

BlinkFruity: A Real-Time EEG Based Neurofeedback Game for Brain-Computer Interface

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Abstract

The Brain-Computer Interface (BCI) is a communication channel between the brain and the computer. It works by detecting the neural signal of brain activity. Brain signals can be detected with various BCI methods that include observing the changes in magnetic fields due to electric currents, changes associate with blood flow and neural electrical activity. Based on the selection of the required area of brain signal and the BCI method, the signal acquisition process might require from non-invasive method to an invasive (surgical) method. Despite invasive methods require a surgical procedure to implement brain signal recording implants, brain signals recorded via invasive methods offers unparalleled spatial resolution with a very low signal to noise ratio (SNR). On the contrary, non-invasive methods are easy to implement and provides good temporal resolution with high SNR. Among many non-invasive brain signal recording methods, Electroencephalography (EEG) is one of the most popular methods. EEG controlled applications widely range from strictly medical to non-medical applications. Non-medical applications can not only be used for entertainment purposes but also can help a subject to experience BCI application, achieve better control with rehabilitation systems and can be a strong motivation to practise the BCI system. Brain signals recorded via EEG are weak and contain several artefacts like muscle movements, cardiac, eye blink, power source, and amplitude artefacts. Although eye blink is considered as one of the strongest artefacts, but it can be used to drive BCI enabled applications. With this in mind, this study uses eye blink as a control signal to play the BlinkFruity game, where users collect fruits into a basket using eye blink only. To attain this objective, at first, the brain activity was recorded using OpenBCI device and 500ms window data was taken to process in real-time. Then the notch filter was applied to remove powerline noise. The eye blink was detected by using the signal thresholding method reading from EEG data. Blink detection average accuracy of 84.8% was obtained using blink control applying on subjects. The primary objective of this study is to design a simple BCI enabled system for users who are experiencing BCI for the first time and find it interesting. Then evaluate the proposed system and user's experience. Even though in this experiment, blink has been used for experiment purpose, there are several areas where blink can be used as home automation, rehabilitation and augmented mobile application experience. Moreover, findings from this study can be resourceful and enhance our understanding and capacity for developing BCI application.

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Chapter 1

Introduction

1.1 Introduction

Brain cells fire electricity within the dendrites and generate brain signal whenever there is any mental activity. These bioelectrical activities differ based on different types of mental activity. The Brain-Computer Interface (BCI) is a communication channel between the brain and the computer which is capable of detecting and interpolating those changes of mental activity or brain signals [1].

In recent years, a wide range of methods has been available to understand these brain activities. These methods to record brain activity can mainly be divided into two approaches, invasive and non-invasive. In an invasive approach, brain signals recorded directly from the brain with a surgical process. Usually in neurosurgical patients undergoing diagnosis and treatment of medically intractable epilepsy needs an invasive approach for a better understanding of their brain activity. Electrocorticography (ECoG), Local Field Potentials (LFP), Deep Brain Stimulations (DBS) and Single Unit Recording are some of the methods in the invasive brain signal recording approach [2].

Although invasive yields higher performance than non-invasive [3], nevertheless non-invasive techniques, specially Electroencephalography (EEG) is being popular as it does not have the complexity of the surgery, ease of use, and it requires low cost [4]. However, there are more non-invasive methods like Magnetoencephalography (MEG), Functional Magnetic Resonance Imaging (fMRI), Photon Migration Tomography (PMT; also called near-infrared spectroscopy or optical imaging) and Transcranial Magnetic Stimulation (TMS). But they require high cost, maintenance and expertise to use [3]. EEG signals can be recorded from the scalp due to the relatively large electrical activity of neuronal populations [5]. As EEG signals are generated from very low amplitudes and bandwidth, unfortunately, they get contaminated highly during recording by other sources of electrical activity [6]. Sometimes these noises are very difficult to remove, even so far some of them are impossible to remove without losing the integrity of data, or to recover the exact information and morphology that was hidden under interference.

1.2 Motivation

Nowadays, BCI becoming a popular communication channel in non-medical applications. Nonetheless, while people are using the BCI system for the first time in the laboratory environment, not everyone feeling comfortable with the system. There have been abundant studies about the effectiveness of the system, ease of use, engagement with the GUI [1], [5], [7]. Study shows that people find BCI system vague and difficult to understand while they experience it for the first time [8]. Users think that they are properly using the system, but the system does not respond to user's acts. Thus, users do not feel in control of the system and the overall process seems vague. This study proposes a simple BCI enabled system for naive users and explores challenges from the user's perspective.

1.3 Objective

BCI offers movement disabled people new hope to interact with their surrounding environment by translating mental thoughts into device control. It is a method of communicating or sending command directly to the computer from our brain. It does not require the habitual path of nerves and muscles [9]. The primary goal of BCI enabled systems is to rehabilitate movement disabled people and support medical care [2]. However, nowadays BCI is not limited to rehabilitation purposes only. Using brain signals BCI afford direct, undirect or hybrid control signal using multiple BCI methods [10]. Besides rehabilitation [11], these control signals can be used for playing games [10]. In most cases, these games are not limited to entertainment purposes only. There are lots of studies is being conducted by researchers from the field of neuroscience and computer science to enhance performance and cognitive skills. To enhance skills and performance they are designing the training system with an entertaining environment. This helps a user to control the BCI enabled system more proficient and enjoyable [8], [12]–[14]. Some of the prominent fields where BCI systems are being studied for enhancing cognitive skills are attention and focus [8], [13], [15]–[21], concentration [13], [22]–[28], relaxation [10], [14], [25], [29], meditative level [17], [30], [31] and memory [17], [26], [30]–[32]. Moreover, it is also being used for pure entertainment purposes only [10]. Some of these systems have been published and validated with therapeutic effectiveness along with entertainment purpose.

Although EEG is the most popular method while developing BCI enabled system, but brain signals recorded via EEG are very weak and highly contaminated with various artefacts both from the subject and from equipment interferences [33]. A 50Hz or 60Hz power line noise (depends based on country) is very common in EEG signals [34]. Our skeletal muscles also produce electrical activity noise which is known as Electromyography (EMG) [35]. Another unavoidable human subject generated noise is Electrocardiography (ECG) which is generated from cardiac [36]. The most strong artefact considered in EEG signal especially signals collected from the frontal lobe [37] is Electrooculogram (EOG) [38], which is generated from eye blinks and eye movement.

Specific objectives of this study have been listed below.

- Designing a simple BCI application for naïve users who are going to use the BCI application for the first time.
- Developing the gaming interface considering human-centred design.
- Development of a BCI protocol for real-life application.
- Evaluating the application with the participants.
- Discuss the feedbacks of the participants about their experience with BCI.
- Sharing the database and source code publicly which has been produced from this study.

1.4 Contribution

In this paper, a real-time EEG based game named BlinkFruity has been proposed which sole purposes are for experiencing Brain-Computer Interface for the first time, practising to enhance neurofeedback-based beginner level system and having fun. Although in EEG data eye blink is considered as one of the strongest artefacts [39], in this study eye blink is not an artefact at all. Instead, here eye blink has been used as the control signal to play the BlinkFruity game. Blink detection accuracy of 84.8% was obtained applying this system on the first five subjects. In this game, a basket is placed at the bottom of the game screen representing the player and fruit is placed in a distance. By detecting players eye blink, the player representing basket move towards the fruit. When the basket reaches near the fruit,

the fruit item gets collected into the basket. BlinkFruity was designed considering that the effectiveness of any game highly depends on its attractive and interactive user experience [12]. The dataset (anonymous) and the source code is publicly available* so that the results showed in this paper can be reproduced.

1.5 Outline of the Thesis

The rest of this book is organized as follows. Chapter 2 describes the background of this study and some literature review. Subsequently, chapter 3 presents the proposed methodology. Then in chapter 4, the interface design, the gaming protocol and the experimental setup has been presented. The results and discussion have been described in chapter 5. Finally, chapter 6 concludes the paper.

The contents of each chapter are listed in the following.

- Chapter 1 introduces the motivation, objective and outcome of this study.
- Chapter 2 provide reviews on different established bio signals, available bio signal recording devices and state of the arts related to this study.
- Chapter 3 is all about the methodology of this BlinkFruity system. The methodology has four modules. These are signal acquisition, signal processing, activity detection and application.
- Chapter 4 is divided into two sub-chapters. The first one in the proposed game. It depicts the game GUI, it's system analysis and the control flow. The second sub-chapter describes the experimental setup which includes ambient and materials, participants and procedures.
- Chapter 5 presents all the findings of this study. This result and discussion chapter evaluate the BlinkFruity game, explores users experience with BCI, presents users discussion suggestions and feedback on the BCI system.
- Chapter 6 concludes after discussing the limitations of this study and proposing future work which has been explored.

* <https://github.com/ranadepto/blinkfruity>

Chapter 2

Background and Literature Review

This chapter is divided into two sections. The first section is about the background and motivation of this study. Then in the second section, some of the works of literature related to this study has been discussed.

2.1 Background

BCI is the direct communication medium to control a computer or other devices without the help of conventional communication channels, nerves and muscles [9]. In the BCI enabled system, only brain signal is used and this is still a new area to explore. It has not been stable yet for the development of consumer-grade products. Most of the BCI systems are primarily focused on making the system workable in a controlled lab environment. Hence, these systems fail to perform out of the lab environment in most cases. On the other hand, neither the Graphical User Interface (GUI) nor User Experience (UX) does get priority here. This happens because most of these systems are developed by researchers for experimental purposes without the help of professional developers. Studies show that most of the experiment participants were finding the BCI system vague and complex [12], [8]. They were not being able to understand what and how should they respond. They thought that they are fully focused on the task to control the system and expect some action in return. But the system was not being able to detect or respond to their action [12]. In the BCI enabled system, only brain signal is used. Hence the user gets helpless if the system does not respond.

So, in this study, we wanted to explore the answers to some questions.

1. Why novice users find the BCI system vague and complex?
2. What users expect that how this communication system should be?
3. What should keep in mind while designing and developing a BCI system?

Consequently, we are proposing this system, named BlinkFruity. We experimented on 10 participants to observe them and take their feedback.

2.2 State of the Art of Brain Signals

Our brain generates various type of responses due to the mental activity which includes electrical, magnetic, and metabolic responses. With appropriate devices and sensors, these responses can be detected and identified for further analysis. There are two ways to record brain signals namely invasive and non-invasive [2]. A surgical and complexed procedure required in an invasive method. On the other hand, non-invasive, which can record brain signals from the scalp using dry or gel conducted electrodes without any complexity of the surgery.

An invasive approach produces very detailed information about mental activity. It can detect and decode complex movement intentions from a particular area of our brain. Single Unit Activity (SUA) and Local Field Potentials (LFP) are examples of the invasive approach of brain signal recording technique. In an SUA, microelectrode arrays implanted in the brain which record the activity of single neurons. On the other hand, for recording small neuronal populations, LFP is used.

Magnetic fields can be recorded with magnetoencephalography (MEG), while brain metabolic activity - reflected in changes in blood flow - can be observed with positron emission tomography (PET), functional magnetic resonance imaging (fMRI), and near-infrared spectroscopy (NIRS) [40]. Unfortunately, MEG, PET and fMRI operate in special facilities with sophisticated devices. Additionally, professional and skilled people required to acquire signals with these methods.

However, an excellent quality brain electrical activity in a low spatial and low temporal resolution can be acquired with low-cost portable devices. In a non-invasive brain signal recording technique, electrodes are placed on the surface of the brain which detects the overall concerted activity of neuronal populations. Electroencephalography (EEG) is one of its kind which is one of the most popular non-invasive brain electrical activity measuring method which records the synchronous activity of thousands of cortical neurons.

The next sub-section describes some popular research and commercial grade EEG signal recording devices.

2.3 State of the Art of Signal Recording Devices

Nowadays, there are a number of hardware devices available in the market which provide raw EEG data. Among them, some also provide a class label or quantified data to detect relaxation level, meditation level and sleep state.

Table 1: This table includes portable and low-cost EEG recording devices detailing no. of channels, electrode type, raw data, cost, weight, comfortability, mobility or sleep ability, customizability, relaxation, meditation, sleep class label or quantifiability comparison

Devices	Muse	NeuroSky	BrainCo	Emotiv	OpenBCI
Properties					
No. of Channels	4 (+3 Ref.)	1 (+1 Ref.)	5 (+1 Ref.)	5, 14, 32 (+2 Ref.)	4, 8, 16 (+2 Ref.)
Electrode Type	Metal	Metal	Metal	Gel/Saline	Dry
Raw Data	Yes	Yes	Paid	Paid	Yes
Cost	Low	Low	Low	Medium	Medium
Weight	Light	Light	Light	Medium	Heavy
Power source	Li-Ion	1x AAA	Li-Ion	Li-poly	4x AA
Running time	10h	8h	4h	6h-12h	40h
Comfortable	Yes	Yes	Yes	No	No
Mobility or sleep ability (wearing the device)	Yes	Yes	Yes	No	No
Customizable	No	No	No	No	Yes
Replaceable sensor	No	No	Yes	Yes	Yes
Relaxation	Yes	Yes	Yes	No	No
Meditation	Yes	Yes	Yes	No	No
Sleep	Yes	Yes	No	No	No

Muse [32], BrainCo [41] and NeuroSky [42] are some of the commercial company who has developed and using their customized hardware and software. All these companies also provide a software development kit (SDK) for researchers and developers to experiment and develop products using their hardware. A comparison among various low cost and portable EEG devices are presented in Table 1.

As can be seen from Table 1, Muse, NeuroSky and BrainCo provides relaxation meditation and sleep data with either a class label or in a quantifiable format. These hardware are lightweight and comfortable to use. The subject even can sleep wearing Muse and BrainCo device. Between Muse and BrainCo, Muse provides their SDK free, and it has a better battery lifetime of 10 hours. Analysing these parameters, it can be concluded that Muse can be a good pick among these already existing brainwaves recording hardware.

2.4 Literature Review

The idea of making the Brain-Computer Interface started in the early 1970s. Since then, it has become a very interesting topic among scientists and as well as science fiction writers. Nowadays, some of the BCI technology has come out of the laboratory and become consumer-grade products. Several applications have already been made. Mindflex and visual P300 speller are good examples. Mindflex is a best-selling game that is based on Electroencephalography (EEG). P300 speller is used as a communication channel by severely disabled people [43].

In medical science, BCI has several applications. As an assistive device, BCI or Human-Computer Interaction (HCI) plays a great role in making life better for those who are physically challenged or locked in due to accident or diseases. Some applications of HCI in medical science are artificial organs, prostheses, joint or limb replacement, and another rehabilitation engineering that helps disabled peoples [44].

On the other hand, non-medical approaches are also taken. Some of the non-medical applications are device control, user state monitoring, training, education, gaming and entertainment, and safety and security [45]. Figure 2.1 shows device control and an entertainment feature of BCI.



Figure 2.1: BCI for device control and entertainment [45]

Studies have demonstrated some other BCI applications in such well-known games as Pacman [46], Pinball [47], Tetris [48], and World of Warcraft (WoW) [49], as well as new customized games, such as MindBalance [50], Bacteria Hunt [51], and others [52]–[56].

As well as that, some studies have been conducted about the effectiveness of BCI implemented system GUI. Some experiments have been conducted to take user feedback through both informal or formal interview session with previously established games interfaced with BCI technology [8]. Even some simple BCI applications are also available for solely entertainment purposes. However, some systems which are partially related to this system has been discussed in this sub-section.

2.4.1 BLINK: A Fully Automated Unsupervised Algorithm for Eye-Blink Detection in EEG Signals

BLINK is a simple eye blink detection system in the EEG signal [38]. It self-learns user-specific blinks from the brainwave. The advantage of this system is, it only requires single-channel EEG data and does not require Electrooculography (EOG) data. Additionally, this system is capable of detecting the start and the end timestamps in a precise manner. This ensures clean EEG data along with insights of eye blink duration.

Without an explicit requirement of fine-tuning algorithmic parameters, this algorithm can be considered as a single universal algorithm to detect eye blink with higher accuracy, which is consistently over 98%. Some of the eye blinks were missed because of its abrupt pattern. Figure 2.2 illustrates cases where BLINK misses to detect vs the regular eye blink pattern.

