaged together. Most times, event related potentials, ERPs, originate as postsynaptic potentials (PSPs) that occur when the neurotransmitters bind with receptors to change the flow of ions across the cell membrane.

Some benefits of ERPs include determining processes that they can be identified by experimental manipulation, covert measurement of processing, assessing time course of processing, used as biomarkers, and for measuring neural performances with high temporal resolution. Also, they are more appropriate for monitoring and measuring the timing processes that occur prior to a stimulus and the corresponding behavioral response during and after the stimulus presentation [40, 41]. In most cases, ERPs are used in determining the exact cognitive process influenced by a given experimental manipulation [42]. Furthermore, ERP techniques are not as invasive and expensive as other techniques like Positron Emission Tomography (PET) and Functional magnetic resonance imaging (fMRI) [43]. These advantages of the ERP technique have encouraged numerous studies in cognitive research. Luck et al. conducted an ERP experiment to study schizophrenic patients using a visual oddball paradigm [44]. The study showed that there were delayed reaction times in the patients due to impaired response selection and preparation process. Kropotv et al. also used ERP recorded in a cognitive control experiment to investigate the effects of aging on individuals [45]. Their result showed that task performance entailing cognitive control reduced as age increases. A recent study by Cai et al. used ERP recordings with auditory stimuli to examine attentional biases in height dissatisfied young males [46].

A major challenge in ERP studies is that because ERP is extracted using an averaging technique, it is not as useful in situations where this technique cannot be applied. From [37], ERPs can be measured on the scalp only when the dipoles from several similarly oriented neurons are added together. Thus, it can be quite complex for EEG to map spatially into the brain and ERP activity that can be detected in humans is from a given part of the brain's activity [3]. Another challenge with ERPs is that it can be difficult to deconstruct the ERP waveform, which consists of a mixture of many components, into individual ones. Different ERP components can be evoked using different types of stimuli, also known as events.

2.3 ERP Components

ERP components are either positive deflections or negative deflections at specific latencies. two main properties that describe an ERP component are its amplitude and latency. Amplitude in ERP is defined as the measure of the distance between the mean prestimulus baseline voltage and the maximal peak of the same waveform within a time window. It is recorded in microvolts of electric potential (μV). Latency in ERP is defined as the measure of time between a stimulus onset and the point at which maximum or peak positive amplitude occurs and it is recorded in seconds (ms) [5]. The popular nomenclature for these components is to use letters that indicate the direction of the waveform: P (positive amplitude), N (negative amplitude), or C (no specified polarity). The number after the letter indicate the latency between the presented stimulus and the component [47]. elicited using diverse types of stimulus (events). ERPs are classified as either exogenous (early component elicited during the first 150 ms) or endogenous (elicited after 150 ms) [48]. The following partial list of ERP components been used in a lot of cognitive and neuroscience research

and some of them are labeled in the waveform shown in Figure 2.2. give some insight to have components are identified and named. Different ERP components can be elicited using diverse types of stimulus (events).

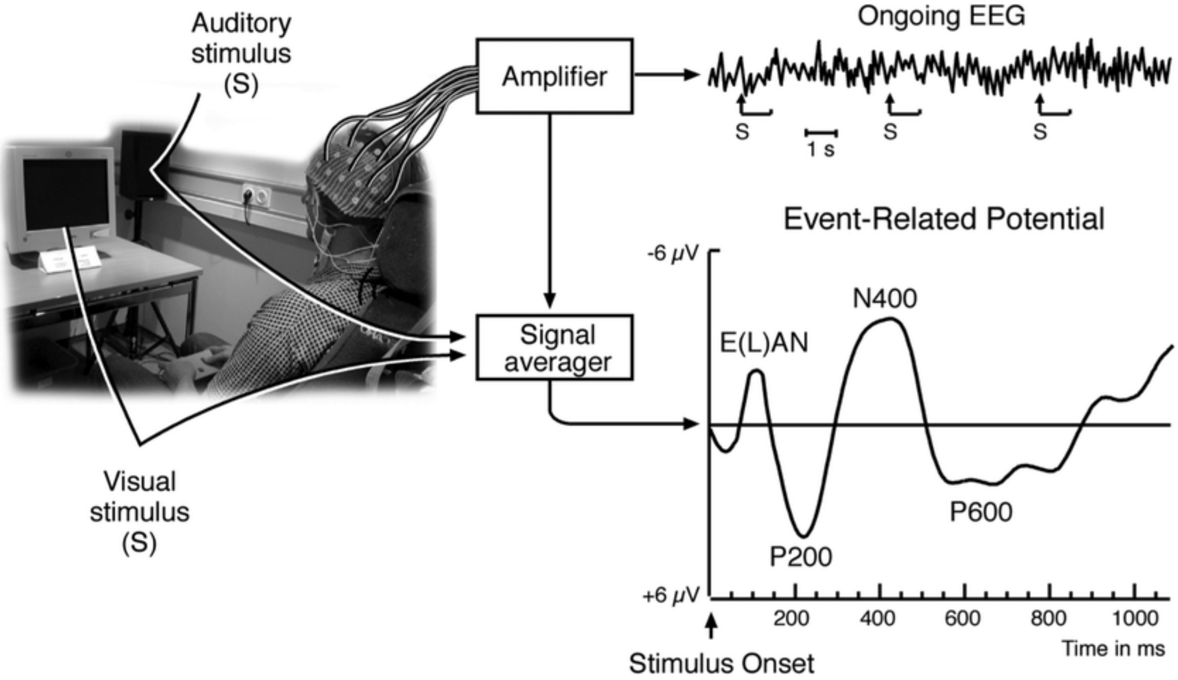


Figure 2.2. Different ERP components simulated in response to auditory and visual stimuli. After the raw EEG data is collected, it is processed to show the different ERP components generated. Different ERP components can be generated depending on the type of experiments conducted [2].

The following partial list of ERP components give some insight to have components are identified and named.

a) Contingent Negative Variation (CNV): This negative voltage is the first described cognitive ERP component, and it was observed by Grey Walter [49] in 1964. It was reported to have been elicited in response to a subject's anticipation of an upcoming target stimulus. The CNV component is commonly known as a slow ERP due to it been evoked several seconds after an event has been elicited [50].

b) P50: The P50 component is an auditory evoked potential that has a positive waveform at approximately 50 ms after an auditory stimulus has been presented. It is mostly studied in schizophrenic patients because they have relatively small P50 auditory-evoked response amplitude in response to click stimuli when compared to normal subjects, who have large P50 amplitude [51].

c) P100: P1 wave, which is observed over posterior electrode sites with a peak latency of approximately 100 ms.

d) P200: P200 is a positive ERP component that is elicited at between 150 – 250 ms peak time after a target stimulus is presented. It responds to auditory, visual, and somatosensory stimuli and is connected to context updating and stimulus evaluation. The P200 has a large response to stimuli with target features and this response is enhanced when targets are uncommon.

e) P300: The P300 is a very common positive ERP component that has a peak period at approximately 300 ms after a stimulus onset. However, the range of its latency lies between 250 to 750 ms. P300 response is generated when a series of stimuli are presented to the subject. P300 is mostly measured using the oddball paradigm.

f) N100: N100 is a large negative auditory evoked potential that occurs at a peak time between 100-200 ms after a stimulus onset. This component is made up of at least three subcomponents (one at the anterior and at least two at the posterior) and has. One of the properties of the N100 is that it is refractory, meaning there is a drastic reduction in the response of a stimulus if that stimulus is preceded by another stimulus at a short delay [3]. Its latency depends on the attentional demand or processing effort of the work. Like P50, it is commonly studied schizophrenic patients and speech segmentation [52, 53].

g) C100: The C100 component is one of the first visual evoked ERP components and is the largest component at posterior midline electrode sites and its polarity varies, hence the convention 'C'. This component is elicited when the primary visual cortex originally responds to stimuli. Studies have shown that when neutral visual stimuli are used, there is no C100 modulation resulting from spatial attention tasks. The C1 has high sensitivity to visual stimulus parameters and has an onset time of 40-60 ms and a peak time of 80-100 ms poststimulus [54-58].

h) P600: This component, also known as Synaptic Positive Shift, is regarded as an ERP of language. It is both auditory and visually evoked and is associated with processing grammatical or hearing errors. The P600 is a positive deflection with a peak time of approximately 600 ms and has been observed to reflect varying syntactic violations [59-62].

Dr. Luck however stated in [3] that sometimes, the naming of these components is not always consistent and can be quite challenging to keep track of, especially novices in ERP researches. Sometimes, when dissimilar sensory modalities are put into consideration, a name given to a particular component may refer to a totally different one under other test conditions. Resolving the confusion in identifying the names of the ERP components requires practice and mastery. ERP components could also be classified based on the stimuli they act on. The different types of stimuli used in ERP studies include the auditory, visual, and somatosensory stimuli.

When using an auditory stimulus, an ERP can be elicited by a novel audio tone is presented over earphones. In a case of visual stimulus, an unpredictable appearance of a character on a visual screen, while using the somatosensory stimulus involves the sudden pressing of a button by the subject. In this project only visual stimuli are considered and are generated to elicit a specific ERP component. The visual stimuli system presented here will be evaluated using a P300 experiment. The P300 component will be discussed in more detail later in this chapter.

2.4 Procedures involved in ERP experiments

This section provides more details on various aspects of how ERPs are recorded and processed.

Recording of EEG data: EEG data is recorded using wet or dry electrodes. These electrodes are placed on the scalp to make a stable electrical connection and the electrical voltage from each electrode is recorded as data. The recorded continuous voltage signal is then converted to a series of discrete signals and stored on the computer.

Computing average ERP waveforms*:* An averaging technique is applied to EEG recordings to extract the desired ERPs. In this technique, event codes that mark events at specific times are included in the EEG recordings. Afterwards, the codes are used as time-locking points to extract EEG segments (referred to as epochs) surrounding each event. Typically, an epoch will extend from 200 ms before the onset of the event to 1800 ms after the onset of the event. Epochs from similar events are then averaged into a single waveform. This results in an enhancement of neuronal activity that is associated with event while simultaneously suppressing neuronal activity that is not related to the neurological processing of the event. The number of trials that must be averaged depend on the size of the desired component and the amplitude of EEG activity not associated with the event.

Artifact rejection and correction*:* The EEG recordings consists of neural activity in the brain, and several physiologic and non-physiologic artifacts that results in noise in the data recording. The physiologic artifacts are electrical potentials produced from other parts of the body such as the eyes, tongue, skin, and muscles. Non-physiologic artifacts include external electrical activities from the electrode wires, improper placement of the electrodes on the scalp, and noise from other electrical devices in the test environment. Non-physiologic artifacts can be minimized by taking necessary precautions. The trials containing eye movements, eye blinks and other physiologic artifacts can be removed with the averaging approach or by rejecting such trials without affecting the task performance. Other approaches have also been developed to estimate artifacts and deduct them from the waveform.

Filtering: Filters are used in ERP experiments to remove noise signal frequencies so that the signal of interest can be retrieved. Noise signal frequencies include very slow voltage changes (< 0.01 – 0.1 Hz) and fast voltage changes (> 15 – 100 Hz). Filters, however, can cause deformation of the time course of ERP waveform and induce artificial oscillations. Therefore, care must be taken when using filters in EEG and averaged ERPs.

Qualification of amplitude and latencies*:* Amplitude and latency of peak voltages within a specific time window are measured to quantify the magnitude and timing of an individual ERP component. A second method would be to measure the mean voltage over a specific time window.

Statistical analysis: After the amplitude and latency of the ERP component is measured, they are statistically analyzed. However, the implicit and explicit use of these statistical comparisons in a study of ERP experiments can occur, leading to an occurrence of error.

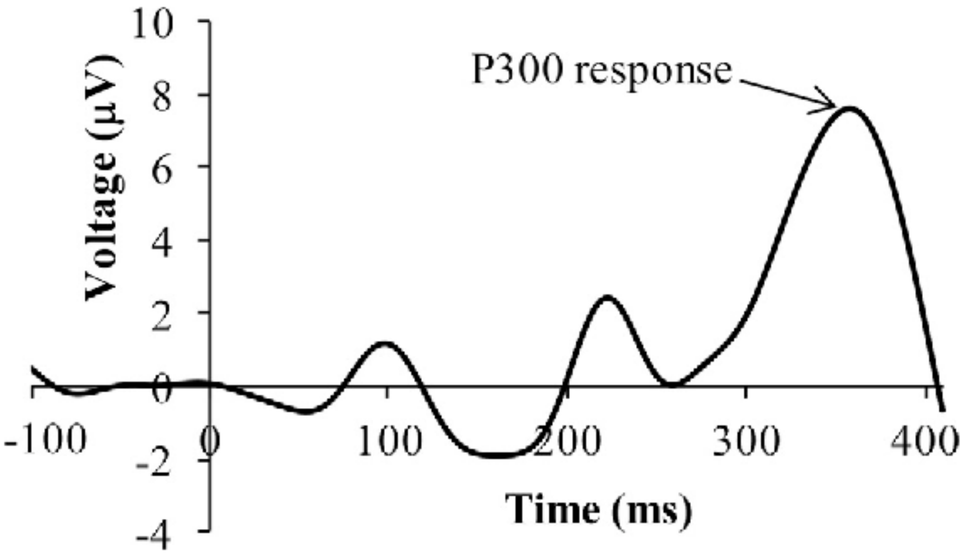


Figure 2.3. P300 waveform generated in response to an external stimuli [4].

To minimize challenges associated with electrode sites and measurements windows, new statistical methods have been established.

2.5 The P300 ERP Component

P300, also known as P3, is a well-known component in ERP research because of its effectiveness in testing attention and perception in humans. This effectiveness is due to the precision of its temporal resolution [3]. The component is mostly evoked in cognitive or decision-making processes by either auditory or visual stimuli. As an endogenous component, the P300 is dependent on a person's neurological response to a stimulus [63]. A waveform showing a P300 response is shown in Figure 2.3 above.

The P300 is made up of two subcomponents: the frontally maximal P3a and parietally maximal P3b. The similarity between the two components is that they are both elicited by irregular and infrequent stimuli changes. However, the stimuli change for p3b component are task-relevant whereas the stimuli changes of P3a, which has a slightly earlier positive deflection, are task irrelevant. The amplitude of the P300 waveform is dependent on the target probability of the stimuli: low probability and high discriminability of target stimuli increases the P300 amplitude. P300 latency, however, increases when discriminability of target stimuli from standard stimuli are more challenging. The P3 latency indicates the timing of prior cognitive performances and has often been closely associated to response time [64]. Latency measures the stimulus classification speed whereas amplitude is dependent on the number of attentional resources devoted to the task and the degree of information processing necessary. Changes in the amplitude and latency reflect changes in the brain's function and or structure. For instance, an increase latency and decreased amplitude of the p3b component indicate presence of diseases like neurodegeneration [65]. Amplitude and latency of a P300 component can be measured using 'standard' and 'oddball' stimuli in a technique called the oddball paradigm.

The P300 component is also a prominent brain signal in BCI control applications and can be observed by recording and measuring EEG. It is used for many brain-computer interface (BCI) applications including but not limited to web browsers, spellers, and environmental controllers. One great advantage of BCIs is that they can be used as devices to provide communication in situations without requiring any voluntary muscular operation [66]. The first P300 based BCI application was developed using an oddball paradigm. During the experiment, a positive deflection in EEG was observed 300 ms after the rare stimulus was presented.

Single-stimulus, oddball, and three-stimulus paradigms are the three different paradigms through which stimuli are presented in ERP experiments. In the single-stimulus paradigm, only a single type of stimulus is presented occasionally. In an oddball paradigm, two stimuli (rare and frequent) are presented with varying probabilities in a random order, and a test subject must identify the rare stimuli. The three-stimulus paradigm is quite similar to the oddball, in that it includes an irregular nontarget stimulus as a distractor in addition to target and standard stimuli [67].

2.6 Generating P300 using visual oddball experiment

An oddball paradigm is a common technique with two classes of stimuli: the frequent or nontarget and rare or target. In the paradigm, a set of events is displayed with different probabilities in a random order so that a participant can detect the oddball event. The response of the participant to the oddball stimulus is then recorded. The oddball stimulus is also known as the target or rare stimuli while the control stimulus is also called the frequent or non-target stimulus and they are used interchangeably in this thesis paper. It is the occurrence of the oddball event that elicits the P300 component into the EEG at approximately 300 ms after the stimulus onset as shown in Figure 2.4. P300 responses are also observed in other cases where nontarget stimuli are interrupted by stimulus omissions, which underlines the endogenous nature of this component.

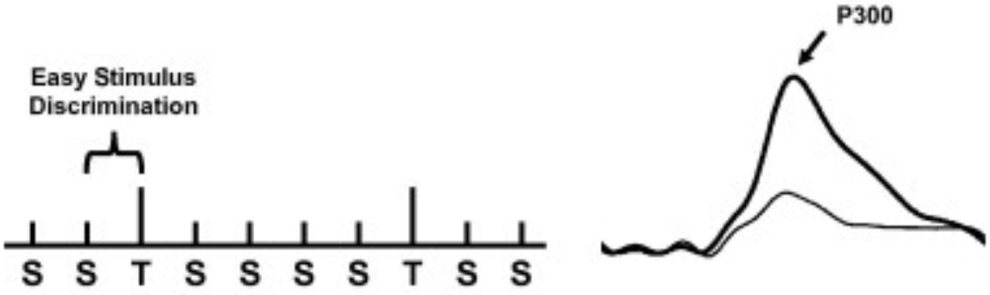


Figure 2.4. Schematic illustration of an oddball paradigm eliciting a P300 ERP component. The stimuli are presented randomly with the target (T) stimulus occurring less frequently than the standard or nontarget stimulus (S) [5].

On one hand, the frequent stimulus, which is the distractor, elicits P3a component which is large over the frontal/central area [68]. On the other hand, target stimulus elicits a P3b, which is large over the parietal electrode sites. To generate a strong and noticeable P300, the test participant is required to accurately identify the stimulus event. Typically, a P300 waveform is much larger for the target stimuli than for the non-target stimuli [42]. In many studies, it was observed that the P300 amplitude and latency vary with the difficulty of discriminating the target stimulus from the standard stimuli [69-71].

The oddball approach was first used in an ERP research by Nancy Squires, Kenneth Squires, and Steven Hillyard where they presented rare and unpredictable auditory stimulus [72]. During their study, they were able to observe that a P300 wave occurred when the test subject was actively engaged in the task of detecting the target stimuli. A P3a component was elicited when the test subject was ignoring or attending to the present audio tones, while a P3b component was produced when the test subject was only actively attending to the tones. The stimuli used in an oddball paradigm could either be auditory or visual so that they are called auditory oddball paradigm or visual oddball paradigm respectively. Hill et al. proposed an auditory P300 BCI in which the auditory stimuli were composed of target and standard tones [73]. However, this study focuses only on the visual oddball technique.