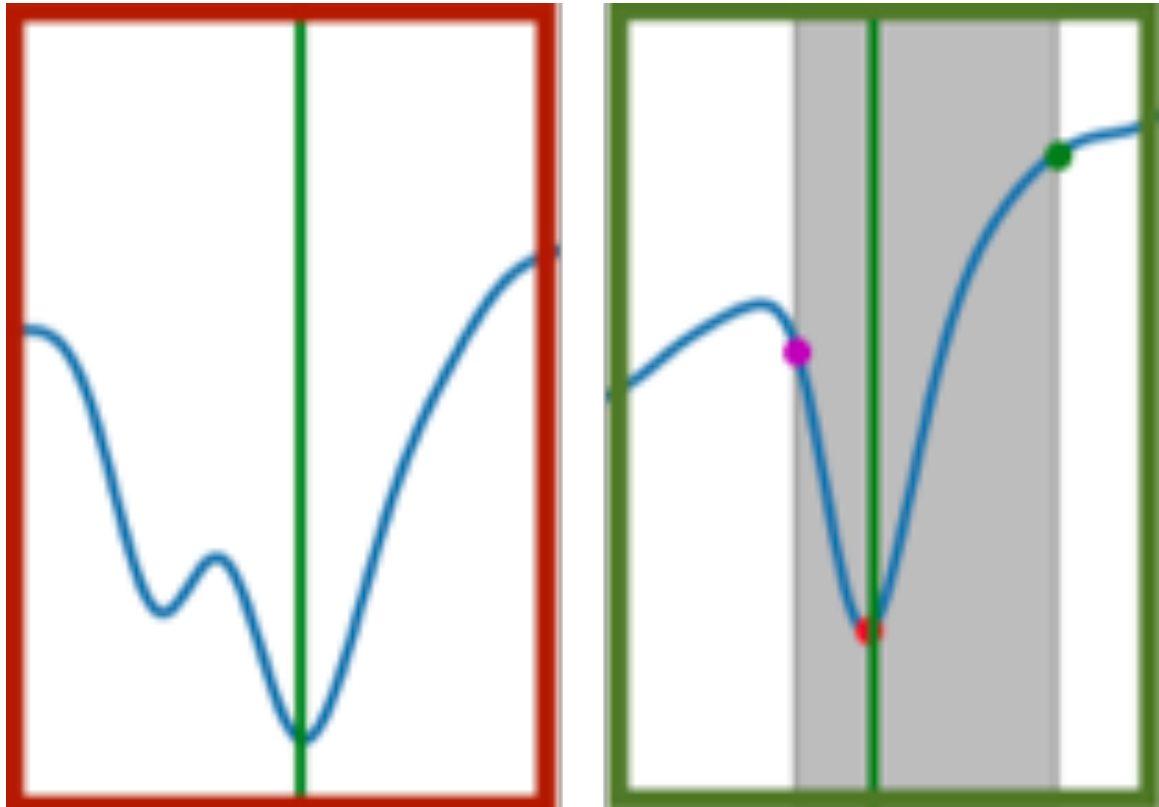


Figure 2.2: Failure cases of Blink algorithm: (left red marked box) failed to detect abrupted eye blink pattern, (right green marked box) the regular eye blink pattern [38]

2.4.2 The influence of graphical elements on user's attention and control on a neurofeedback-based game

In most cases, BCI games are designed and developed by researchers to conduct scientific research and evaluate the accuracy of the system. Thus, these systems often tend to be simplified or have poor graphics. On the other hand, a BCI system uses mental focus as a control signal. Having heavily animated effects of Game Graphical User Interface (GGUI) can distract users. Consequently, this study [8] uses the mind-controlled computer game “Tug of War” to experiment with the influence of graphical elements on the user's attention and control. Additionally, it also investigated the absent of graphical elements on the user's performance. Figure 2.3 depicts the GGUI of their system. A total of 8 subjects participated in this experiment and who played a total of 240 game matches. The experiment presents many insights regarding the impact of graphical elements. In addition to this, they also provided some user feedbacks regarding the first time BCI experience.

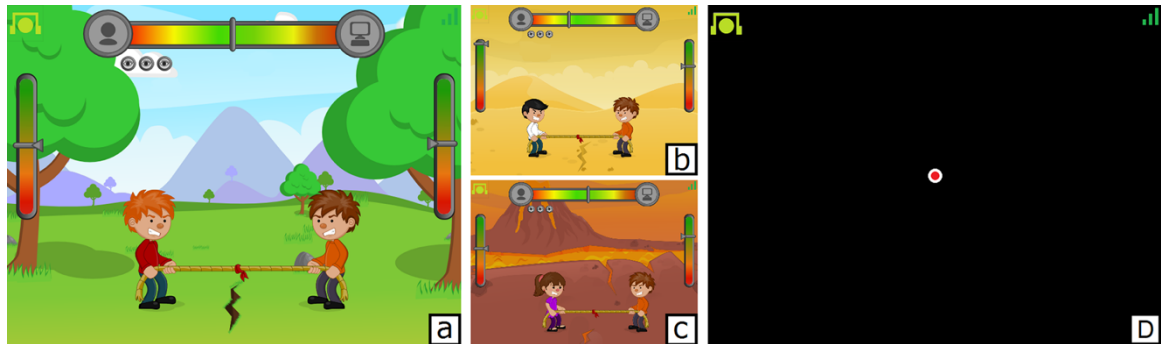


Figure 2.3: Game interface in the (a) easy, (b) medium, and (c) hard difficulties; and (d) the game without the Game Graphical User Interface configuration [8]

They found that the participants who were able to win the game against the system or had a higher level of average attention level, those participants rated a higher level of satisfaction. Nonetheless, they did not feel the system in their control.

Some subjects reported that they were being able to be more attentive without the graphical elements. However, the great majority of the participants found GGUI enjoyable. They even reported that without the GGUI they got tedious and monotonous after a while. Above all, the animated element and colourful GUI made the participants even more engaged, focused, motivated and influenced.

2.4.3 The Mind Garden: A Brain-Computer Interface Game

The Mind Garden is a simple BCI system where two skills are used to increase, attention and meditation [31]. Initially, a colourful environmental scene is presented to the user (showed in Figure 2.4). The user will need to drag a tree from the top-left corner of the screen and to add environmental elements. On the other hand, the user will have to drag items from the top-right corner of the screen using a mouse.

After placing elements, the user can start playing the game and practise increasing their attention and meditation skill. User can control the growth of their planted trees using their attention level. To decorate the garden user will use their meditative level. The outcome of playing the game has been shown in Figure 2.5.

There are some lacking in this study. Although, The Mind Garden is a novel BCI system to practise attention and meditation, no GUI, User Experience (UX) or user feedback has not been taken. There was no system evaluation either. In addition to that, a statistical analysis could have been taken in this study.



Figure 2.4: The initial GGUI of The Mind Garden [31]

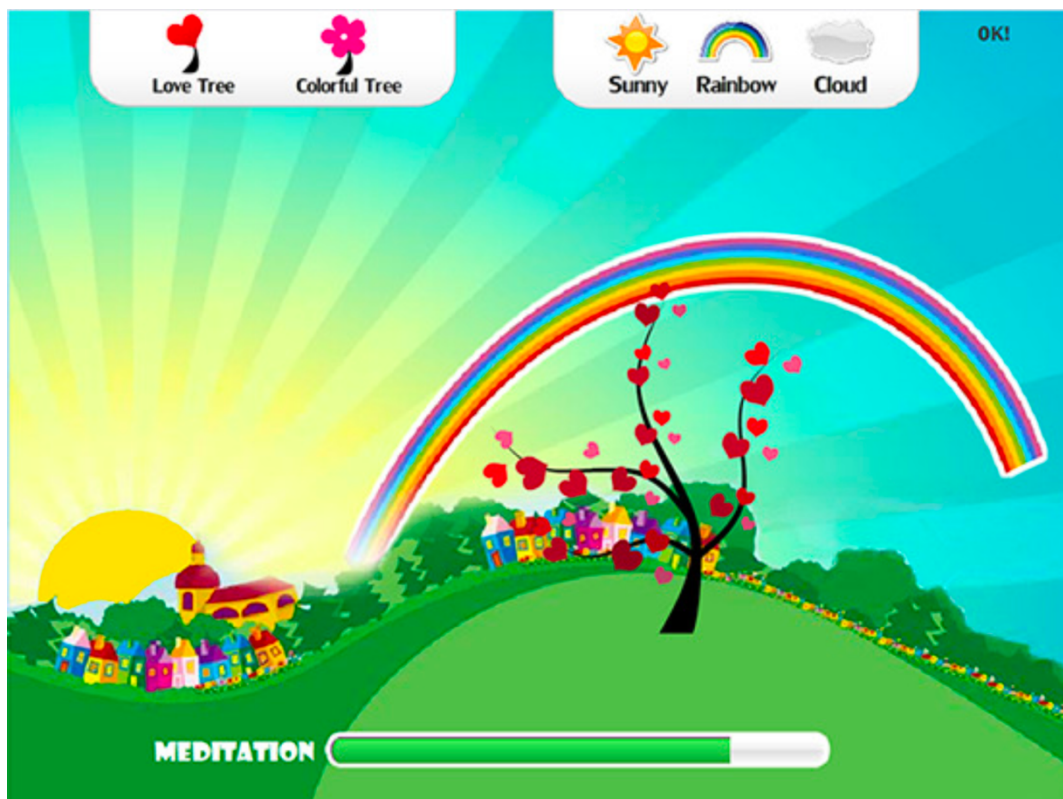


Figure 2.5: The final GGUI after adding environmental elements and decorating the garden using attention and meditation score [31]

2.4.4 Design of an Online EEG based Neurofeedback Game for Enhancing Attention and Memory

According to the study in [57], attention is a combine feature of sustained attention, selective attention and active working memory. Therefore, this system [58] evaluated users attention by combining these three values. The primary focus of this system is enhancing attention and memory. So, this system has a poor GGUI to fulfil its objective.

In this system, the user is shown a 3 x 3 matrix with some random numbers. Based on players selection on Level-1, Level-2 or Level-3, the system will show 3, 4 or 5 numbers respectively for 2 seconds long (Figure 2.6). Within these 2 seconds, the user will have to memorize these numbers and then place those numbers into the box one by one. After that, the screen will turn black for 4 seconds period. Then the user will need to use their attention to activate the option of selecting the right number between two numbers. When the user will cross the user-specified threshold value of attention, the GGUI will show two options to select the right one using the keyboard (showed in Figure 2.7).

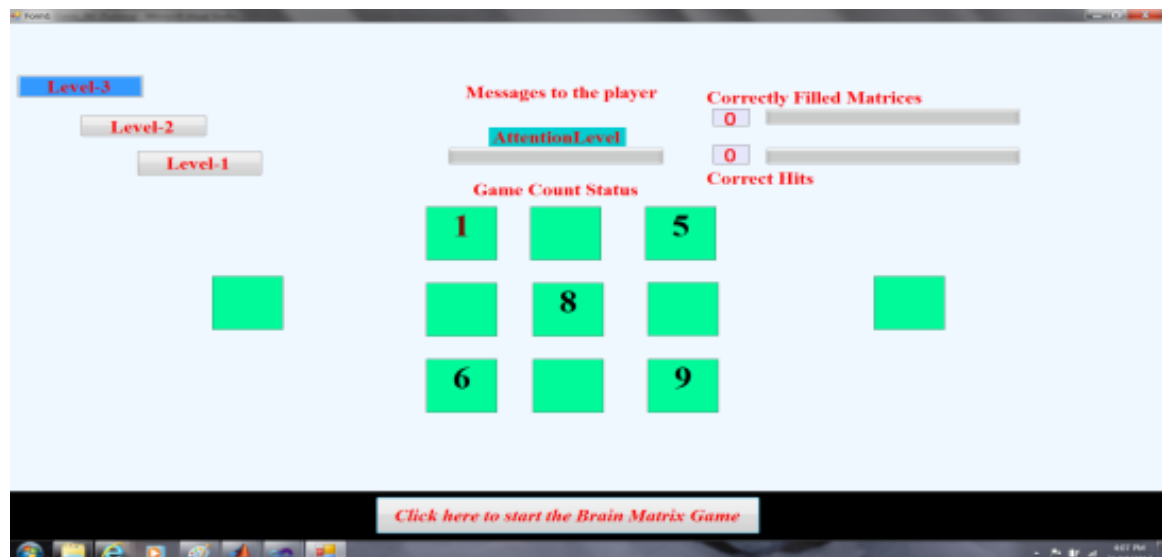


Figure 2.6: Proposed GGUI showing numbers for 2 seconds to memorize [58]

On the contrary, if the user cannot reach the specified threshold value of concentration, the selection option of arrow keys won't appear on the screen. In that case, the user will miss that step and the next element will be highlighted.

The experiment was conducted on 5 healthy subjects. The results show that all participants were able to make progress and their performance improved by playing this game. All of their game completion time was comparatively lower in the last session than in the first

session. However, this study did not conduct an interview session with the participants either.

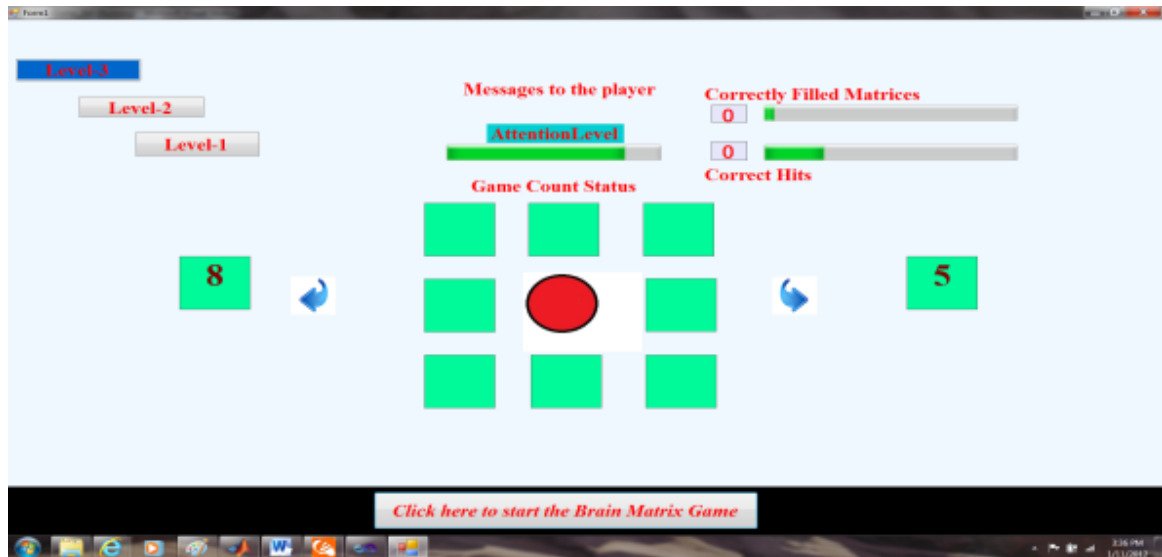


Figure 2.7: Proposed GUI during the answer selection process using attention level [58]

2.4.5 FOCUS: Enhancing Children’s Engagement in Reading by Using Contextual BCI Training Sessions



Figure 2.8: A primary school student is using the FOCUS system [59]

FOCUS is a neurofeedback based real-time engagement level monitoring system [59]. It monitors a child’s reading engagement level and if it finds the engagement level low, the system triggers a content-related BCI training system. This way it reengages the child to the study. The system has been evaluated both in EEG-based evaluation of reading

engagement and teacher's evaluation measurement of the reading outcome by applying it on 24 primary school students. The study provides empirical evidence that this kind of training can improve reading engagement.

The system was evaluated by the participants. Although there was no GUI, the system was interacting with the user. Figure 2.8 showing a primary school student using the FOCUS system. As per their feedback, all students enjoyed experiencing this system and wearing the brain wear recording device. Furthermore, they felt a sense of achievement to complete BCI training tasks with the power of their focused attention.

2.4.6 Virtual Keyboard BCI using Eye blinks in EEG

Virtual keyboard using eye blink has been developed targeting the paralyzed and disabled people [5]. In this system user can type with their eye blinks only. The user will be showed a total of three 3x3 matrices (showed in Figure 2.9). There have three events. Single eye blink, two eye blink and three eye blink events. Single blink will select the first matrix, two blinks will select the second matrix and three blinks will select the third matrix.

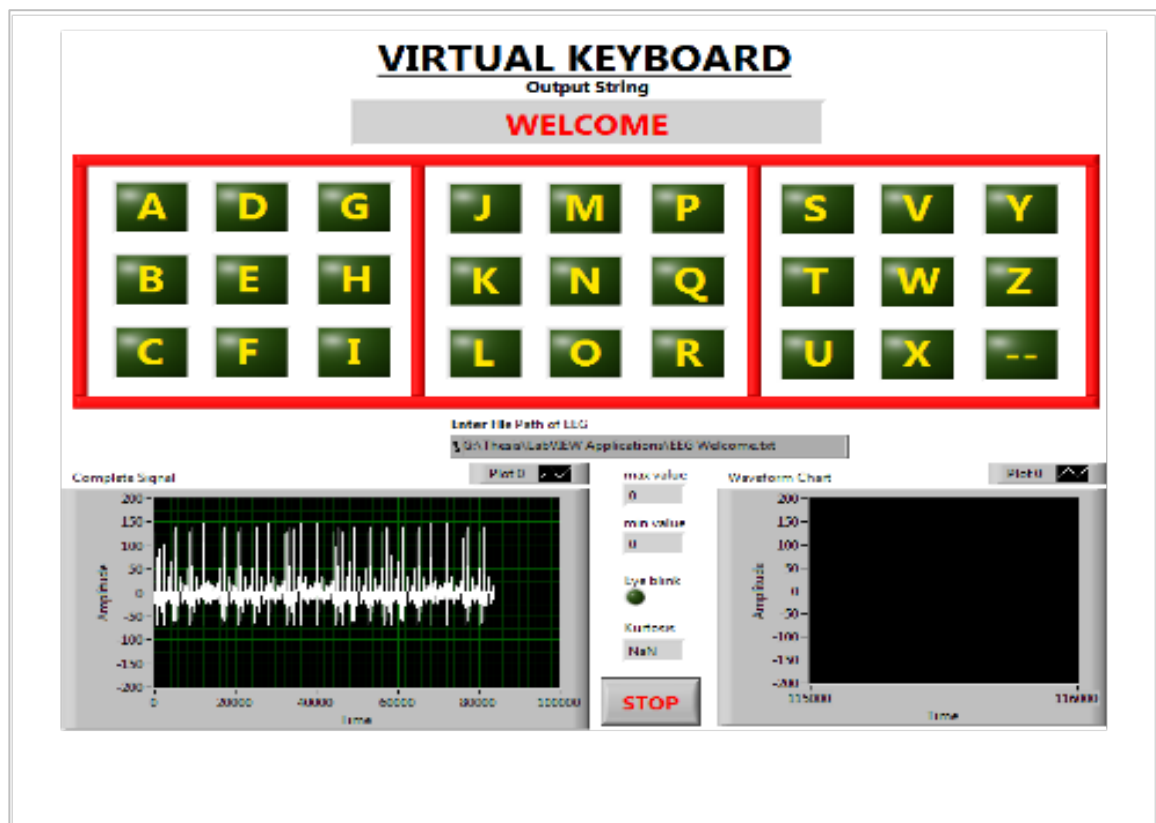


Figure 2.9: Initial GUI of Virtual Keyboard [5]

The system detects blink in a 5-second window. It takes 4 steps and a total of 20 seconds to select an alphabet. Figure 2.10 depicts the selection scheme of this virtual keyboard. A total of 14 subjects participated in this experiment.

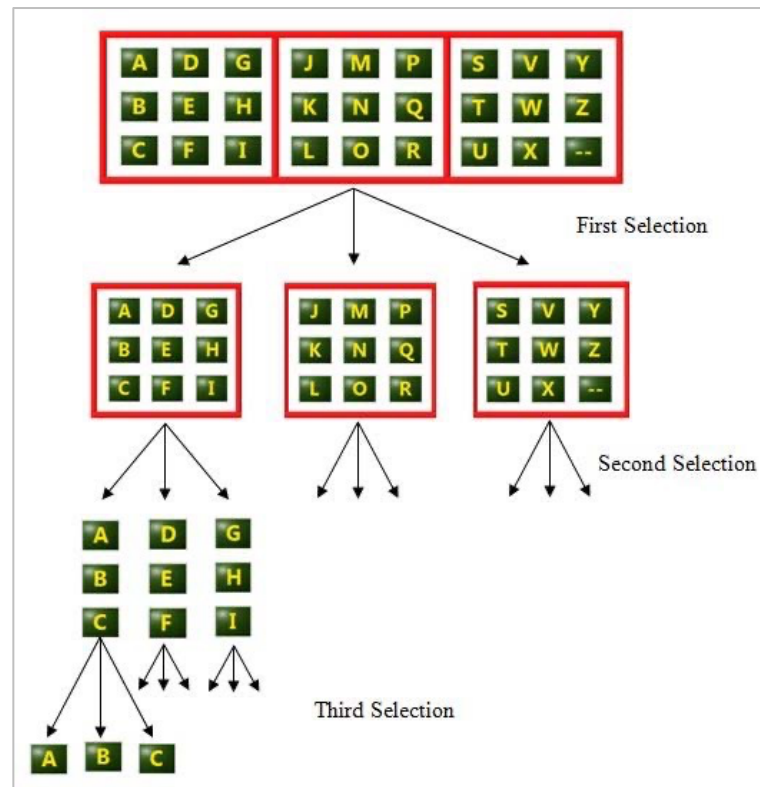


Figure 2.10: Alphabet selection scheme in Virtual Keyboard [5]

2.4.7 Real-Time Control of a Video Game Using Eye Movements and Two Temporal EEG Sensors

EEG-controlled gaming applications range widely from strictly medical to completely nonmedical applications. Along with serving entertainment purposes, games can be a strong motivation for practice. Thereby it can help to achieve better control with the rehabilitation system. This study proposed a novel approach of detecting six distinguished classes of eye movements (blink, centre, left, right, up and down) using wavelets [60]. This system requires only two sensors placed in the temporal lobe (behind the ear) to acquire brain signal data. They applied their algorithm in a real-time 2D game with two types of eye movement (left and right) and idle state detection. 5 subjects participated in this experiment for 20 minutes each without any training session or calibration phase. The gaming control flowchart along with the game graphical user interface has been illustrated in Figure 2.11.

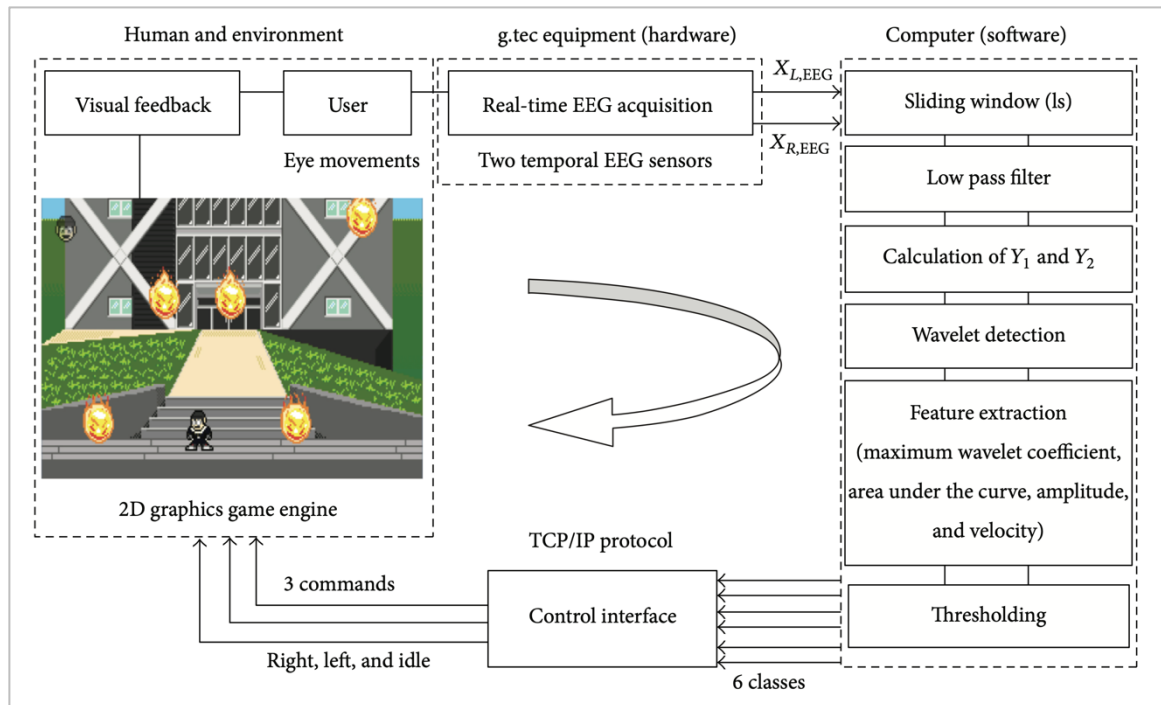


Figure 2.11: The control flowchart of a real-time eye (moving eyes left and right) controlled game [60]

2.4.8 Applying Brain-Computer Interface Technology for Evaluation of User Experience in Playing Games

Several studies have been conducted either on emotion detection or gamification. However, this is the first of its kind where the UX of a game has been evaluated using directly brain signal data rather than taking a survey or interview. This study has explored and evaluated the user experience of playing the game from EEG data [12]. A total of 20 participants played the “DX-Ball” game and the raw EEG data was collected from those participants while they were playing the game. Then these brain signals were evaluated offline to analyse emotions and moods. Total six emotions have been evaluated in this system which is labelled as Stressed, Relaxed, Reluctant, Anxious, Focused and Lack of Attention. The proposed system has been depicted in Figure 2.12.

The emotion evaluation has been done using two frequency bands (alpha and beta). Each band has been subdivided again into low, optimal and high. As human emotion does not change very frequently, this study has considered 5 seconds window EEG data to evaluate emotions. The proposed emotion detection method has been illustrated in Figure 2.13.

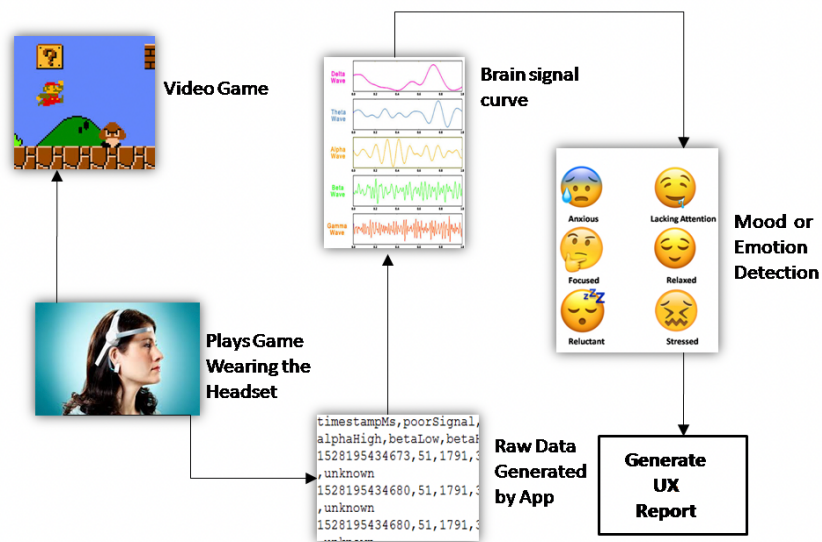


Figure 2.12: The control flowchart of user experience evaluation of a BCI system [12]

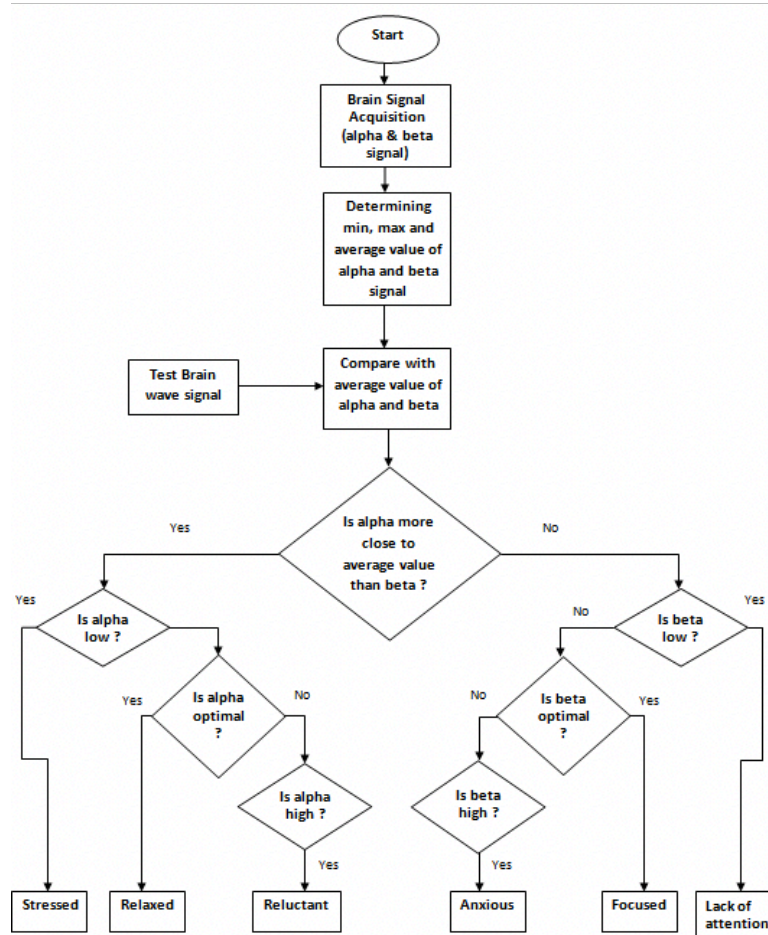


Figure 2.13: The emotion detection flow diagram [12]

2.5 Comparative Analysis

In the previous Literature Review section, literature has been discussed avoiding all the technical details. Whereas, this section discusses the comparative analysis of existing systems in terms of device used to record the signal, electrode position, signal processing and algorithms applied. The overview of the report has been pointed out in Table 2.

Table 2: Comparative Analysis of Existing Systems

Properties	Device	Electrodes	Signal Processing	Algorithm	Accuracy	Real-time System	Game/GUI	GUI Simplicity	Control Signal	Participants	User Feedback
Literature											
BLINK: A Fully Automated Unsupervised Algorithm for Eye-Blink Detection in EEG Signals	OpenBCI, Muse	Fp1	Lowpass filter	BLINK	98.96, 99.2	Yes	No	N/A	N/A	20	No
The influence of graphical elements on user's attention and control on a neurofeedback-based game	Neurosky Mindwave	Fp1	N/A	eSense	N/A	Real-time, Offline	Tug-of-War	No	Attention	7 M, 1 F	Yes
The Mind Garden: A Brain-Computer Interface Game	Neurosky Mindset	Fp1	N/A	Neurosky	N/A	Online	The Mind Garden	Yes	Attention, Meditation	N/A	No
Design of an Online EEG based Neurofeedback Game for Enhancing Attention and Memory	Emotiv Epoc	AF3, F7, F3, P7, O1, O2, P8, F4, F8, AF4	50Hz Notch, 0.2-45Hz Bandpass	SampEn	N/A	Online	Proposed	Yes	Attention	5	No

Properties	Literature									
	Device	Electrodes	Signal Processing	Algorithm	Accuracy	Real-time System	Game/GUI	GUI Simplicity	Control Signal	Participants
FOCUS: Enhancing Children's Engagement in Reading by Using Contextual BCI Training Sessions	Emotiv Epoc	O1, O2	N/A	$\frac{\beta}{\alpha + \theta}$	N/A	Realtime	No	N/A	Engagement	10 M, 14 F
Virtual Keyboard BCI using Eye blinks in EEG	Biopac MP36	Fp1, F3	0.5-35 Hz Bandpass, 66.5Hz Cut-off	Kurtosis	N/A	Yes	GUI	Yes	Eye Blink (Single, Double, Tripple)	N/A
Real-Time Control of a Video Game Using Eye Movements and Two Temporal EEG Sensors	g.USBamp	2 upper area behind left and right ears	0.5-100 Hz Bandpass, 48-52 Hz Notch	Proposed	77.3	Real-time, Online, Offline	Yes	Yes	Blink, Eye Movement (Center, Left, Right, Up, Down)	4 M, 1F
Applying Brain-Computer Interface Technology for Evaluation of User Experience in Playing Games	Neurosky Mindwave	FP1	N/A	Low, high and optimum value of Alpha-Beta	N/A	Offline	DX-Ball	Yes	Emotion	20
										No

Most of the systems reviewed here have used the consumer-grade device NeuroSky [42], Muse [32], Emotiv [61] or OpenBCI [62] as the brain signal recording device. These devices have been popular in the area of neuroscience and BCI research for their cheap cost and they are easy to use. Additionally, they are also capable of providing standard quality

data. However, two studies have used devices with an amplifier to record high dimensional and better quality data [5], [60].

The electrode placement was set based on the requirement of the study. Those who have studied attention, focus and concentration, they placed electrodes in the pre-frontal and frontal lobe (Fp1, Fp2, F3, F4, F7, F8 using the international 10-20 system [63]). On the other hand, blink artefacts impact the pre-frontal lobe (Fp1, Fp2) the most as its nearest to the eyes. So these electrodes used in eye blink related studies [5], [38], [60].