In a visual oddball paradigm, test subjects or participants will be presented with a sequence of images on a screen. Afterwards, participants will need to attentively identify which of the images is the oddball and their response is then recorded. The oddball paradigm also allows for the comparison between the results from emotional images and visually evoked potentials (VEPs) [74, 75]. In this thesis project, the flashing method will be used to present the visual stimuli because it will be easily detected by the photodetector circuit proposed. Farwell and Dochin first used a visual oddball paradigm approach where they displayed a 6 X 6-character matrix as a visual stimulus on a screen. The matrix contained the target and standard stimuli, and after a given number of row and column simulation, the computer identified the matrix element that the participant has been attending to as the intersection of the row and column that elicits the largest P300 waveform, which is then displayed on the screen [76]. In a study by Pollatos et al. using the visual oddball paradigm, 80 white and 20 red crosses were presented randomly [75]. The white crosses served as the standard stimuli and was displayed with an 80% probability of occurrence, while the red crosses, the target stimuli were displayed for the remaining 20% of the time. Another study where the flash method was used was done by Fabio et al. where they presented a rare and target stimuli in session for a period of 1000 ms with an inter-stimulus interval of 1500 ms [77]. The stimuli were flashed in a predictable manner for the first 40 trials while the last 60 trials were flashed randomly.

2.7 Stimuli timing and synchronization in ERP experiments

The precision of the timing of a stimulus onset and the response to the stimulus is very important in ERP studies because the components can be brief and regularly timed [16]. ERPs are time-locked and as a result, it is important to know the exact stimulus onset. If the event codes are recorded at times varying from the exact time the stimuli are presented, the epochs are segmented at inaccurate times, thereby reducing the quality of the data.

Any variability in the timing of stimuli display and synchronization can significantly influence the data analysis and results [11, 78, 79]. There are two main approaches for synchronizing events and EEG data in ERP studies: hardware and software synchronization approach.

a) Hardware Synchronization: In the hardware approach, stimulus onset can be detected and recorded by a light sensor connected to the display monitor to detect changes in light intensity. Another option is the TTL technique where the computer system recording the EEG data and the one presenting the stimuli are connected by sending a digital synchronization signal via a cable connection [80].

b) Software Synchronization: In this approach, a software application is designed to connect the systems involved in conducting ERP research such that the event codes are synchronized with the recorded EEG data. Two examples of software synchronization approach are but not limited to TCP/IP and Start-stop synchronization. In the TCP/IP, a software is generated to create a connection based on TCP/IP protocol between the systems to be synchronized. For the Start-stop synchronization method, the systems are started and stopped simultaneously. The challenge with this approach is that computer systems may not have the exact same initialization times due to varying factors [80].

Knowing which of the synchronization approaches to use depends on the type of experiment being conducted and the processing involved. In this thesis, hardware synchronization method was selected because of the type of EEG hardware that will be used and essentiality of timing accuracy required. Several studies have already been carried out to measure both stimulus and response timing. Kayser et al.(1997) conducted a cognitive study to test emotional perception using visual stimuli [79]. To analyze the time course of the ERP components, visual stimuli of 182 x 137-pixel resolution were displayed on a left or right side on a dark background of a monitor. The duration of each stimulus was 250 ms and a photoresistor was attached to the monitor to detect light sensitivity. Another study presented quick and predictable stimuli on two monitors for a duration of 250 ms using the Micro Experimental Laboratory (MEL) software. A single photoresistor was attached to the surface of the monitor screen to measure the exposure times and trigger delay. To account for any potential stimulus exposure variation, the two monitors were switched for half of the participants.

Furthermore, Bridges et al. used a photodiode, placed at the center of the display screen, to measure the timing of visual stimuli and synchronize the data [16]. They compared their results with the timing performance of other lab-based systems and software packages. An approach to accurately measure the timing of visual stimuli was proposed by Ohyanagi and Sengoku [21]. SMART was designed with a photodiode, USB dongle, and expansion card. The photodiode was placed on 1x1 cm white square displayed on the left center of the screen to detect the target stimuli onset. Each participant pressed the mouse on recognizing the target stimulus, which was a white 1 cm diameter circle. On conducting their experiments, they were able to demonstrate the accuracy of the SMART. In this thesis, a sequence of stimuli will be presented, and a photodetector circuit will be built to synchronize the event stimulus time with the EEG data associated with the brain response to the presented stimuli. The photodetector design in this thesis will contain four photoresistors instead of the conventional one or two photosensors.

CHAPTER 3

PROJECT DESIGN

This chapter focuses on the design of the oddball paradigm and the photodetector circuit to synchronize the stimulus time with the generated EEG data. Furthermore, the P300 ERP experiment carried out using an OpenBCI system to test the validity of the designed solution was explained.

3.1 Stimuli Setup

For the system implemented in this thesis, the oddball paradigm is made up of geometric shapes (a black square and a black circle) generated using a java programming language. The black square represents the frequent (nontarget) stimulus, while the black circle represents the oddball (target) stimulus. The shapes were made to appear randomly at the center of a white screen. Asides the main white screen, a smaller black screen is fixed on the top left corner of the screen; this is where the photodetector circuit will be placed. Along with the displayed stimuli, two smaller white squares with dimensions 1cm X 1 cm are flashed on the smaller black screen. When nontarget stimulus appears, one of the white squares appears at the top left corner of the black screen and when the target stimulus is presented, the other white square appears at simultaneously at the top right corner of the black screen. This means that when the photodetector senses a light intensity change at the top left corner of the black screen, it sends a trigger indicating that the nontarget event has occurred. Similarly, when a light intensity change is detected on the top right corner of the black screen, a trigger indicating that the oddball event has occurred is sent.

The code was written to generate a configuration text file that shows the parameters of the stimulus images so that it is easy to make any needed adjustments in the parameters without breaking the code. In presenting the visual stimuli, the main white background with a black dot (used to draw the focus of the test subject) initially appears on the screen with the small black background on the top left corner of the screen indicating the start period and the interval between the two stimuli. The paradigm is designed to present each stimulus image on the screen for a duration of 250 ms. After the stimulus image has been displayed, the stimulus image is removed,

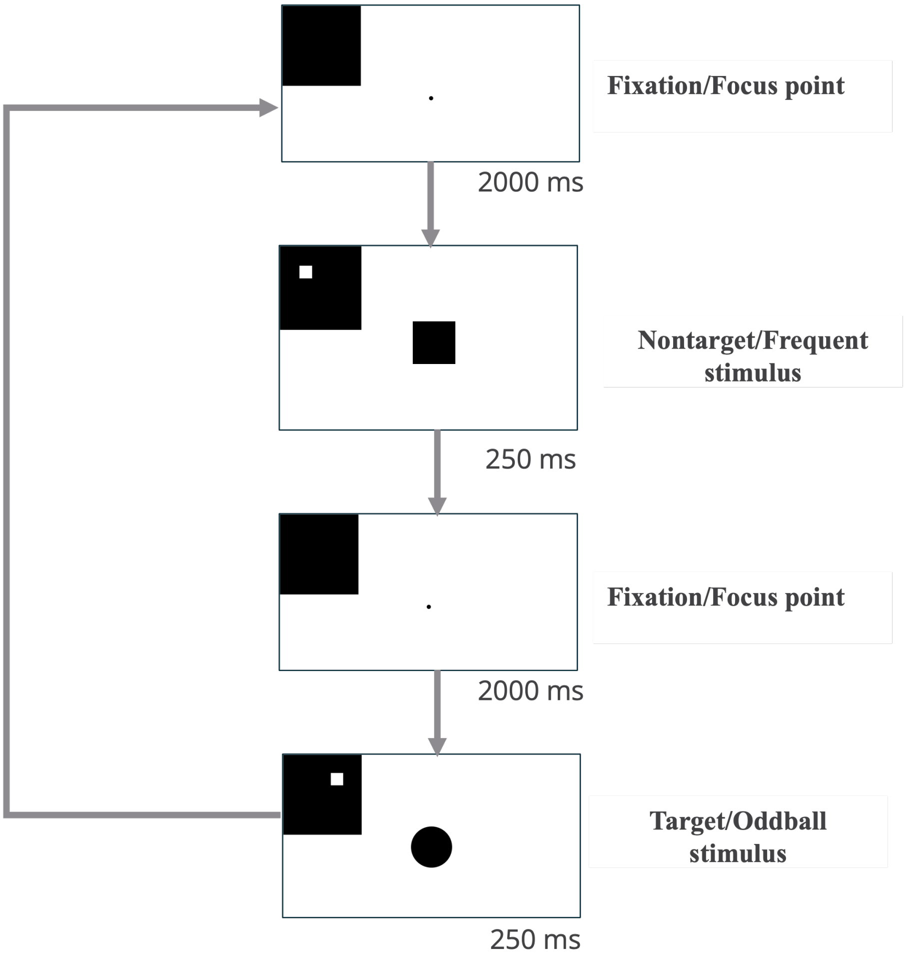


Figure 3.1. The designed visual oddball paradigm showing the sequence of the stimulus display and timeline of the oddball task.

and the screen returns to the white background with the back attention focus dot. The screen remains in this mode for approximately 2000 ms at which point the next stimulus image is presented. Figure 3.1 shows the designed visual oddball paradigm and the sequence at which the stimulus images are presented.

It is important that the stimulus images are not presented too frequently. When the stimulus images are presented too close together, the neurologic response from the first stimulus image can overlap into the neurologic response for the next stimulus image resulting in unpredictable changes to the amplitude of the P300 ERP that is vital for information transfer [39]. The stimuli will be presented for a total of 50 times in each experimental session, the rare stimulus will appear 20% of that time while the frequent stimulus will appear for the remaining 80%. The time interval between the disappearance of a stimulus image and the appearance of the next one, the screen goes to an attention fixation view indicated by the black dot in the center of the display screen. Attention fixation is accomplished by instructing the test subject to focus on the black dot in the center of the display screen in the time between stimulus images. The attention fixation process helps the test subject remain focused on the ERP experiment rather than letting their mind "wander" randomly between stimulus images. Use of an attention fixation process helps establish a solid baseline of neural activity that is more easily averaged out in the data averaging step that is characteristic of ERP data analysis.