All of the studies had to apply a 50 Hz or 60 Hz notch filter to remove power line noise. An additional bandpass filter was applied based on their required signal area. However, these filtering techniques are so common and obvious in EEG signal processing that some studies have not even bothered to mention them [8], [12], [31], [59]. Altogether, signal processing includes some range of bandpass filtering or converting the signal from the time domain to the frequency domain.

The algorithms used in these studies to detect control signal was mostly system-specific and previously established. Most of the system tried to validate the system or explore knowledge about how users are reacting to the GUI or BCI system [12], [58] or what are their feedbacks [8]. So other games like Tug of War and DX-Ball have been integrated with the BCI control signal. All of those studies had GUI except one which continued without any game or GUI [38].

The number of participants in all studies found low. That's because acquiring EEG signal is time-consuming, needs expertise and difficult to collect. Apart from these, it requires a silent, noise-free and controlled lab environment. As consequences of all these challenges, collecting brain signal from numerous numbers of people mostly becomes impossible. Collecting brain signal from 10-20 participants considered as the minimum during an experiment [64].

BCI system is challenging to run in real-time as the accuracy can't be obtained enough in the natural environment due to signal to noise ratio (SNR). Nonetheless, some researchers and developers are trying to design real-time systems with pretty good performance [8], [59], [60].

2.6 Conclusion

In this section, the background of this study, different types of brain signals, these brain signal recording devices and the state of the art have been discussed. Following these discussions from chapter 2.2, it is obvious that EEG is the most suitable brain signal recording method for this type of experiment. Devices used for recording brain signals in the EEG method are available at low cost and can be maintained easily. In chapter 2.3 we have discussed several EEG signal recording devices that are compatible to be used in this experiment. However, in this experiment, we have decided to use the OpenBCI device for recording brain signals with this in mind that, OpenBCI provides good quality raw data and these data are open sources to use. In chapter 2.4 we have discussed some literature review and the state of the art which are similar to our study. However, chapter 2.4 avoids the technical details like signal processing methods, devices used and algorithms applied. These comparative analyses have been discussed in chapter 2.5. The literature and state of the art have been selected based on users BCI experience evaluation, BCI system GUI evaluation and eye blink related systems. Studying this literature and systems it is clear that designing and evaluating a simple BCI enabled system and evaluating its user experience has not been undertaken yet. Hence, proposing this type of system and evaluating user experience would be a good contribution to the neuroscience community.

Chapter 3

Methodology

The proposed BCI system is composed of four modules. The schematic of the system is shown in Figure 3.1. These modules are named as (i) EEG signal acquisition module, (ii) Signal processing module, (iii) Activity detection module, and (iv) Application module. These modules are explained below in details.

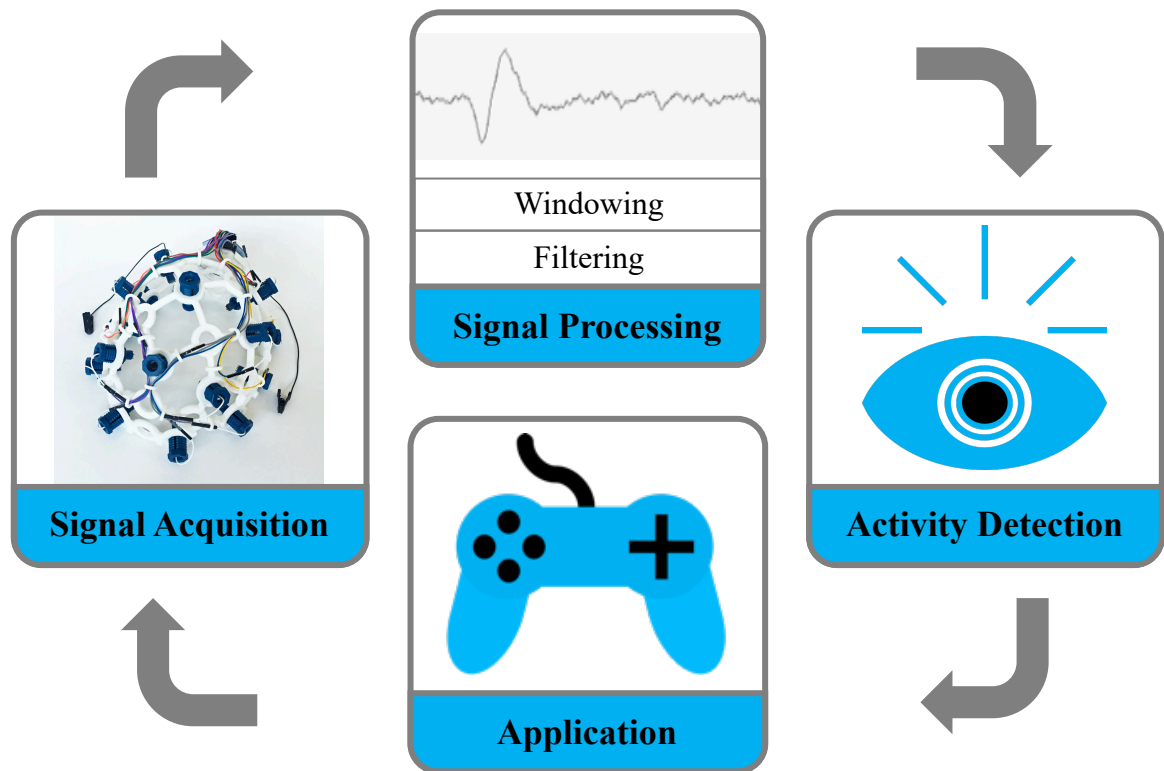


Figure 3.1: Proposed methodology of BlinkFruity

3.1 EEG Signal Acquisition

In this investigation, EEG data was measured with OpenBCI Cyton Biosensing Board (8-channels) [62] and as a brain wear OpenBCI Ultracortex "Mark IV" EEG Headset [65] was used. In this experiment, we have collected, processed and saved raw EEG data directly from our developed application BlinkFruity in real-time. BrainFlow library was used to acquire raw EEG data and to apply filter and pre-processing algorithms [66]. Both OpenBCI hardware and BrainFlow library are open sources and free to use. BrainFlow provides API for multiple programming languages including Java, Python, MATLAB, C#

and C++. BlinkFruity has been developed in the Java programming language. More details about the BlinkFruity application have been explained in Chapter 3.4.

After acquiring raw data at a sampling rate of 256 Hz, they were amplified. The pre-frontal lobe is the nearest to the eyes and gets affected the highest by eye blink artefacts. As the artefact of eye blink can similarly be found in both Fp1 and Fp2 [38], among eight channels, only Fp1 was used from the pre-frontal lobe. The eight electrodes were placed following the international 10-20 systems, two additional ear clips A1 and A2 were connected with two earlobes as ground and reference. Figure 3.2 illustrates the international 10-20 electrode positions [63].

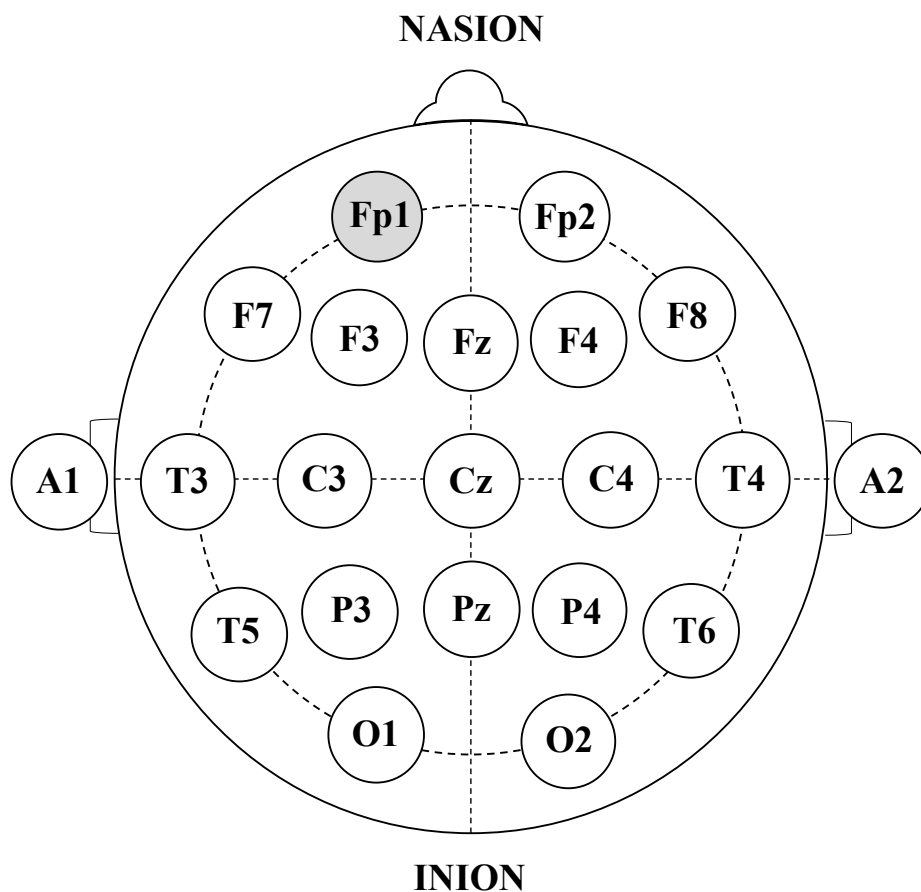


Figure 3.2: The international 10-20 system for electrode placement in the context of EEG

As EEG data are weak and contains lots of artefacts, recording EEG signal requires to take extra precautions. The procedures of recording brain signals from subjects and precautions have been explained in details in Chapter 4.2.

3.2 Signal Processing

After acquiring and recording raw data from participants, some signal processing techniques have been applied. These were required to apply to reduce noises in the EEG signal. EEG signals contain several artefacts which may interfere with extracting information, even information like eye blinks. As this is a real-time system, in this experiment, data were periodically recorded, pre-processed and analysed in 500 milliseconds segmented window. A normal eye blink requires around 200 milliseconds to occur [5]. So, for a safe zone, we have considered a 500 milliseconds window to detect eye blink in this BlinkFruity system. Figure 3.3 shows 10 seconds of raw EEG data containing 9 eye blink artefacts.

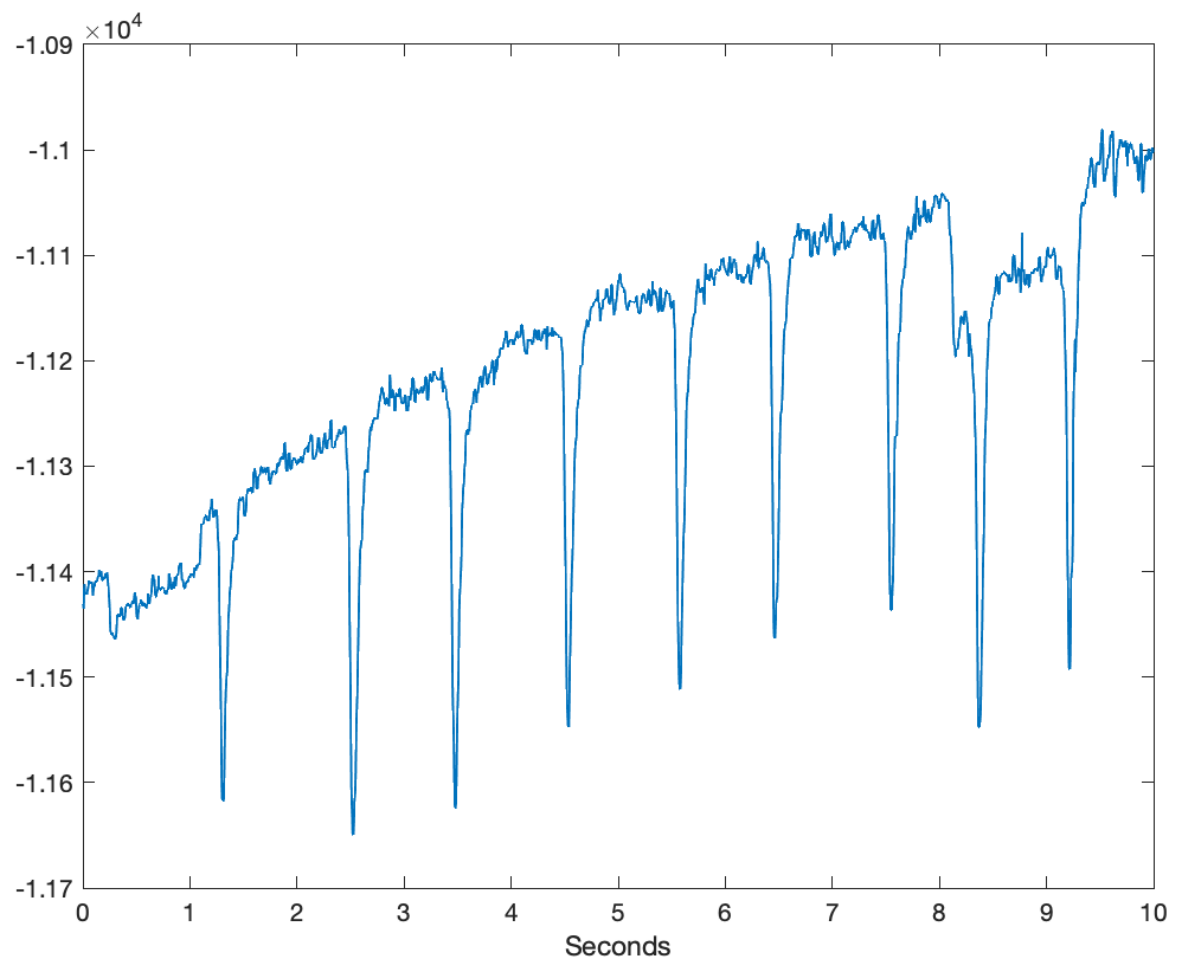


Figure 3.3: 10 seconds of raw EEG data with noise

In the USA and Asia Pacific region, electrical power line and devices generate a 50 Hz noise which can be seen in the Fast Fourier Transform (FFT) plot. While we were observing

our data, we found that our data contains a strong power line noise which is not always exactly at 50 Hz. Figure 3.4 depicts that the peak of the noise can be found around at 52 Hz. Because of this, after recording and amplifying raw EEG data a 48-52 Hz 4th-order Butterworth notch filter was used to remove power line noise. Then a 0.5-45 Hz 3rd-order Butterworth bandpass filter was performed. Figure 3.5 shows plotted EEG data after applying a notch and bandpass filter.

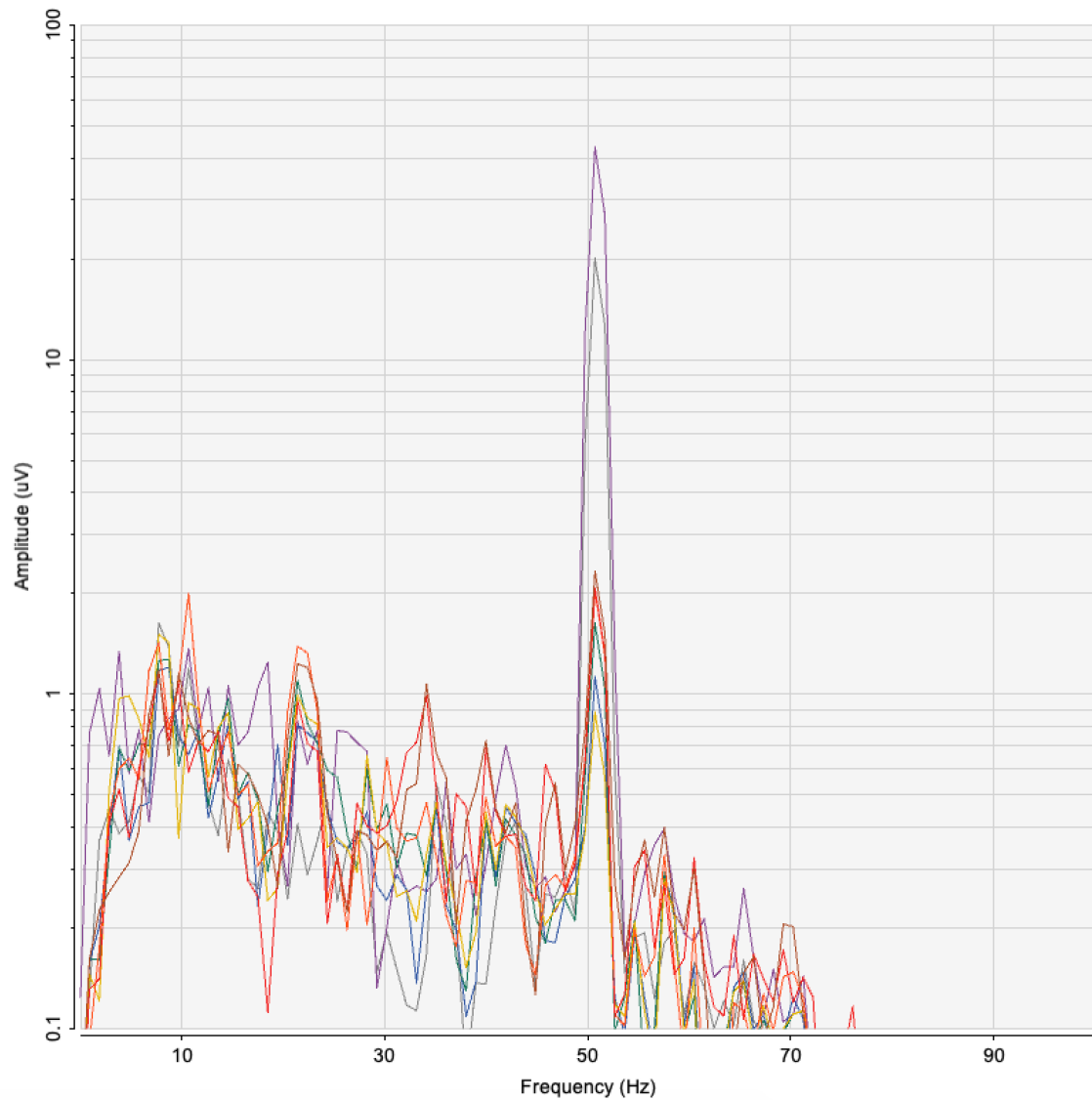


Figure 3.4: 50 Hz power line noise in the Fast Fourier Transform (FFT) plot

Finally, with the median operation, a sixth-period rolling filter was performed. Since blink is using as a control signal, no other filter or signal processing technique had been used which can interfere with detecting blink artefacts. Figure 3.6 illustrates a blink that took 250 milliseconds.

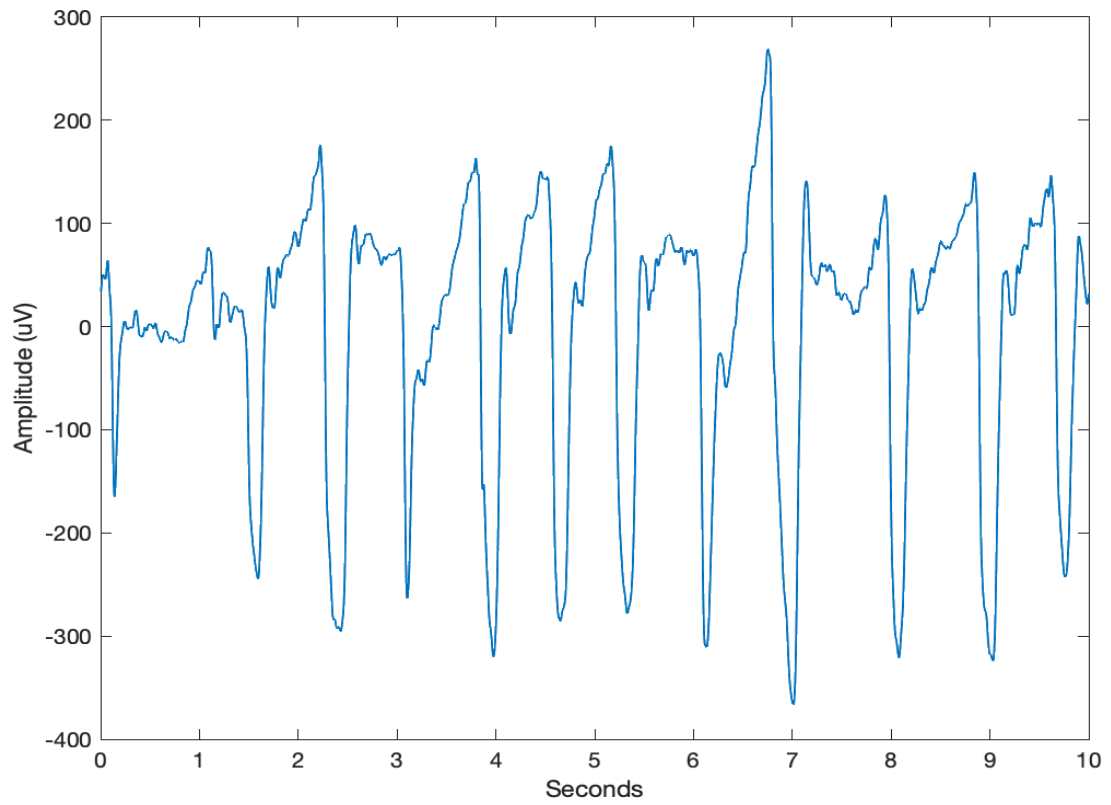


Figure 3.5: Brain signal after applying notch filter and bandpass filter

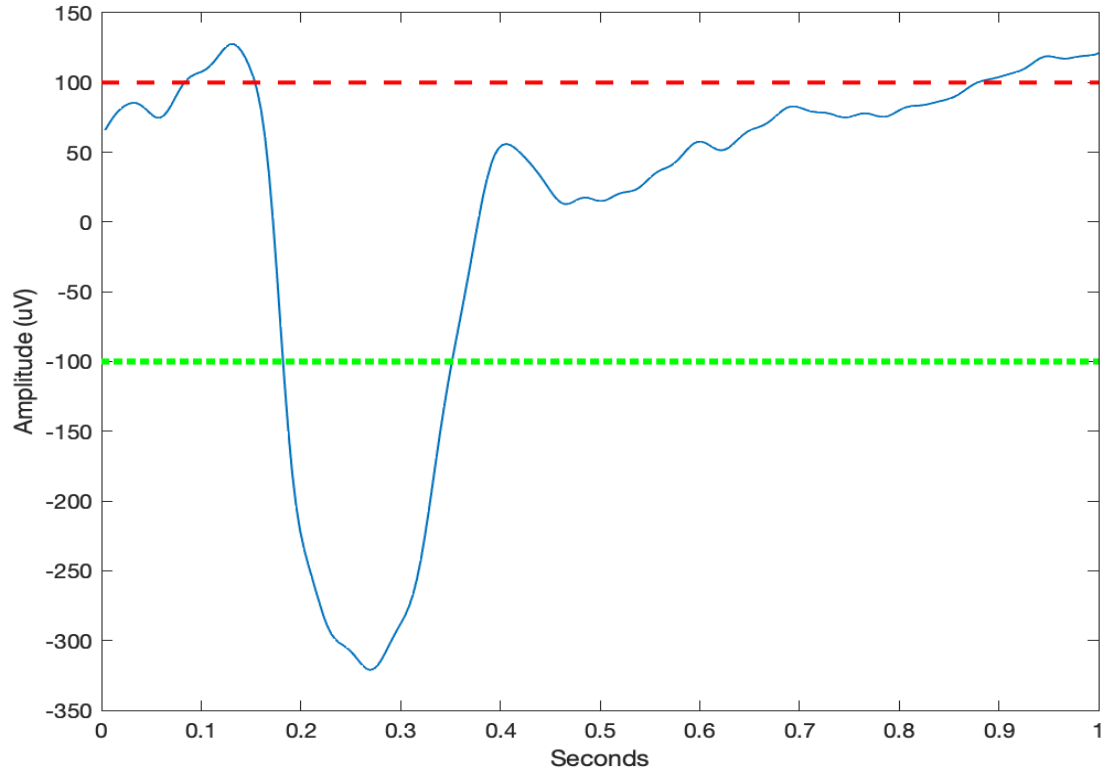


Figure 3.6: A 250ms duration blink recorded in the EEG signal (150ms – 400ms). Red dashed line and green dotted line indicate the threshold of detecting eye blink

3.3 Activity Detection

In this system, eye blink is the control signal. There are abundant methods available to detect eye blink from EEG data ranging from simple threshold to complex pattern recognition and machine learning approaches [38]. As detecting eye blink with a higher level of accuracy is not the primary focus here, so in this system, eye blink has been detected using a simple thresholding method. Another reason for avoiding a complex machine learning approach is the time complexity cost of the machine learning algorithm. As this is a real-time system, activity should be detected within a minimum amount of time even in a low configuration device.

Eye blink has been identified from the idea that an eye blink generates a strong electrical impulse. When an eye blink happens, the difference between the absolute value of the newest EEG data in general and the mean EEG data from the channel that we are interested in is bigger than 100 uV [67]. An eye blink has been illustrated in Figure 3.6. The red dashed line and the green dotted line indicating the threshold of detecting eye blink. For simplicity, only one channel (Fp1) was used for the calculation of detecting eye blink. The equation to detect eye blink has been provided in equation (1).

$$\mathbf{BLINK} = abs(fp1_{data\ newest\ uV}) - fp1_{mean} > 100 \ \& \ abs(fp1_{data\ newest\ uV}) > 100$$

..... (1)

In the real-time system, by following equation (1), it was found that on each 500ms window there was more than one peak point which was greater than 100uV. For an instance, in the context of Figure 3.6, the equation (1) would find 4 blinks from the first 500ms window. On the contrary, the second 500ms window contains one blink according to our blink detection algorithm.

$$\begin{aligned} & \text{for (all samples in 500ms window data)} \\ & \quad \text{if (BLINK)} \\ & \quad \quad BlinkCount = BlinkCount + 1 \\ & \quad \text{if } BlinkCount > 3 \\ & \quad \quad BlinkDetected \end{aligned}$$

..... (2)

So, in this algorithm, we had to count the number of blinks to deal with this situation and check another condition. Equation (2) shows the modified version of equation (1). If the number of blinks is higher than 3, then we considered it as a proper blink. This ensured that the normal EEG data which does not contain eye blink (can be seen at around 875ms of Figure 3.6) does not count as an eye blink. However, even though applying this condition increases the accuracy of detecting a proper eye blink, nevertheless, there are some situations where the number of blinks does not reach that threshold. In that scenario, blinks do not get detected by the system (false negative). Similarly, sometimes normal EEG data reach the threshold value and the blink count rises and gets detected as a blink (false positive).

3.4 Application

The application has been developed using Java language (version 11). JavaFX desktop application framework [68] and JavaFX game engine FXGL [69] were used to develop the game's Graphical User Interface (GUI). The application manages all four modules sequentially. At the opening of the game GUI, it asks for players information. After providing the subject's information, the application initiates the OpenBCI data acquisition session, apply filters, detect eye blinks. All these procedures have been implemented with the help of the BrainFlow library [66]. Finally, the eye blink has been used as the control signal of the game GUI. Detail's explanation of the gaming protocol has been described in Chapter 4.1.

3.5 Conclusion

The simple proposed system has consisted of four core modules only. Based on the study of chapter 2.2 and chapter 2.3 the OpenBCI device has been selected for EEG signal acquisition. As per the system requirement, only Fp1 channels data has been used. Then in the second module raw EEG data has been processed using Butterworth notch and bandpass filter. Afterwards, the third module explains the activity detection process. We have detected blink activity using the thresholding method. Finally, the blink has been used as the control signal of our application. More details about the application have been explained in chapter 4.1.

Chapter 4

Proposed System & Experimental Setup

4.1 Proposed Game

The proposed BlinkFruity game has been kept simple considering few people found the BCI system vague and complex [8]. BlinkFruity can be a good platform for people who do not have prior experience with BCI and wants to learn or enhance skills to use BCI implemented systems. This can be helpful for both practising and having fun with this new area. Since this is a brain actuated system, blink is being used as the only control signal detected from EEG data. The game procedure is described in steps 4.1.1 to 4.1.4 as follows:

4.1.1 Initial Screen

The subject is shown a random fruit and a basket on the opening screen. A red text will appear titled “Click here to set subject details and start the game”. Figure 4.1 shows the initial game screen of this proposed game GUI.

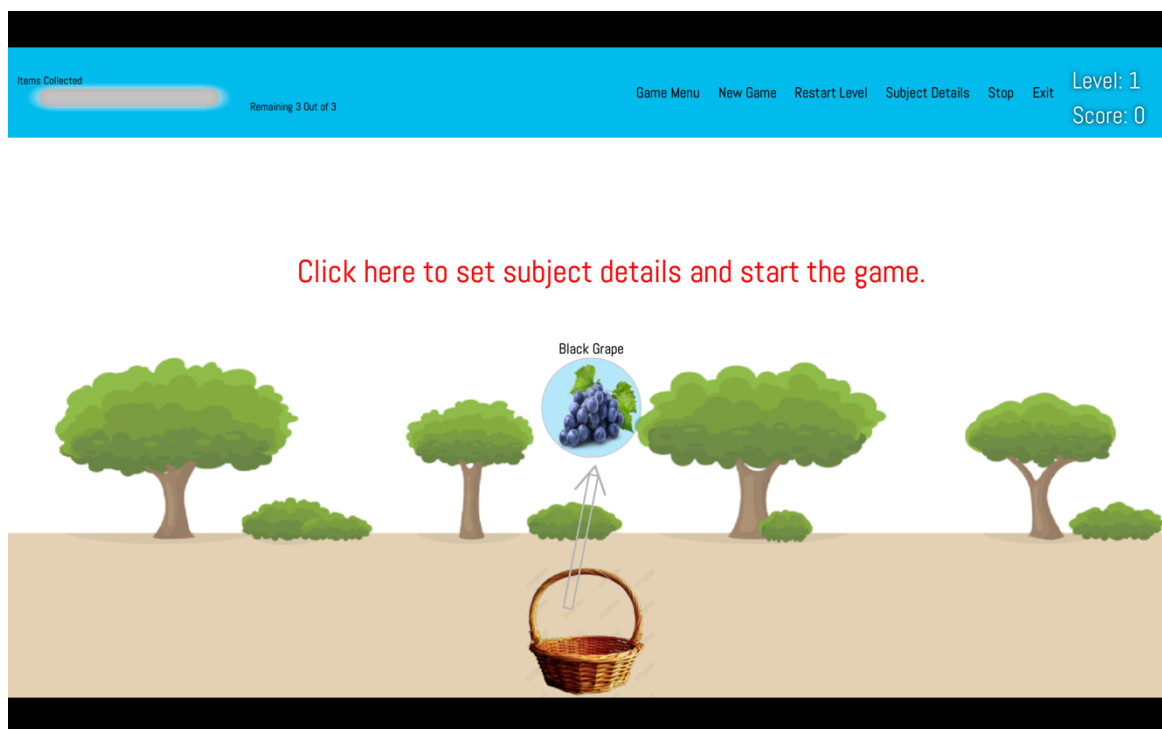


Figure 4.1: The initial Graphical User Interface (GUI) screen of the proposed BlinkFruity

4.1.2 Subject Details

To collect the subject's or player's information, a small window will pop up either by clicking on the red text or by clicking the 'Subject Details' button from the menu bar. Figure 4.2 shows the window. The purpose of collecting this information is only to identify each subject data for post-processing and analysing. Although the raw EEG data has been published to the scientific community for further study, none of the participant's identity has been published.