3.2 Materials

A simple photodetector circuit was designed using voltage divider as shown in Figure 3.2. The purpose of the photodetector circuit is to synchronize the event stimulus time with the EEG data associated with the brain response to the presented stimuli on the computer screen. While building the photodetector circuit, phototransistors were initially used; however, they had poor sensitivity. This will be discussed further in the design validation section. The circuitry consists of:

- 1 printed circuit board
- 4 light sensors
- 4 load resistors
- 1 inverter
- OpenBCI System

These electronics and how they were used in the circuit are discussed below.

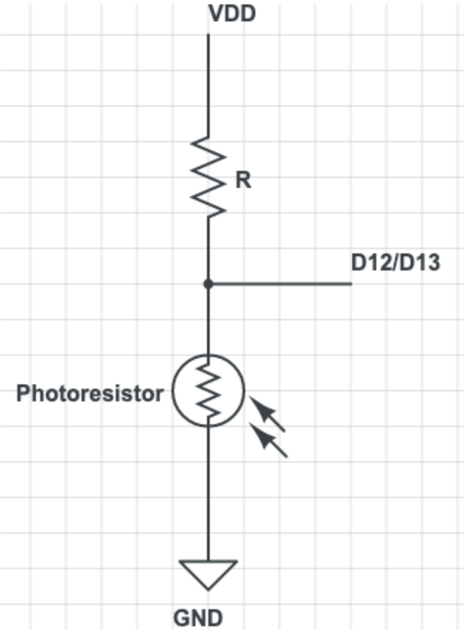


Figure 3.2. A simple voltage divider circuit diagram used in designing the photodetector circuit.

3.2.1 Printed Circuit Board (PCB)

PBCs are used to connect electrical components using conductive pathways like soldering. They are light, cheap, and have small weight which make them very convenient and easy to use. The electronic components for the proposed photodetector circuit are soldered on a 5 x 7 PCB shown in Figure 3.3.

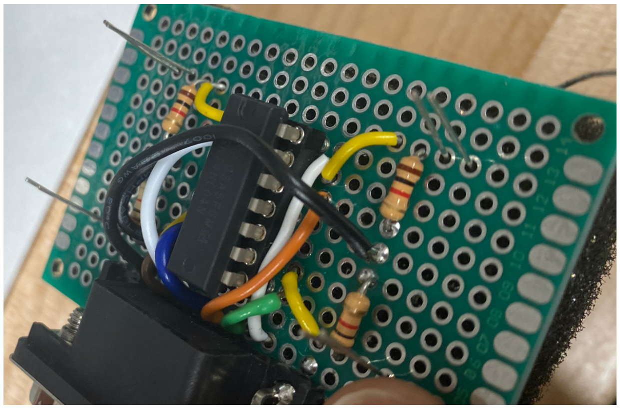
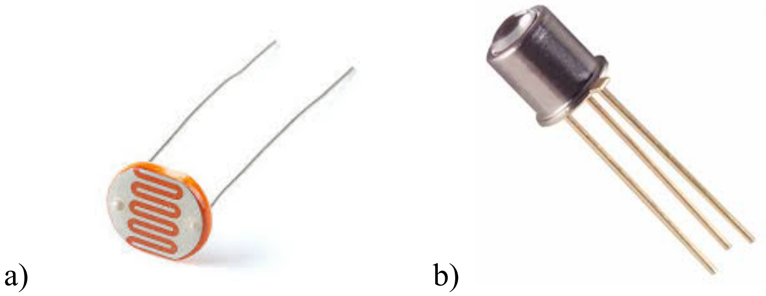


Figure 3.3. The printed circuit board used in this project to connect the electronics.

3.2.2 Light Sensor

In determining what light sensor would be more appropriate for this project, both phototransistors and photoresistors were tested for. Figure 3.4 shows examples of the packaged photodetectors that were evaluated for this project.

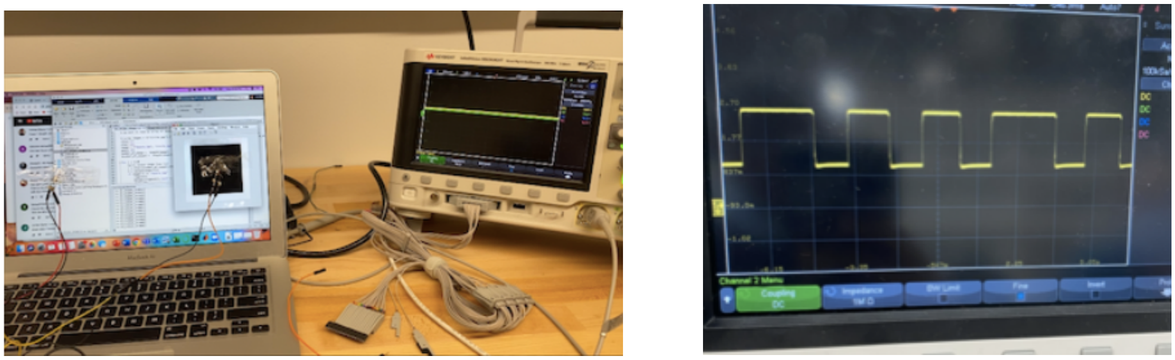
The phototransistor was connected to a load resistor and a 3.3V power supply on a breadboard and a MSOX3024T oscilloscope was used to record the sensor's data. An appearance of a pulse is meant to indicate the "on" and "off" of the phototransistor as the



a) b)

Figure 3.4. Light sensors used in the project. a) Photoresistor varies in resistance in response to light b) Phototransistor uses light to produce current.

stimulus appeared and disappeared on the screen. Initially, the phototransistor responded to the occurrence of stimuli by moving up and down as a straight line on the oscilloscope screen, but no pulse was generated shown in Figure 3.5 a. After a while, the phototransistor stopped responding to the stimuli altogether. The load resistor was varied to get a better output voltage and pulse; however, there was no difference.



a) b)

Figure 3.5. Results from the light sensor tests. a) The result using the phototransistor showed no pulses on the oscilloscope b) using the photoresistor yielded the required train of pulses in response to the presented stimuli.

The initial thought was that there was a problem with that specific sensor and other available phototransistors were tested for in the circuit, but the result was still the same. When tightly pressed to the screen, the sensors generated no pulses. On taking a more manual approach, the phototransistors were covered by hand to check for their sensitivity to changes in light intensity but there were no remarkable changes. Eventually, it was observed that the problem was with the sensitivity of the purchased phototransistors. On testing the photoresistors, the result was a stark difference from the that of the phototransistors. The photoresistors were able to generate very accurate and consistent pulses each time the stimulus appeared and disappeared as seen in Figure

3.5 b. This result led to the conclusion that the photoresistors had better sensitivity compared to the phototransistors for this circuitry.

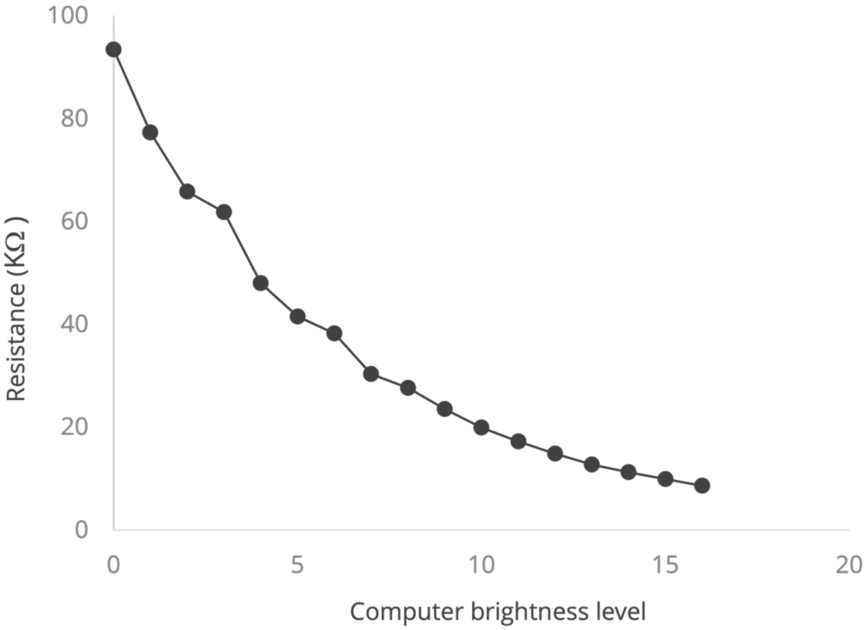


Figure 3.6. Photoresistor versus light intensity graph. An increase in the brightness level of the computer screen caused a corresponding decrease in the photoresistor's resistance.

A photoresistor is a light-dependent variable resistor whose resistance changes with variation in light. When there is an incremental change in light intensity, the resistance of the photoresistor decreases and vice versa when the light intensity decreases as seen in Figure 3.6. Photoresistors, due to their sensitivity to light, are used in this project to detect variations in the light intensity of the computer's screen. The photoresistors has a resistance value range of 4 KΩ - 40 KΩ when the light intensity of the used laptop screen was varied.