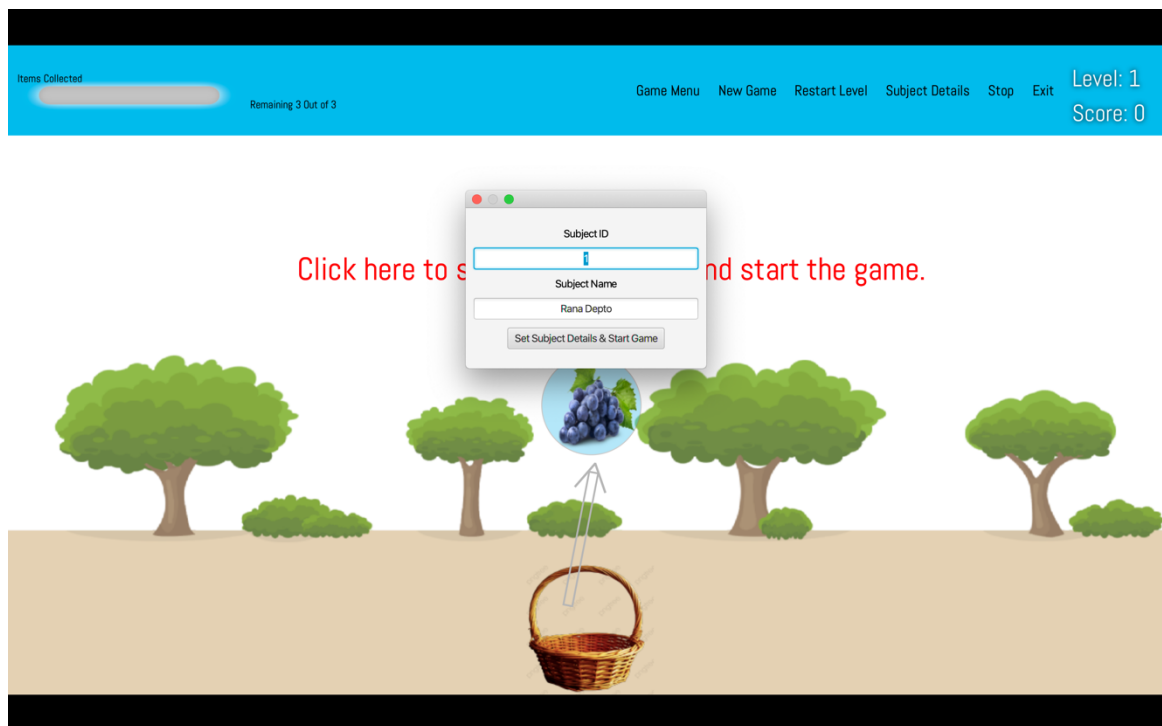


Figure 4.2: Proposed BlinkFruity GUI with a popup window to collect subject information (name and id) to identify subject data

4.1.3 Data Acquisition and Signal Processing

When the subject's information would be provided, then the "Set Subject Details & Start Game" button would be needed to be clicked. Afterwards, the application will initiate a countdown from three to one to let the player be prepared for the session and exclude the first 3 seconds of data. It's been observed that the first 3 seconds of data contains some spikes which are not blink, but since they are higher than 100uV, thus the system identifies them as blink. After the countdown finishes, the OpenBCI data recording session and the game get started. When OpenBCI will start the session, it will initiate providing the raw

data and the application will keep reading, filtering, processing and analysing the data to control the game by detecting eye blink.

4.1.4 Gameplay

Eye blinks can be classified into three types. These are voluntary, reflexive and spontaneous [5]. Apart from that, based on duration eye blinks can be divided into two types. Slow eye blinks and fast eye blinks. Those blinks which take less than 200ms are considered slow blinks. On the contrary, if a blink duration is higher than 200ms is considered as a fast blink. To play the game, the subject will only have to blink his/her eyes. Blink can be intentional or unintentional, steady or continuous. This BlinkFruity system can detect all these kind of blinks with precise accuracy. When the BlinkFruity system will detect a blink, the basket will automatically start moving towards the fruit each step for each blink. The fruit would be collected as soon as the basket would reach near to the fruit. Figure 4.3 shows the game GUI after collecting two fruit items.

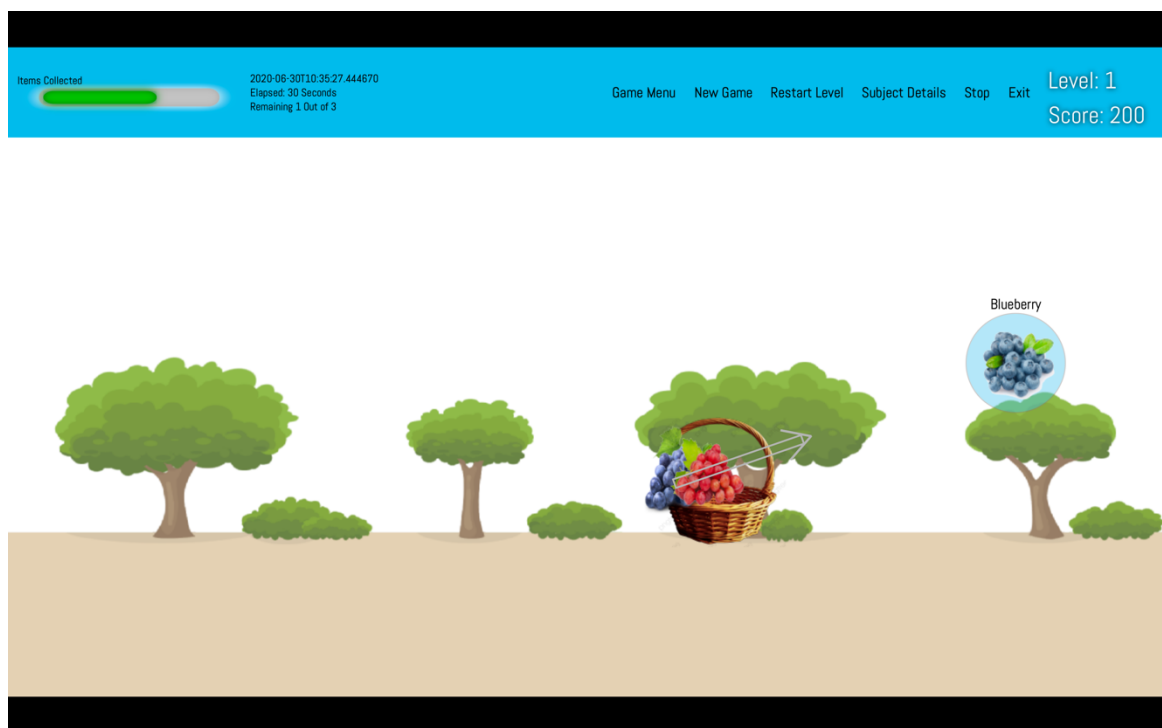


Figure 4.3: Proposed BlinkFruity GUI after collecting two fruit items

Studies show that users engage more and the feeling of boredom reduces if the game has multiple levels and the level of difficulty increases [12]. Thereat, a total of 3 levels have been induced in this game. In level 1, level 2 and level 3, the subject will need to collect 3,

5 and 7 fruit items respectively. Even though a random fruit item is being shown each time, but the position of the fruit is fixed for each level regardless of the subject. This ensures that every subject's game completion time is evaluated based on the same required steps to collect all fruit items. Figure 4.4 shows the screen at the end of level 1.

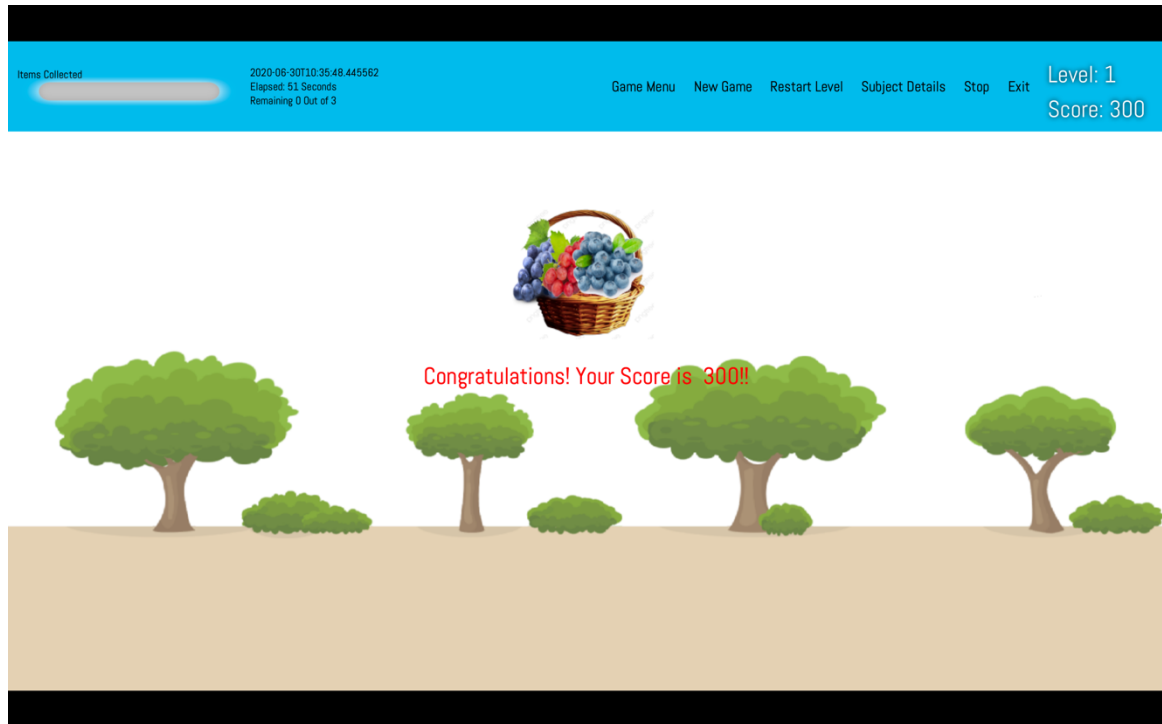


Figure 4.4: Proposed BlinkFruity GUI showing score after finishing level 1

However, this game has a bug that was not identified until the experiment process had been started. As the experiment process already started and every participant should face a similar experience, thus the bug was not fixed for this study. The bug was that sometimes the basket does not move with the eye blink when it reaches very near to a fruit item. The user faces this bug once in level 2 and twice in level 3. At that moment, the basket needs to move manually with the keyboard. However, this bug explored new findings of the use of BCI enabled application. These findings have been discussed in Chapter 5.2.

4.2 Experimental Setup

The experiment has been designed and conducted following a controlled experiment methodology [70]. The experiment was designed in such a way that subjects can participate in the experiment uninfluentially. The possible number of factors that could distract, interrupt or annoy subjects were evaluated, especially the game GUI. Studies show that

unnecessary animations and graphical elements can severely distract participants [8], [12]. The secondary factor that could be distracting for a participant is a noisy and uncontrolled environment. To resolve this issue, the experiment was conducted in a lab environment (closed and silent room) so that the noises can be reduced to as low as possible. Another distracting factor in the BCI experiment is wearing the brain signal recording device for a long time. Especially high-density EEG (HD-EEG) devices and gel applied EEG signal recording devices make participants uncomfortable on focusing the experiment [71]. In this experiment, a dry electrode device has been used. Additionally, the experiment has been conducted with the proposed game where the graphics are also attractive so that the participant can enjoy and does not feel boredom. Moreover, the experiment was taken in three levels. After completing each level, they were asked to take a break for making the participation spontaneous. Participant's ease and comfort were also paid heed to. However, since this experiment uses only eye blink which does not require cognitive skills, thus possible distractions raised from cognitive skill interruptions were not considered [72]. This chapter describes the method employed to perform the experiment.

4.2.1 Ambient and Materials

The experiments were done in a lab environment (closed and silent room) so that the noises can be reduced to as low as possible. During the experiment, only the subject and one researcher were present in the room. The same EEG recording device and computer were used for all the participants. Water bottle and tissue box were available near their hand considering that they might need them. An adjustable-height arm-rest chair was provided for the participants. Before starting the session, they were asked if they are feeling comfortable with the setup.

EEG data was measured with OpenBCI Cyton Biosensing Board (8-channels) [62] and as a brain wear OpenBCI Ultracortex "Mark IV" EEG Headset [65] was used. OpenBCI is a low-cost research-grade bio-signal recording device. This device used here can be used in recording EEG (brain signal), EMG (scalp muscle movement) and EOG (eye blink/eye movement) signal. The devices are customizable as per research and development purposes and they provide raw data. Both the device and raw data are open sources. The electrode was positioned in Fp1, Fp2, C3, C4, P7, P8, O1 and O2 positions following the international

10-20 electrode placement system (showed in Figure 3.2). In this experiment, only Fp1 channel data has been used.

The computer used in this experiment is MacBook Pro (15-inch, 2017) with a 2.9 GHz Quad-Core Intel Core i7 processor and 16 GB 2133 MHz LPDDR3 RAM. macOS Catalina 10.15.4 (19E287) was installed as an operating system.

4.2.2 Participants

In this experiment total, ten healthy subjects (S1-S10) volunteered to run the experiment and record their brainwave. All of them were 25 to 52 years old (Mean, $\mu = 32.2$; SD, $\sigma = 6.98$), being four males and six females. While selecting experiment participants, we tried to bring a diverse group of people like Age, Eye Problem, BCI Experience, Practice Meditation and Education. Table 3 briefly contains information about all participants. Nevertheless, this experiment participants do not have enough difference concerning age and education, although they have diversities in other areas. As a continuous process of an extended experiment, in these study only healthy, young and higher educated participants have been considered.

Table 3: Information about Experiment Participants

Subject	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
Group										
Gender	M	M	F	F	M	M	F	F	F	F
Age Group	25 - 29	30 - 34	30 - 34	25 - 29	30 - 34	20 - 24	30 - 34	25 - 29	50 - 54	30 - 34
Eye Problem	Dry, Glass	No	No	Glass	No	No	Dry, Glass	Glass	Glass	Glass
BCI Experience	Yes	No	No	No	No	No	No	No	No	Yes
Practise Meditation	Yes	No	No	No	No	Yes	Yes	Yes	No	No
Education	BSc	MA	MA	MA	BBA	BSc	MSc	MBA	Illiterate	PhD Scholar

There were different group of people who participated in this experiment. Two of them had previous experience with BCI. But the rest of the participants did not have any prior experience with BCI implemented system. A total of six participants were diagnosed with eye problems and used power glasses. Among these participants, two participants had dry eyes problem. The other four participants ensured that they do not have any difficulties with their eyes. Moreover, four of the participants practised meditation. The minimum educational status of 9 participants out of 10 is graduate. Five of them either have completed their post-graduation or pursuing the degree. One of them (P10) is a PhD scholar. However, there was a participant (S9) who is not only ever has experienced computer, but also does not have literacy. Table 3 briefly contains information about all participants. The only adopted selection criteria were that the participant had no metal plate implant in their scalp area. It's because, metal can create noise, interfere or even can completely block the signal acquisition as brain waves are weak electrical signal [8].

4.2.3 Procedure

At the beginning of the experiment session, the user was asked to take the seat in the data collection room of the lab. They spend some time having some casual conversation to get adjusted to the experimental environment. After a while when they felt comfortable, they were provided with a brief explanation about the brain signal recording device, how this device works, how is the game and how is the experiment going to be conducted. While explaining the working procedure of the device, technical terms were avoided. Additionally, they were ensured that wearing the device does not have any negative impact on their brain or health. It only records brain activity that is already generating. It works just like a thermometer which measures our body temperature.

Each participant had to participate in one individual session and play three levels of the game. With the participant consent, every session was recorded with a digital camera (using the zoom app) to identify and verify blinks. The interview session was recorded as well. They were ensured that the recording would not be published. The subjects were free to ask any question at any time and leave the experiment at any moment without explanation.

Some safety precautions were taken to reduce the EEG signal noise (generated from the device or subject's body) to as low as possible. In the experiment room, there were no laptop charger or any other chargers were connected to the power line. Subjects were asked

to refrain from any kind of movement as much as possible. They were also asked to remain silent. Additionally, they were requested to keep their phone switched off so that they do not get distracted in the middle of the experiment.



Figure 4.5: The experimental scene with a subject (sitting on the right side in this photograph) during an empirical session

During the experiments, the subject was sitting in a height-adjustable arm-rest chair, keeping in an upright position, facing the computer monitor 60 cm apart and wearing the brain signal recording device. An experimental and data collection scene has been shown in Figure 4.5. In this figure, a female participant (sitting on the right side in this photograph) was playing the BlinkFruity game in the experimental session. One of the researchers was present (sitting on the left in this photograph) to observe the experiment and help the participant. Figure 4.6 presents the illiterate participant playing the BlinkFruity game. She participated in the experiment in the home environment during the COVID-19 pandemic situation. At the end of each level, participants were asked if they want to take any break or put down the brain signal recording headset. But all the participants completed the session without taking any break.