3.2.3 Inverter

An inverter, as its name implies, inverts the input signal applied to it. For instance, when a low input voltage is connected to it, the output voltage becomes high and vice versa. The SNxHC04 Hex inverter shown in Figure 3.7 was used for this project. This inverter has the V_{CC} and GND pins through which input voltage is supplied and twelve total independent inverter input and output pins. Out of these twelve pins, four of its input pins were connected to the photodetector circuit, while the corresponding output pins were connected to the cyton board. An inverter was used in this circuitry because of its high gain, I/O logic levels, and high transition speed. My circuit is designed to give high-to-low logic level for a black image on a white background. However, the photodetector will be placed on a black background where white images will appear. As a result, the inverted changed the logic level of the circuit by inverting the voltage output so that it records high when the white image appears and returns to low when the white image disappear.

Figure 3.7. The SNxHC04 Hex inverter was used in this project to invert the output voltage of the designed circuit.

3.2.4 Load resistor

To choose the appropriate load resistor for the photodetector circuit, the resistance of the photoresistor and the input voltage value from the power supply is taken into consideration. An adjustable potentiometer was first connected to one of the photoresistors to monitor the luminance range of the black and white background on the computer's screen. A multimeter was used to measure the resistance ranges of the potentiometer on a black background, $R_{potendark}$, and white background, $R_{potenwhite}$, while varying the light intensity of the screen. The results of the potentiometer's resistance were plotted against the varying light intensity of the screen for both black and white background in Figure 3.8. It was observed that the sensitivity of the photoresistor is greatest when the output voltage, V_o, is in the middle of its range.

$$R_{poten} = \frac{R_{potenwhite} + R_{potendark}}{2} \qquad \text{Equation (3.1)}$$

$$R_{poten} = \frac{44.2 + 21.9}{2}$$

$$R_{poten} = 33\ K\Omega$$

The average resistance of the potentiometer, R_{poten}, when the screen's light intensity was at mid-level and at $V_o$was 33 KΩ as calculated in Equation (3.1). The load resistance, R_{load}, was selected such that R_{poten} = R_{load}. Due to the scarcity of 33 KΩ resistor in the lab, a 32 KΩ resistor was selected instead.

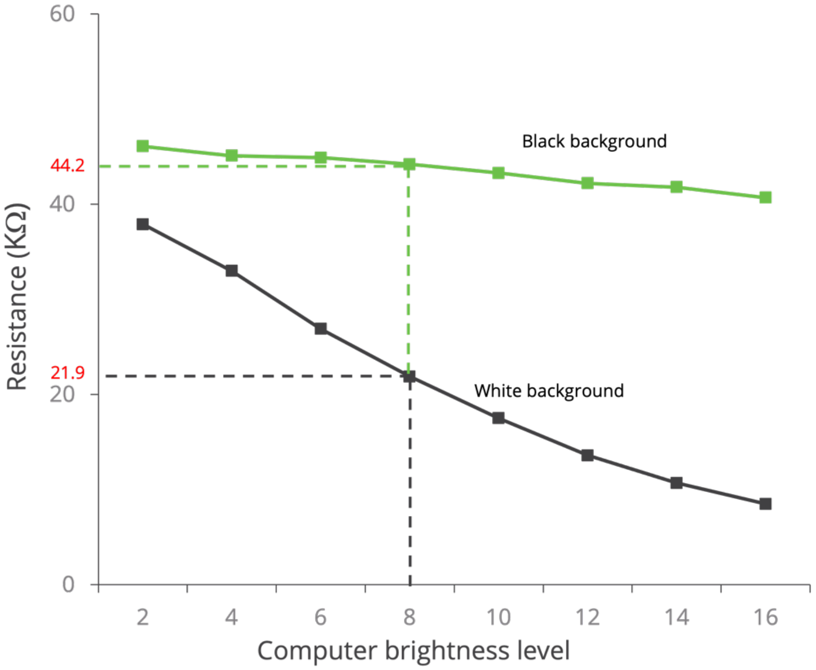


Figure 3.8. Graph of the resistance of the potentiometer plotted against stimuli varying the computer's brightness.

3.2.5 OpenBCI System

The primary function of the OpenBCI system is to detect and record the EEG and communicate it to a computer. OpenBCI system is a noninvasive approach for recording EEG, and it consists of the Ultracortex Mark IV headset, a cyton board located on the headset, a dongle, and a Graphic User Interface (GUI). The headset is designed with electrodes that connect with the scalp when the headset is worn. The headset is powered by the cyton board that is a microcontroller with 5 digital input-output pins to read from (D11, D12, D13, D17, and D18) and a 3.3V digital operating voltage. An OpenBCI GUI is the interface that allows a user to interact with the electronic headset to record and visualize EEG data. The EEG data from the headset is transferred to the second computer with the OpenBCI GUI through a USB dongle. The dongle enables the cyton board communicate with computer by connecting its RFDuino with the cyton board's RFDuino based on Bluetooth. An image of the cyton board and dongle is shown in Figure 3.9. When the connection between the dongle and cyton board is established on the GUI, the data from the cyton board is streamed in real time, recorded, visualized, and saved.

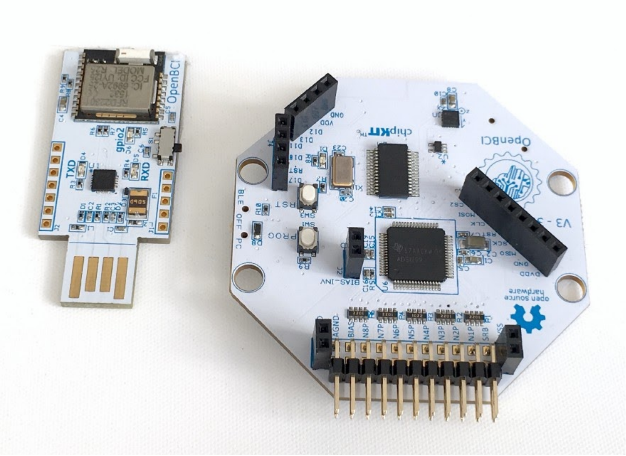


Figure 3.9. An OpenBCI dongle and cyton board. The dongle allows the cyton board communicate with computer.

3.3 Hardware Design

Now that the input voltage, V_{in}, resistance values of the photoresistor, and load resistors are known, a voltage divider is used to connect the photoresistors and load resistors as shown in Equation (3.2) to measure the output voltage V_o.

$$V_o = V_{in} \frac{R_{photo}}{R_{photo}+R_{load}} \qquad \text{Equation (3.2)}$$

R_{photo}= resistance of photoresistor

R_{load}= resistance of load resistor

V_o = output voltage

V_{in} = input voltage

The photodetector design and connection to the cyton board is shown in Figure 3.10. Four photoresistors are soldered in series to the four load resistors while the other legs of the photoresistors and resistors are connected to GND and V_{DD} of the cyton board respectfully as seen in the figure. The connection between the photoresistors and the load resistors are soldered to input pins of the inverters while the output pins are connected to the four digital pins of the cyton board: D11, D12, D13, and D18.

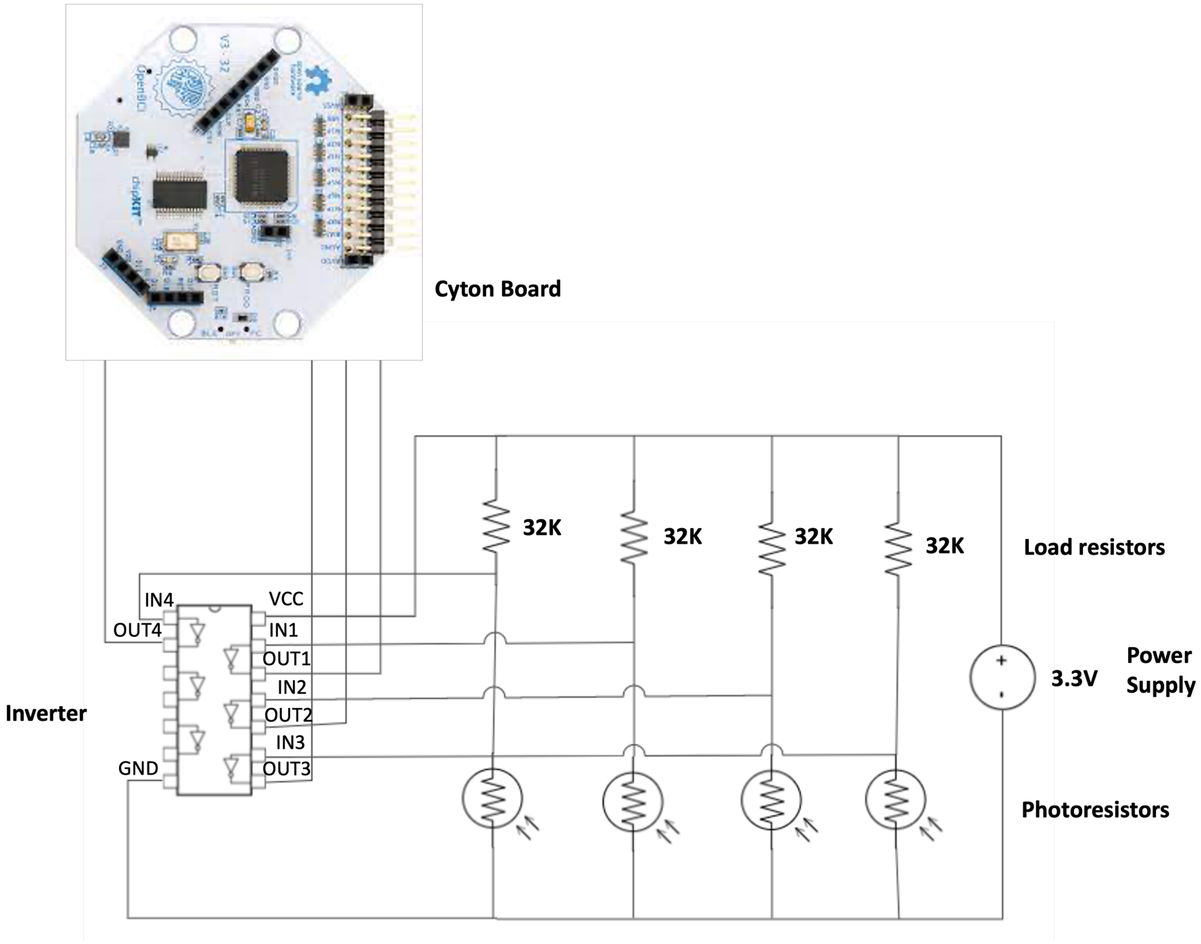


Figure 3.10. Circuit diagram of the photodetector circuit.