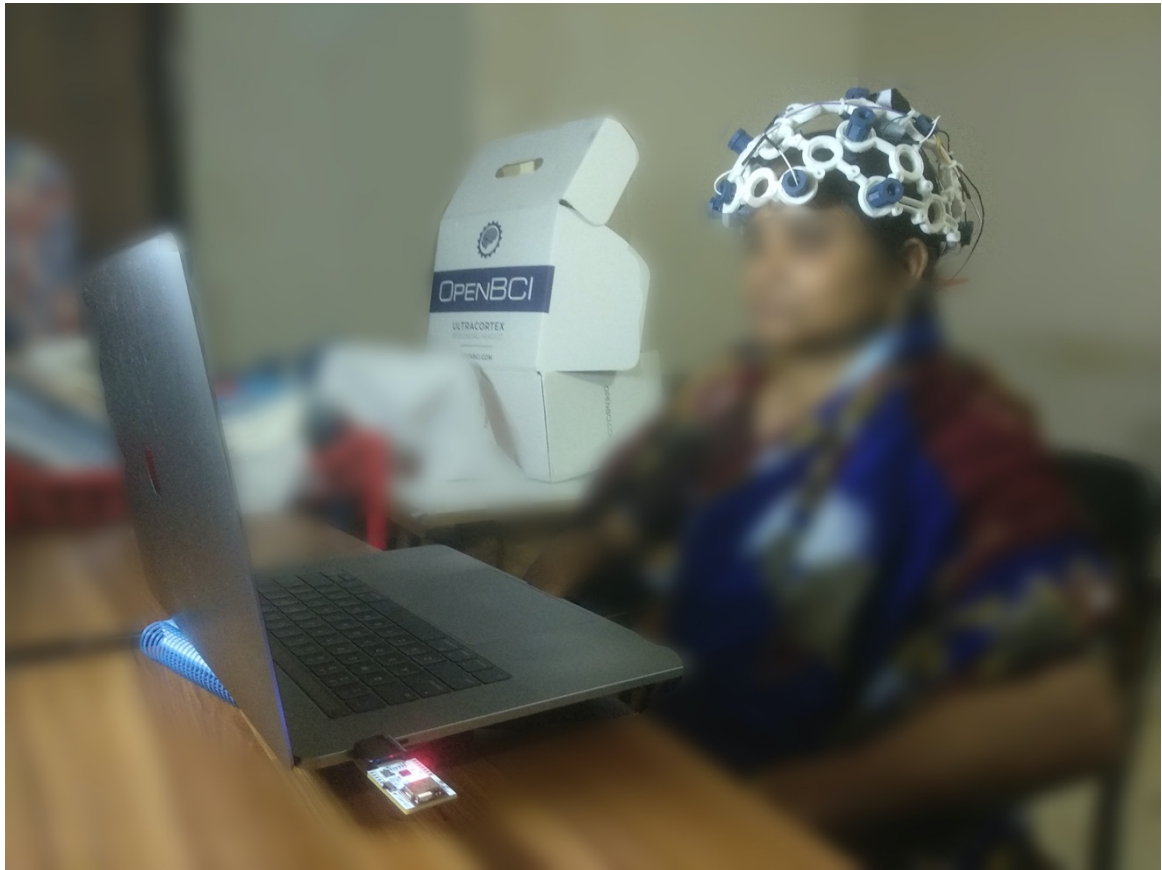


Figure 4.6: The experimental scene with the illiterate participant in the home environment during the COVID-19 pandemic situation

Before joining the session, along with verbally explaining the game, experiment and the device, they were shown a demo video explaining the game and how to play, so that every subject receives the same explanation about the game in details. All of their questions about the experiment were answered. When they were ready, they were provided with the consent form to read and sign. Before running the experiment, every subject played the first level of the game to understand the gaming environment. Then subject started to play the game for three matches in three levels (Level 1 – 3; easy, medium and hard). The interview questions were not provided beforehand so that they do not get time to prepare an answer. This made sure that they can provide instant and spontaneous feedback.

4.3 Conclusion

Chapter 4 is divided into two parts. Firstly, chapter 4.1 has presented the proposed application with more details. It has depicted the game graphical user interface, which is the user end application. Secondly, the experimental protocol has been narrated in chapter

4.2. It includes the ambient and materials used for the experiment, details about the participants without revealing their identity and the procedure that involves the experiment. Two experimental scenes with participants have also been illustrated for a better understanding.

Chapter 5

Results & Discussion

The whole BCI system has been evaluated in two steps. Firstly, the game GUI and the proposed BCI system has been evaluated by measuring game accuracy and level completion time. As this evaluation requires a manual process, thus only the first five subject's data were considered here. After considering the validation of this game, the user experiences with this BCI system have been assessed and discussed by a subjective measure. Since this proposed game is for the people who find the BCI system vague and complex, evaluating user experience is much more important for playing games using EEG in the BCI system.

5.1 Game Evaluation

The first step to evaluate user experience and feedback, it was also necessary to evaluate the performance of the game accuracy. According to an offline analysis of a BCI study, it was found that higher BCI classification accuracy could impact user experience along with their performance [73]. They compared two Steady-State Visual Evoked Potentials (SSVEPs) based study on 13 participants. Since this BlinkFruity study is focusing on evaluating user's simplicity and comfort, the accuracy needs to evaluate first to clarify lower accuracy is not affecting user experience. The accuracy of playing the game using eye and the impact of playing the game has been evaluated considering:

- a) Percentage accuracy of blink detection by the BlinkFruity.
- b) Time taken to complete each level.

The accuracy was calculated using equation (3) given below.

$$Accuracy = \frac{tp + tn}{tp + tn + fp + fn} \dots\dots\dots (3)$$

In this equation, tp stands for True Positive, tn stands for True Negative, fp stands for False Positive and fn stands for False Negative.

Since the primary goal of this proposed BlinkFruity system is to evaluate user experience and help users to experience BCI for the first time, so establishing a sophisticated system had not get the primary attention here. As well as that, each subject needed around 12 to 25 minutes duration to play 3 levels of the game. Each session contains on average 892 blinks which were detected by the system. There are more blinks found in the video recording which was not detected by our system. On the whole, there are lots of blinks to identify and validate which involves a manual process. All these blinks need cross-check and verify with the video recording to find the accuracy. Manually cross-checking and verifying these blinks with video and data is extremely time-consuming. Hence, to save time and effort, the accuracy was calculated with the first five participants data.

The whole experiment was video recorded with the Zoom app to detect eye blinks. On the other hand, eye blinks detected by the BlinkFruity were also saved with a timestamp in a CSV file. After finishing the experiment, the accuracy has been calculated by manually cross-checking the blink timestamp and the video. If the eye blink was found in the video at the time recorded in the CSV file, it's a TP. Similarly, FP and FN were calculated.

Figure 5.1 demonstrates the confusion matrix of the first five subjects. Based on the first five subject's data it is noticeable that there is no true negative (TN) value available in any system. The reason behind this is that when a user was not blinking, time-stamp was not being considered by the BlinkFruity system. As a result, these time-stamps were also ignored by the system during cross-checking with video recording. Hence, there was no true negative value.

Figure 5.1 (a) depicts a good accuracy of 91.1%. This is the result of S1 who has experienced BCI user and have got the chance to play and practice this game several times before participating in this experiment. On the other hand, S3 and S4 were blinking slowly and softly. As a consequence of their slow and soft blink, the system missed many blinks and the false positive rate got increased. However, even though during the experiment S2 was not found steady, but during the evaluation, the number of the false positive and false negative of S2 has been found balanced. Similar goes for S5.

After evaluating subject-specific accuracy, the average accuracy has been evaluated which is illustrated in Figure 5.1 (e). Based on this evaluation, BlinkFruity has obtained 84.8% blink detection accuracy.

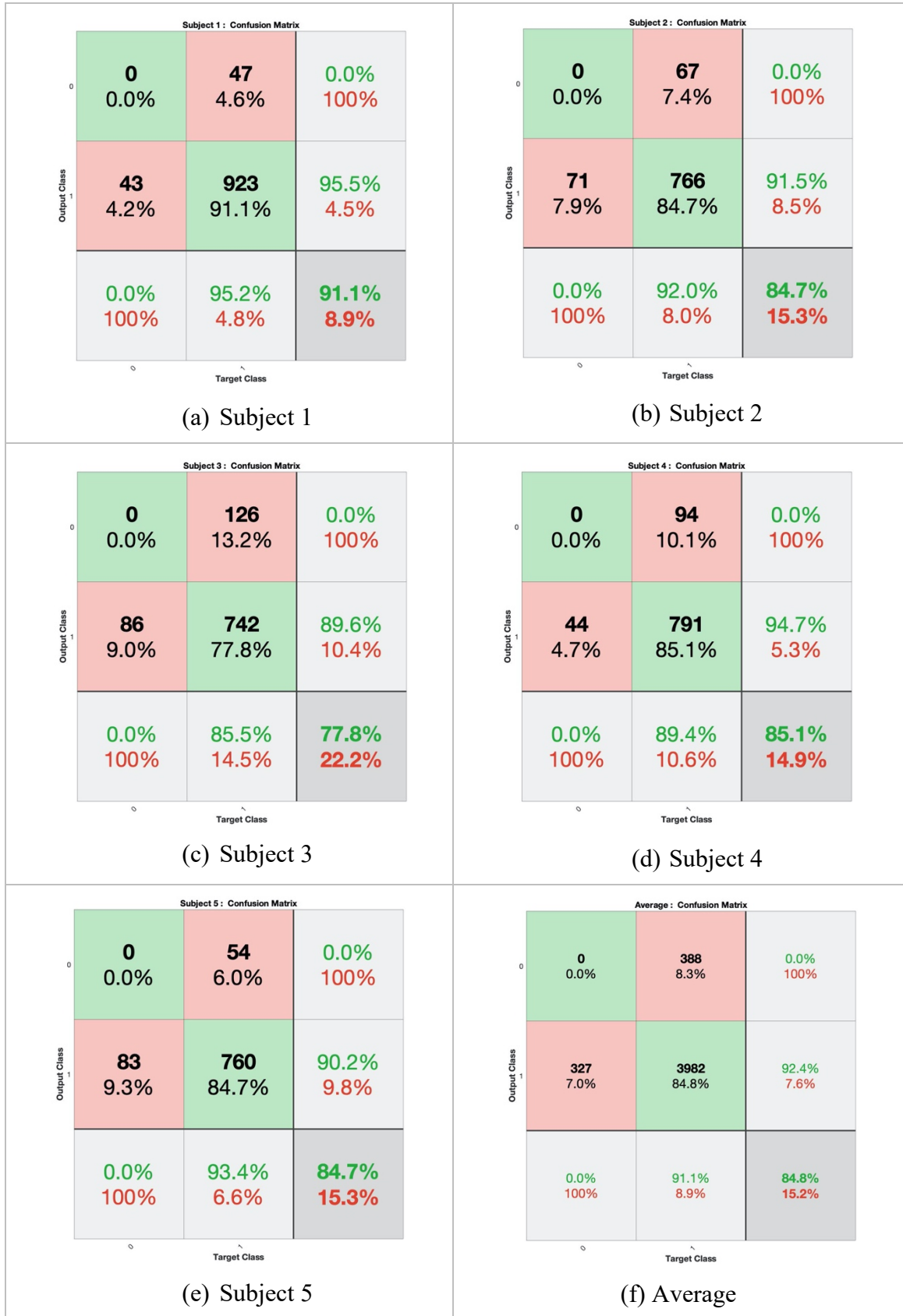


Figure 5.1: Confusion matrix of (a) Subject 1, (b) Subject 2, (c) Subject 3, (d) Subject 4, (e) Subject 5 and (f) Average of all five subjects

Figure 5.2 illustrates the time taken for each subject to complete each level. In this experiment, S6 made good progress and to complete the game he took the lowest time (with Mean=180.67 and SD= 103.26). Moreover, he was able to make a steady advancement, even though he was not an experienced BCI user. On the contrary, S7 needed the highest time (with Mean=464.67 and SD= 307.16). This happened because the system was not being able to detect her blink properly. Moreover, she was blinking softly in slow frequency. More details about challenges with S7 and results on different types of blinks have been discussed in Chapter 5.2.

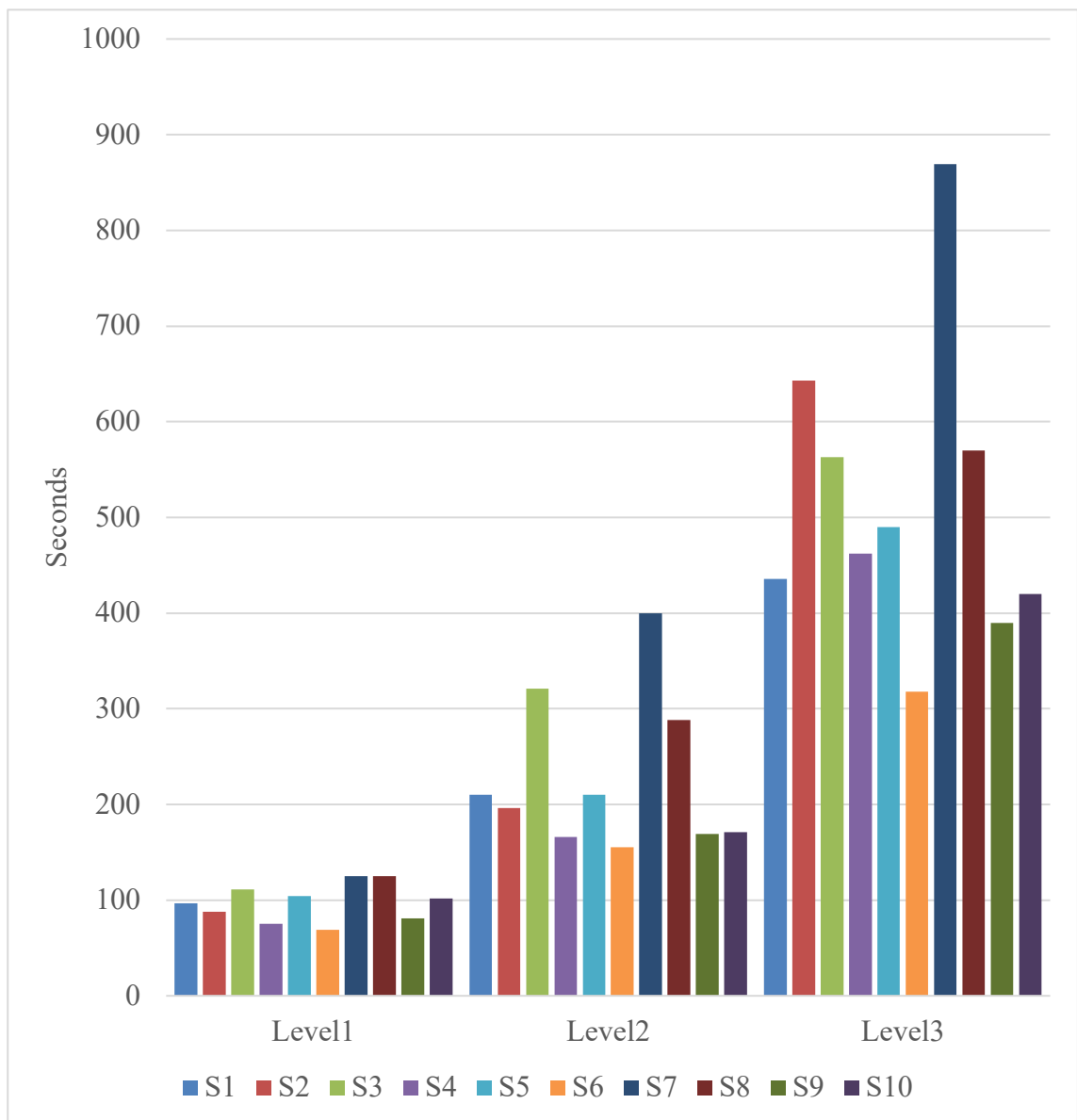


Figure 5.2: Time taken (in seconds) to complete each level for players

5.2 Users Experience with BCI

The second step of evaluating the system was evaluating the feedback of participants. As the system is ultimately developed for the end-users, so their feedback and suggestions could provide good insights about how a BCI system should be designed, what features should they contain, what are the things users find enjoyable and what they find annoying. One of the important results from this study is exploring this information which can be helpful for better understanding the user's requirements for BCI enabled systems.

To obtain this goal, there was a short informal interview session with the participants at the end of the experiment session about their experience with playing this game. All of them were excited as they were experiencing such new BCI technology for the first time. A total of six short questions were asked to the participants to get an overview of the experiments. These short questions and their answers have been presented in Table 4.

Table 4: Experiment Participants Question-Answer and Observations

Subject	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
Question										
Did you feel uncomfortable participating in this experiment?	No	No	No	No	No	No	No	Nervous	No	Yes
How frequently did you blink while playing the game?	Fast	Fast	Mid	Fast	Fast	Fast	Slow	Mid	Mid	Fast
Were you blinking softly, gently or strongly while playing the game?	Strongly	Gently	Gently	Strongly	Gently	Strongly	Softly	Softly	Gently	Strongly
How were you feeling wearing this OpenBCI device?	Awesome	Good	Awesome	Good	Fine	Good	Awesome	Pained	Good	Pained
Was this game or the GUI felt challenging to understand?	No	No	No	No	No	No	No	No	No	No
Rate 1 to 5 about your BCI experience playing this game.	5	5	5	5	4.5	4.5	2.5	4	5	2

At the end of the experiment session, the first question was if the participant was feeling uncomfortable with the experiment or not. This question was also asked after setting up the device and every time after completing each level. In this experiment, S8 was feeling nervous from the beginning of the experiment. This might happen for being performance conscious. However, according to her statement, after a while, she started to apply some techniques which she learned from practising meditation. Seemingly it worked, from level 2 of the game she was observed calm and relaxed. Although both S8 and S10 reported that the experience of wearing the brain signal recording device was unpleasant for them after passing a few moments. For this reason, they reported that the experiment was uncomfortable for them.

The second question was about how frequently they were blinking. S7 was blinking in low frequency because her observation was that if she blinks quickly, the system was not being able to detect those blinks. The rest of the participants were blinking very fast so that they can complete the game in less time. As there was a time counter in this game to calculate the game completion time, all participants were somewhat feeling compelled to complete the game within a minimum amount of time. However, as this system was designed with a 500ms window, some of the fast blinks were missed to detect by the system. Normally to occur an eye blink requires a 200ms time duration on average [5]. Fast blink requires less than a 200ms time duration. So, when a participant blinks too fast and keeps blinking continuously, sometimes that participant blinks more than once within a 500ms window. But the system only detects one blink within the 500ms window. Figure 5.3 illustrates a blink in EEG data, which has been taken from S1's brain signal.

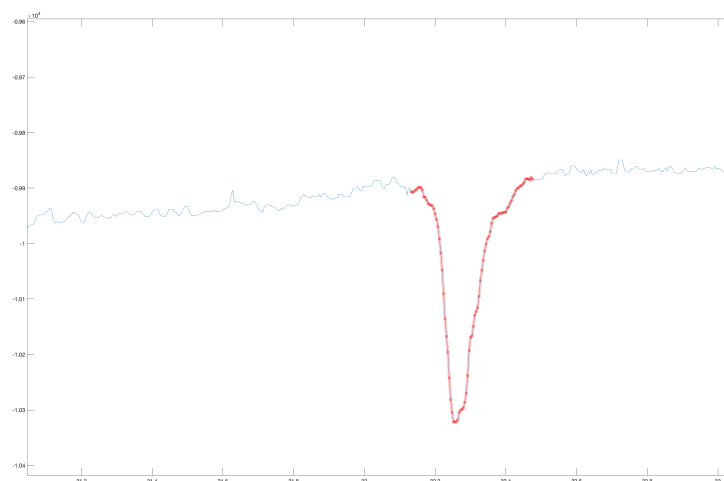


Figure 5.3: Blink artefact in EEG data

There was another observation about how strongly they are blinking. Are they blinking softly, gently or strongly? As the system detects blink by using the thresholding method while eye blink generates a spike from eye muscle movement, so most of the soft blinks got missed. When a blink occurs, it generates a very strong electrical impulse, which is higher than 100uV. But a soft eye blink does not generate enough electrical impulse. For this reason, \ participants who blinked softly, some of their blinks were not being able to detect. On the contrary, those who blinked gently and strongly, most of their blinks were detected. In this experiment, S7 and S8 were blinking softly. However, there was an unusual finding about S7. We plotted the signal in OpenBCI GUI [74] and found that, even though she was trying to blink strongly, her eye blinks were not being able to generate a strong electrical impulse.

One important part of using BCI enabled system is wearing a brain signal recording device. There are several brain signal recording devices are available in the market in the category of wired and wireless. Research grade and medical-grade devices are mostly wired. In this experiment, we have used the OpenBCI device which is wireless. It transfers data to the computer over low energy Bluetooth. The participants were asked about their experience wearing the brain signal recording device (OpenBCI). Most of the participants were excited about wearing this kind of recording device for the first time. There was only two negative feedback from S8 and S10. S8 reported that wearing the device for a long time (after 20 minutes) two electrodes were placed in her forehead (Fp1 and Fp2 position) was causing a mediocre pain on her forehead skin. This was because the electrodes are broadleaf and those were creating pressure on S8's skin. S10 advised that this device should set up with more experience and professionalism. During setting up the device, the broadleaf sensors were tightened which was causing her pain. Altogether, the only reason for negative feedback of wearing the device was for the broadleaf electrodes. Other participants were easeful with wearing the device.

GUI plays an important role in BCI enabled system. It should be clear and self-explanatory. In this study, taking feedback about the game, GUI was another parameter to evaluate a participant's experience. All of the participants reported that it was simple and easy to understand. Even S10 liked the GUI who rated the lowest. They also rated the overall experience of the BCI system pretty good. There were some descriptive feedback and

suggestions from some of the participants which have been presented at the end of this chapter.

5.3 Users Discussion, Suggestions and Feedbacks

Besides these short questions, there were some discussion, suggestions and feedback from the participants. Besides, researchers also observed some behaviours during the experiment which are being presented below. Here we are presenting these findings which can be helpful for future experiment design and BCI system development.

According to S3, she was enjoying playing the game because she did not have to involve her hand or needed any movement as conventional games require. S2 had a similar opinion. Moreover, the lengthy distance between two fruit items in level 3 made S2, S4 and S8 impatience. It was found that those who were physically tired or have restless behaviour, they did not like the concept of lengthy distance between two fruit items. However, S10 suggested that long-distance would not have mattered if the basket could be moved faster. She was annoyed that she had to use lots of blinking to collect fruits. Regarding the steps of basket movement, she advised to speed up to about twice or thrice of current steps. On the contrary, according to S1, S4 and S6, they did not feel any problem with the long distance. Instead, they were enjoying when the fruit items were being collected quickly with their rapid blinking.

During experiment sessions, we also observed that participants with restless behaviour were not being able to stay silent and moveless. S5, S7 and S8 frequently talked, even though they were requested not to talk during three game sessions. Similarly, physically tired or being exhausted after a long day of office work can cause a similar issue. S4 and S5 participated in the experiment after spending the day in their office, and they were not being able to fully focus on this system. According to S4, even though the game has to play with the eye blinks, she had to focus here which needs energy. S5 stated that staying steady for a long time is difficult for him, especially when he is tired. On the other hand, S2, S5 and S8 remembered that movement will generate noisy data and they were dedicated to participating in the experiment. Still, they could not resist movement. Additionally, one of the BCI experienced user S10 was talking in the middle of the experiment, even though she is fully aware that talking generates noise and degrades the performance of BCI enabled

systems. Another interesting behaviour was observed with S7. She thought that she was very steady, but she did not notice that she was unintentionally jiggling her leg.

As in this game, there is a time counter, all participants were trying to complete the game as soon as possible. In fact, S6 was feeling annoyed in level 3 when his basket was stuck for a few moments. S7 also had similar feedback. There was a bug in this game GUI where the basket does not move near the 4th and the 7th fruit item. In that situation, it needs to move manually with the keyboard. With this bug, we found that this type of bugs annoys the subject extremely as they put their focus into the system and expect some action in return, but they have nothing to do if it does not respond. In the BCI enabled system, only brain signal is used. Hence, the user gets helpless if the system does not respond. So before launching a BCI enabled system to the end-users, bugs should be properly tested, or there should be a bypass way to deal with if anything unexpected occurs, or the system should be designed in such a way that it can auto-respond to this kind of situations.

There were some feedbacks about the game GUI and its concept. The simplicity, colourful and attractive design made the participants engaged with the game. S6 liked the arrow direction which was showing from the basket to the fruit item, even though to play this game it was not needed. S3, S4 and S9 liked the concept of collecting fruit items. S3 enjoyed moving the basket each step following her blink signal towards the fruit item. However, S4 and S6 suggested that fruit items should be relevant to the tree. For example, there can be one big apple tree, and some apples can randomly place on the tree. At each level, there would one kind of fruit tree. Then the fruit basket will collect fruits from the tree, which would look more realistic.

Finally, this study evaluated the BlinkFruity system with a different group of participants. There was no performance issue found based on different age group people or the participants who had prior experience with BCI or not. Even being an unexperienced BCI user, S6 was able to complete the game with the lowest completion time. On the other hand, participants who practise meditation did not show any significant result. This might be because this system does not require to use any kind of cognitive skill. As this game has to be played with blinks, participants who had dry eyes problem were facing difficulties. S7 was having very weak eye blink. The system failed to detect most of her blinks. Even one participant is not enough to take any decision, but S9 has made this system confident that,

even an illiterate person can use BCI enabled system if it's explained. At the beginning of the experiment session, she was feeling nervous. But when the device setup was completed and the game began, she started to enjoy it. Even she completed the session within less completion time than some other participants.

5.4 Discussion

In this paper, the quantitative and qualitative results of an experiment with a BCI-based game were presented and discussed. The experiment was conducted with ten subjects, who played a total of 30 matches. The experiment shows that the game can be used as a supporting tool to experience BCI for the first time. This experience can be pleasant, as indicated by the qualitative results.

There were six specific objectives of this study. These are explained below that how these have been achieved—

The first objective was designing a simple BCI application for naive users who are going to use the BCI application for the first time. Chapter 4.1 shows the proposed BlinkFruity system which is a simple BCI application for naive users.

The second objective was developing the gaming interface considering human-centred design. Human-Centred Design, popularized by IDEO.org, is a mindset that overlays design thinking to ensure that the products are actually relevant and beneficial in the long run for the people they are intended to serve. The gaming interface has been applied using one control parameter to keep it the simplest, so that naive users and people who want to experience BCI for the first time can use this application. The user needs to use only a single (voluntary/non-voluntary) eye blink to play this game. In section 5.2 (Users Experience with BCI) it has been shown that participants found this system easy and helpful to experience the BCI system.

Then the third objective was the development of a BCI protocol for real-life application. However, this work yet has not been integrated into any real-life application. In section 6.3 (Future Work) it has been discussed the areas where this system can be integrated for real-life application. These areas range from IoT based application to mobile application (for dialling pre-set numbers as an example).

Evaluating the application with the participants was the fourth objective. This BlinkFruity application has been evaluated by the participants in the context of simplicity, interactive GUI and easy to follow BCI system. In section 5.2 (Users Experience with BCI) participant's evaluation has been shared.

The fifth objective was discussing feedback from the participants about their experience with BCI. In section 5.3 (Users Discussion, Suggestions and Feedbacks) participant's experience has been shared and feedback has been presented. They have also provided some suggestions on making a BCI system interactive based on their perspective and experience.

The final objective was sharing the database and source code publicly which has been produced from this study. The EEG dataset obtained from this experiment (9 participants * 3 levels) has been made publicly available (with the consent of the participants) for further research. Furthermore, the source code of the BlinkFruity application is also available. The GitHub link is <https://github.com/ranadepto/blinkfruity>.

Chapter 6

Conclusion

6.1 Conclusion

BCI is being a new and reliable channel of alternative communication with the computer. In our literature study, we have found that regardless of the abundant experiment and study in the area of a simple and effective system design of BCI, simple and easy to understand system design is not being considered broadly. In this context, a real-time EEG based game has been proposed in this study where both able body and disabled people can play. By playing this game they can experience BCI for the first time, enhance their skill and also can be used for entertainment purpose. In this study, we have presented and discussed both quantitative and qualitative results experimenting on our proposed simple BCI enabled system. There have been studies about the effectiveness of BCI implemented system GUI (through both informal or formal interview session with previously established games connecting with BCI technology). There are also some simple BCI applications available for solely entertainment purposes. But, to the best of our knowledge, this is the first system that has been developed targeting the users who find the BCI system difficult to understand. This system is simple to use, easy to understand, and this system has been evaluated by some participants about its simplicity and effectiveness.

The result shows that the BCI enabled system can be accessed by any group of people. In this experiment, a 50+ years old illiterate subject participated without facing any difficulties. She did not have any prior experience in using a computer either. This participant made our system more confident that even illiterate people can use BCI enabled system if it's explained properly. We found that simple, attractive and interactive GUI help users to understand the BCI enabled system fast and make the experience enjoyable.

This study explores some issues to keep in mind while designing and developing a BCI system. If any steps take a long time or effort, it can be extremely annoying for users. In a brain actuated system if it's necessary to make a step lengthy, there could be rewards for the users in the middle so that the user does not feel monotonous or boredom while completing the task. The same goes for the bug in the BCI enabled system. Having a bug

can be one of the most irritating and unpleasant experience for users. Before launching an application to the end-users, finding and fixing bug should get higher attention. Most importantly, no matter what- some user will move and talk while using the BCI system, which is normal and spontaneous. Even BCI experienced users move and talk. Users can't be asked to stay freeze while using BCI applications. So, noise generated from movement and speech should be handled more cautiously.

This system was developed for experimental purposes only. However, the eye blink can also be used as a control parameter which can especially serve paralyzed and disabled people. Luckily, patients who lose motor control over their body due to sickness or accidents, they still can control their blink. With the combination of different types of eye blinks (for example– long blink, double blinks, triple blinks), these could be used as the control signal to turn on/off light, fan, air-conditioner for paralyzed, disabled and old people. They can also dial a pre-set number in case of need. For serving an advanced purpose, eye blink can even be used as a virtual keyboard to type. Even though it's very troublesome to blink so many times, still this can help some of those people who have unfortunately lost other ways of communication. However, this easy and simple system and its findings can be used as the beginning of the journey in BCI for novice researchers and developers.

6.2 Limitations

This BlinkFruity is a very premature system. Admittedly it fulfils its purpose to help the naive user experiencing BCI for the first time and conducting an experiment, still, there are abundant areas to improve. First of all, more participants from a more diverse group of people can increase the robustness of statistical acceptance. Conducting an EEG-based experiment is difficult in the perspective of experiment subject availability and the complexity of EEG signal acquisition. Based on the literature study it was found that brain signal based experiment conducted with 2 [27], 5 [58][60], 6 [18], 10 [22], 12 [38], 14 [5], 20 participants [12]. So as an initial study, we have conducted this experiment on 10 subjects. However, 10 subjects are not enough to conclude any decision. Additionally, except one, all other participants were higher educated and their ages range from 25 to 35. Child group, teenager group and the older group of people have not been considered in this evaluation. Especially older age group people, disabled and paralyzed people should be

brought under the light of the experiment as they are primary target users. As a continuous process of the extended experiment, in this study, only healthy young participants have been considered. However, it is within the scopes of this study to be used as an assistive technology for disabled and medically diagnosed people in the very near future. There should have some additional gaming interfaces in different levels rather than only fruit item collecting interface for diversity. The evaluation of the experience with the BCI system has evaluated based on interviewing the participants and taking feedback from them, which is not cent per cent reliable. In addition to this, their experience could have been evaluated by analysing the EEG signal.

6.3 Future Work

As mentioned in the previous section, this is still a very premature system. So, in future, we would like to extend this work. Firstly, we would like to develop a system for end-users. People should be able to use this system in their daily life. There are several fields where the combination of different types of eye blinks (for example– long blink, double blinks, triple blinks) can be used to control the Internet of Things (IoT) and household devices. Even though, detecting double and triple blinks are less feasible using the thresholding method, other pattern or machine learning-based approach can be applied for obtaining better accuracy. Conversely, introducing different types of blink will increase multiple ways to control different system. The minimal use is, it can dial some pre-set numbers with the combination of different type of blinks from the old or disabled people's phone.

These are some use cases of this system that can be implemented. However, some other technical improvements should be focused on to increase the accuracy and efficiency of this system. The accuracy of this system is only 84.8% which is not enough for running this system for old and disabled people. Besides the accuracy has not been measured on these group of people either. However, there are more blink detection methods available that can deliver a more accurate result, which is higher than 98%. Additionally, some other inputs can be used as the control signals like eye movement to a specific direction consequently two times, eye close for a specific duration, relaxed state of brain and so on. With the combination of different type of brain activities, the system can be activated, controlled and deactivated.

Appendix A: Key Publications from this Research Work

Published Conference Paper

- [1] Rana Md Shahariar Parbez, Khondaker A. Mamun, “BlinkFruity: A Real-Time EEG Based Neurofeedback Game for Brain-Computer Interface”, *2nd ICAICT*, 28-29 November 2020, Dhaka, Bangladesh.

Ready to Submit Journal Paper

- [1] Rana Md Shahariar Parbez, Khondaker A. Mamun, “A Neurofeedback Based Relaxation, Meditation and Sleep Guiding System Framework to Improve Mental Health”, Ready to submit in *Journal of Neural Engineering*.

In Preparation Journal Papers

- [1] Rana Md Shahariar Parbez, Khondaker A. Mamun, “An Overview of Brain-Computer Interface (BCI) Enabled Systems for Enhancing Concentration Level”, In preparation, to be submitted in *The 14th International Conference on Brain Informatics (BI2021)*.
- [2] Rana Md Shahariar Parbez, Khondaker A. Mamun, “ConcentrateToday: A Real-Time EEG Based Neurofeedback Game for Enhancing Concentration Level”, In preparation, to be submitted in *nature neuroscience*.

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