The light sensor detects changes in the light intensity of the screen where the stimuli images are displayed. When the photoresistor is placed on the screen, light from the screen touches the photoresistor so that the change in the photoresistor's resistance corresponds to a change in the circuit's voltage. By connecting the photodetector directly to the amplifier of the OpenBCI hardware, the stimulus images are detected by the photodetector as soon as they are displayed on the laptop screen. The signals from the photodetector are simultaneously recorded as event codes with the EEG data. The voltage change is sent as an analog signal to the cyton board as a trigger which makes it easy to view on the GUI. The designed circuit is placed in a 3D-printed casing for proper packaging and to shield the photoresistors from other irrelevant light sources as shown in Figure 3.11. Furthermore, the casing is designed such that it can be easily attached to the top corner of the computer screen with the small black background. The OpenBCI headset records the EEG data while the photodetector circuit measures the event codes.

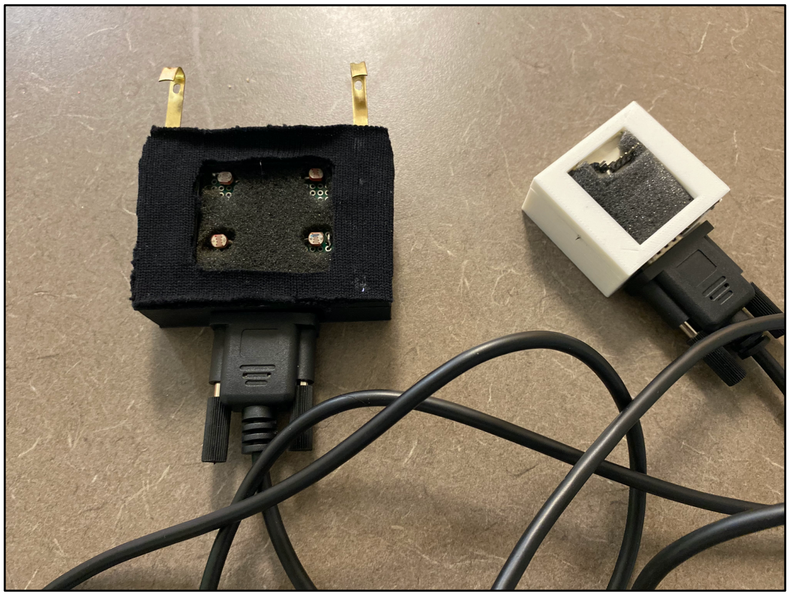


Figure 3.11. The photodector circuit showing the four photoresistors and the VGA cable extending away to cyton board connector.

3.5 Data Acquisition System

The typical data acquisition system setup in this project is shown in Figure 3.12. It includes two laptops, the designed photodetector circuit, and the OpenBCI system. One of the laptops presents the stimuli and the white images to detect the stimuli onset while the other laptop has OpenBCI GUI to visualize the EEG data and events. The photodetector circuit placed on the top corner of the screen detects the stimuli onset and disappearance as events and send them to the cyton board through a VGA cable. This VGA cable connects the photodetector on the screen to the cyton board for proper connection and convenience. Ag-AgCl coated dry electrodes mounted on the Ultracortex Mark IV headset records the brain's electrical activity. In a typical ERP experiment, the choice of the number of electrodes, location of reference electrodes, are experimental factors that must be taken into consideration. Using too many electrodes, specifically

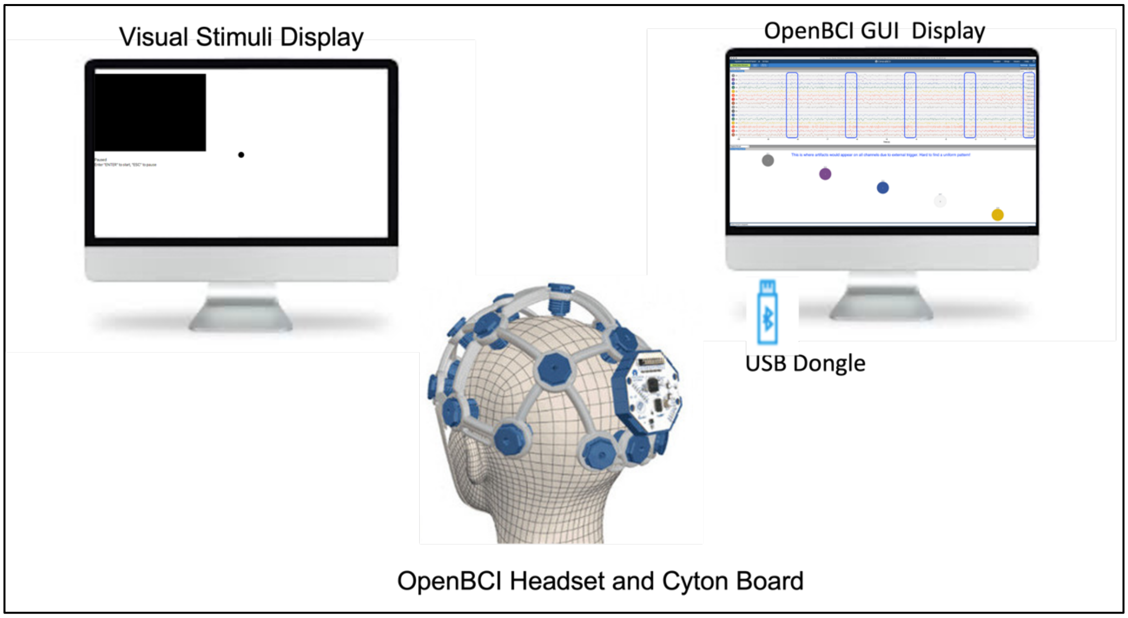


Figure 3.12. Experimental setup for a typical visual oddball paradigm. This setup is made up of two display screens to present the visual stimuli and the GUI and the Ultracortex Mark IV headset to take EEG readings.

more than 32 electrodes, can compromise the quality of recordings due to the huge amount of data. In a small ERP experiment using many electrodes can make it data processing difficult and burdensome. Also, using few electrodes might not provide sufficient information; however, this depends on the experiment type. Also, in choosing the reference electrode site, all EEG electrodes were referenced to two linked electrodes on the left and right earlobes of the participants. As shown in Figure 3.13, channels Fp1, Fp2, C3, C4, P7, P8, O1, and O2 were the eight electrode channels used in this project, A1 was the reference electrode, while A2 was the ground electrode. The 8-channel signals were recorded according to the international 10-20 system (excluding some electrodes).

CHAPTER 4

DESIGN VALIDATION AND DISCUSSION

This chapter focuses on the P300 experimental procedure conducted and the analyses of the results of the validation tests.

4.1 Validation Tests

Two validation tests were carried out using a digital oscilloscope and the OpenBCI system. These tests were conducted to validate the usability and accuracy of the designed photodetector device. In the first test the photodetector was attached to a laptop screen where the oddball paradigm was presented and directly connected to an oscilloscope while in the second test the device was connected the OpenBCI system. The oscilloscope result shown in Figure 4.1 shows that the photoresistors correctly generated the pulses from the from the stimulus presentations. When each of the two stimuli appeared on the screen, a signal from the sensor was sent to the

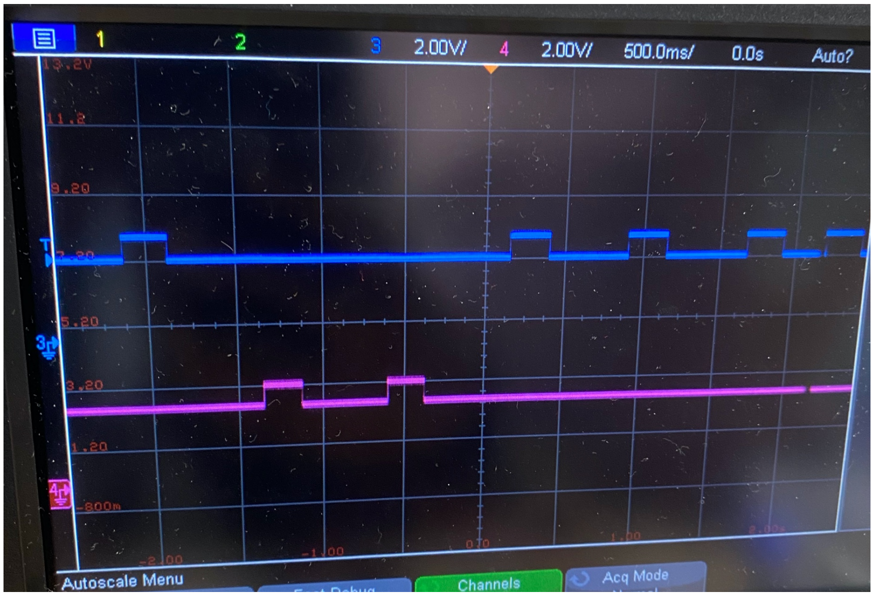


Figure 4.1. Pulses generated by the photodetector circuit recorded by the oscilloscope.

oscilloscope. The photodetector signal appears as pulses on the oscilloscope. From the result shown in the oscilloscope in Figure 4.1, it is obvious that the photoresistors were sensitive to black-to-white and white-to-black changes on the computer screen and accurately measured the stimuli onset and interval and synchronized the event codes with the raw EEG data. The rise time of the pulse was measured on the oscilloscope, which gave a corresponding time delay of 26.7 µs as seen in Figure 4.2.

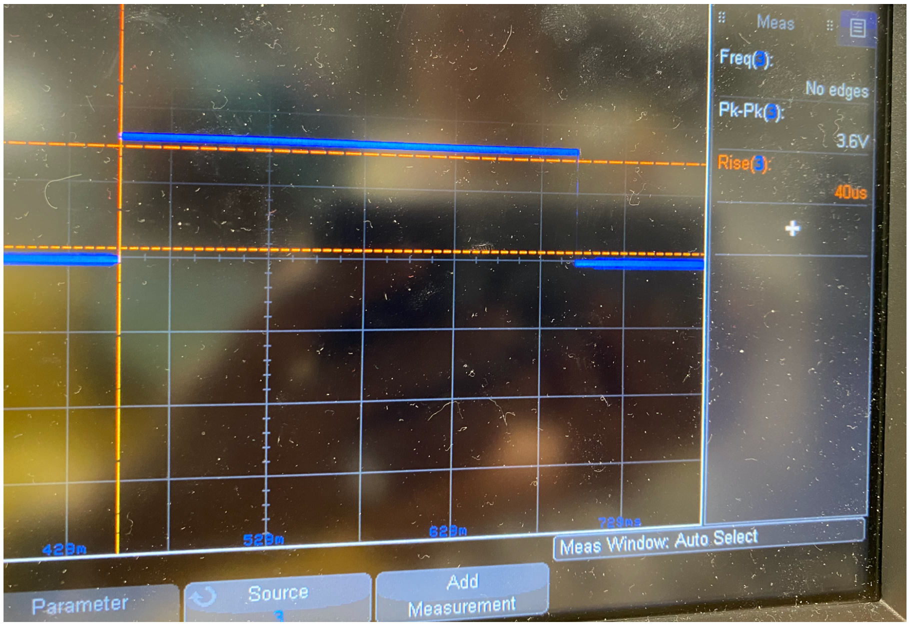


Figure 4.2. Oscilloscope measurement showing the rise time of the stimulus.

In the second test, the photodetector circuit was connected to the OpenBCI system and a P300 experimental procedure was done, and stimulus events were monitored on the GUI. The "Analog Read" widget was initially turned on to observe the pulses associated with the onset and disappearance of the stimuli as shown in Figure 4.3. Each pulse lasted for about 250 ms before going to rest.

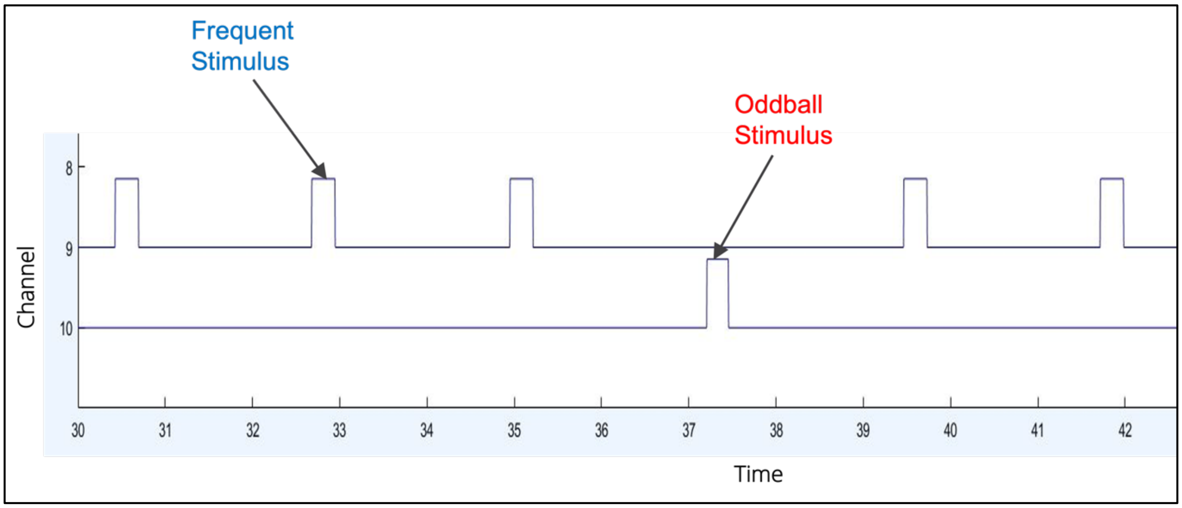


Figure 4.3. Stimuli onset and disappearance showing as pulses on the channel data plot.

Please note that the results recorded with the oscilloscope and analog read on the GUI were done before taking readings from any of the participants. When it was time to take the EEG readings of each participant, the "Digital Read" widget was turned on. Digital pin D12 recorded the non-target stimulus while pin D13 recorded the oddball stimulus. At the appearance of the oddball stimulus, the D12 circle on GUI reads 1 and reads 0 when the stimulus disappears as seen in Figure 4.4. Similarly, the nontarget stimuli's appearance and disappearance reads as 1 and 0 respectively.

4.2 Performance Analysis

The second design validation test was the oddball experiment that was conducted. EEG data recorded from the OpenBCI headset was processed offline using the EEGLAB and ERPLAB toolboxes in MATLAB. Before processing, the raw data including the events was first imported, sampled at 250 Hz and filtered to remove noise due to eye movements and blinking. A Butterworth filter with a passband of 0.5 Hz to 30 Hz is used to remove DC effect and minimize artifacts at the epoch boundaries. Afterwards, a 60 Hz notch filter was used to remove resonance in the data. Artifacts such as eyeblinks and horizontal eye movements were done offline using RUNICA on the EEGLAB toolbox. The channel data was then plotted to visualize the filtered data and associated events. The channels with the events of interests and the ERP component were extracted from the continuous EEG data and plotted in Figures 4.4 and 4.5 respectively. Figure 4.4 shows the measured events of the stimulus images collected by the photodetector. These events, as mentioned in the project design section, are the oddball and frequent stimuli onset and disappearance. The measured events can be seen in channels 9 and 10 as shown in the figure, with the nontarget stimulus appearing in channel 9 and target stimulus appearing in channel 10. The frequency of stimuli is also indicated in this figure: the stimulus in channel 9 occurred more frequently than that of channel 10. The timing of the stimulus onset is locked to the rising edge of the pulse, which is the photoresistor signal, and the falling edge of the pulse indicates the stimulus' disappearance.

Max Freq: 60 Hz
Max uV: 100 uV
Log/Lin: Log
Smooth: 0.9
Filters?: Filtered

Figure 4.4. D12 circle on "Digital Read" widget of the GUI reads 1 when the nontarget stimulus is presented while the other digital pins read 0.

This event plot is very similar to the plot on the oscilloscope and GUI and precisely corresponds to the oddball paradigm timing presented during the experimental procedure. The results of these tests show that the designed photodetector accurately detected the onset and disappearance of the stimulus images and synchronized the generate visual stimuli with the recorded EEG data. The EEG data for each of the five participants was processed separately. For each participant, ERP waveforms were generated in response events of interest by averaging the segmented EEG data for each electrode. After processing the data, the ERP waveform for each electrode generated in response to the oddball and common stimuli was plotted.

It is important to note that the maximum refresh rate of the MacBook pro used in this study to display stimuli is 60 Hz, therefore, the time between the display of the two stimuli is a multiple of 16.67 ms. However, this time delay will not really impact the onset timing in EEG data analysis since the time delay of the circuit is less than that at 26.7 μs. Therefore, any latency caused by the refresh rate is not significant enough to affect the analysis result.

4.3 Confirmation of Device Operation in an ERP Experiment

To test the effectiveness of the designed photodetector circuit in its intended operation within an ERP experiment, an oddball experiment was carried out on several participants. The test participants were seated in a comfortable chair 50 cm away from the display screen of the computer. It is important to note that the factors such as the poor test environment and motivation, fatigue, and discomfort in humans can create be confounds which can affect data quality. Presence of background noise can make it very difficult to detect the P300 response in the EEG data. Therefore, before the commencement of each test session, all electrical appliances not in use in the lab were turned off. The headset was placed on the head of the participants to ensure that the electrodes had proper connection with the scalp and the ear clip electrode, reference electrodes,

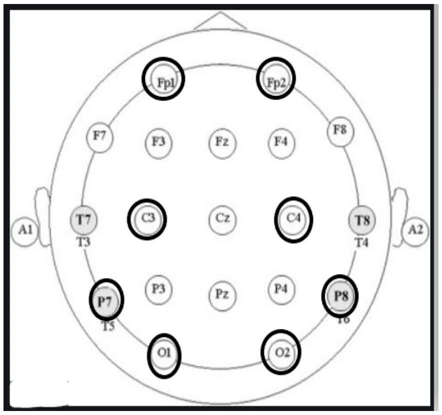


Figure 4.5. The 8 electrode channels for the EEG headset. Channels used were Fp1, Fp2, C3, C4, P7, P8, O1, O2 and A1(reference) and A2 (ground) are the testing configuration used in the experimental setup for the EEG experiment.

were attached to the earlobes. Figure 4.5 shows the electrode placement used in the collection of EEG data for evaluation of the stimulus synchronization module. After the electrode and experimental setup, the participants were presented with the visual oddball paradigm.

During the oddball session, the test participants were presented with a series of black square and circle for 250 ms in the center of the main white screen. The black square was presented as the frequent or standard stimulus while the black circle was presented as the rare or target stimulus. Different set of rare and frequent stimuli were presented to avoid confounds associated with stimulus-specific conditions. At the beginning of each trial, before the onset of the first stimulus and between each stimulus presentation, a black fixation dot was displayed for 2000 ms. The paradigm consisted of 50 train of frequent and rare stimuli: 20% for the oddball stimulus and 80% for the frequent one.

An instruction was given to each participant to maintain central fixation, focus only on the oddball (black circle), and mentally count the number of black circles within each trial block. On completion of one session, participants were rested for 3 mins before the start of the next trial block. Overall, each participant completed 2 trial bocks during an experimental session. During the experimental sessions, the GUI on the EEG data acquisition computer showed the live data stream from the electrodes and the event codes from the digital pins. To measure the data from the digital pins, "Digital Read" widget on the OpenBCI GUI was selected and turned on. The EEG data, which include the participants' responses to the displayed visual stimuli, and the event codes from the photoresistors were recorded and saved as text files on the computer. Figure 4.6 shows the full experimental setup in use for a visual odd-ball paradigm experiment.

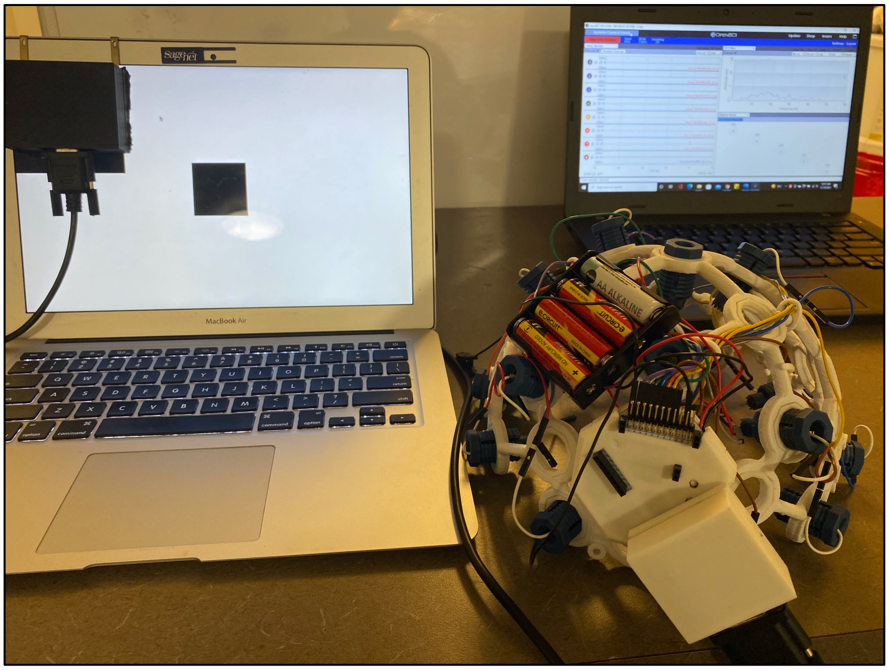


Figure 4.6. The setup used in the experimental procedure. The case mounted on the laptop with a stimulus image showing on the laptop screen and the GUI on the second laptop screen.

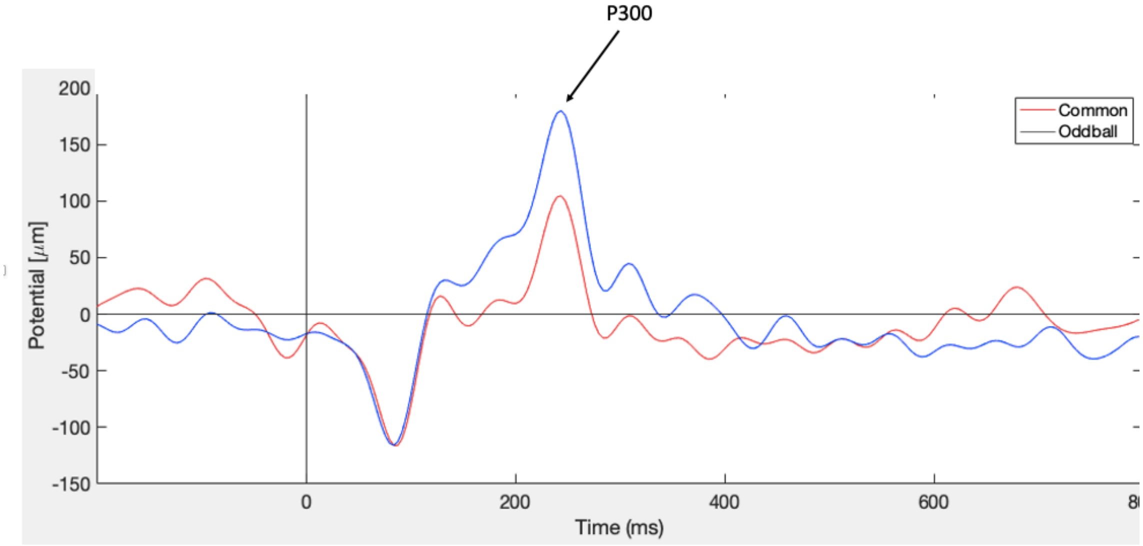


Figure 4.7. The generated ERP waveform showing the elicited P300 from the oddball and common stimuli.

After collection of data using ERP system as shown in Figure 4.6. the collected data was analyzed as described in section 2.4. The resulting P300 curve elicited by the oddball and common stimuli is shown in Figure 4.7. This result confirms that the event synchronization module developed in this thesis can work effectively in an ERP experimental system.

4.4 Adherence to Design Requirement

In section 1.3, the design requirements for the synchronization module were detailed. In this section those design requirements are reviewed with consideration of how effectively the prototype presented here can meet the stated design requirements. Table 4.1. highlights how the prototype satisfies the design requirements.

Table 4.1: Synchronization Module Design Requirements with discussion of prototype performance compared to stated design requirement.

Design Requirement	Prototype Performance
Provide less than 4 ms of jitter in the event code timing compared to when the stimulus actually appears on the stimulus presentation screen	Jitter in the event code timing was less than 1 ms and as such was nonsignificant.
Provide an event code latency of less than 8 ms	The total event code latency was 26.7 μs which is less than the specified 8 ms.
Computing platform agnostic (no requirement for specific hardware, software, or operating system)	Prototype is system agnostic and can operate on both windows and Mac OS operating system.
Connect to the stimulus generation laptop without obstructing the center of the screen or limiting interaction with the laptop by the test subject.	The prototype was placed on the upper corner of the screen where the smaller images indicating each stimulus onset appeared. The position of the prototype did not obstruct the stimulus images nor limit test subject's interaction.
Keep anticipated component costs in the final product to less than $5	Total cost of components used in building the prototype was less than $5.

In summary, the prototype developed in this thesis meets all of the design requirements detailed in section 1.3.

CHAPTER 5

CONCLUSION AND FUTURE WORK

The goal of this thesis project is to design a low-cost and easy-to-use synchronization solution to accurately incorporate events codes directly into recorded EEG data. The motivation that inspired this thesis was the need to conduct practical and visual ERP at a very low cost without additional technicality. To achieve this goal, the system presenting the stimuli is connected directly to the amplifier of the EEG hardware with a designed photodetector circuitry. A P300 experiment was conducted to test the functionality of the designed paradigm and photodetector device. The function of the paradigm was to observe the brain's neurological response to rare or oddball events while the photodetector was built to synchronize the generated visual stimuli with the EEG data recorded before, during, and after stimulus presentation. When compared with other commercial synchronization approaches that already exist, the designed photodetector had the lowest time delay in stimulus timing as seen in Table 5.1.

Overall, the proposed solution satisfied the technical requirements listed in Chapter 1. There were no challenges with the code and the stimuli were presented with high precision and milliseconds accuracy. Display of the stimulus images was appropriately timed so that it is not too fast or too slow to avoid cofound in the results. The written java code can operate smoothly on both Windows and MAC operating systems. A configuration file is generated in a text format when the code is run, which describes the parameters of the stimulus images. The text file simplifies program modifications such that the file can be easily edited to automatically update the main code when necessary. The designed hardware is portable and convenient to use given that the setup and two experimental sessions for each participant took a maximum of 10 minutes to complete. It was very easy to connect the circuit to the cyton board without making the participant uncomfortable.

Furthermore, only two small laptops, which are easily accessible, were used in the experimental setup. Results from the tests conducted show that the device achieved its purpose for this research and worked as well as the more expensive conventional use of event markers and synchronizers. The cost of the designed synchronization hardware was compared with some pre-existing commercial synchronization approaches in Table 1.2. Given its low cost and ease of use, the photodetector device significantly enhances the compactness and usability of ERP data collection devices. The potential applications of this hardware are in the study of neurological disorders such as schizophrenia, depression, and in the restoration of mental functioning of post-coma patients. Another application is in studying the brain's response to fatigue in humans.

Although only two out of the four photoresistors were used in this thesis project, the four photoresistors can be used in future visual ERP experiments conducted in the lab. Furthermore, the code can be modified into either a single-stimulus paradigm, three-stimuli paradigm, or other visual stimulus approach to present visual stimuli with high accuracy. Therefore, it increases opportunities for further visual ERP-based projects in the lab. Due to its workability with the OpenBCI headset, more data can be collected from many participants for further processing. Finally, results from software synchronization approach can be compared to that of the designed hardware approach.

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