Enhancing the Self-Regulated Learning Process Using a Brain-Computer Interface with Auditory Neurofeedback

Ari Lee (s2036169)
Creative Technology, EEMCS
a.lee@student.utwente.nl

Supervisor: Mannes Poel
Critical Observer: Max Slutter

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Abstract

While self-regulated learning takes a significant role in the learning process, students struggle with weak performance monitoring and a lack of external aids. Implementation of the Brain-Computer Interface can assist the students in quantitatively measuring their engagement or concentration during self-regulated learning, hence enhancing the self-regulated learning experience by providing real-time feedback for real-time monitoring of performance and correction. In this project, the level of concentration or engagement of the students will be monitored by implementation of a neuro-physiological computing system and calculation of engagement index from alpha, beta, and theta bands of EEG signals. A real-time feedback based on the aforementioned index in the form of audio, background music with dynamic volume will be developed and evaluated.

CHAPTER 1: Introduction

Learning is a complex process that involves obtaining and understanding new knowledge, skills, or actions, and plays an essential part of personal and societal growth. Ensuring inclusive and equitable quality education and promoting lifelong learning opportunities for all is an urgent call, as Goal 4 of the Sustainable Development Goals suggests [1]. However, learners often struggle to monitor their own progress and performance, which is necessary for improving the quality of learning and academic achievement, according to Cassidy [2]. This is particularly prevalent during a self-study session or self-regulated learning, as students are more prone to being distracted if there is little to no external supervision. Although checking the learning progress and getting feedback from external sources is crucial, direct aid from external educators is not always readily available [3]. This highlights the need to develop technology that can give instant feedback regarding a student's real-time learning capability.

1.1 Background Information and Problem Statement

The measuring and recording of neuro-physiological signals, especially the electrical voltage of the brain, is called an electroencephalogram (EEG) and is performed using electrodes attached to the scalp. According to Shad *et al.* [4], EEG is non-invasive and relatively inexpensive, and since it reads and logs brain activity simultaneously and constantly, it is a suitable technique for BCI. There are several types of EEG, but the two major categories are distinguished by whether the electrodes used are dry or wet, with each having its strengths and weaknesses. EEG has been used clinically but is starting to find applications in other fields, such as sports, entertainment, and computer-related functions [4]. However, as mentioned by Shad *et al.* [4], the integration of neuro-physiological computing systems into education, in order to enhance the learning experience, is still in its early stages. This is where this project aims to explore further.

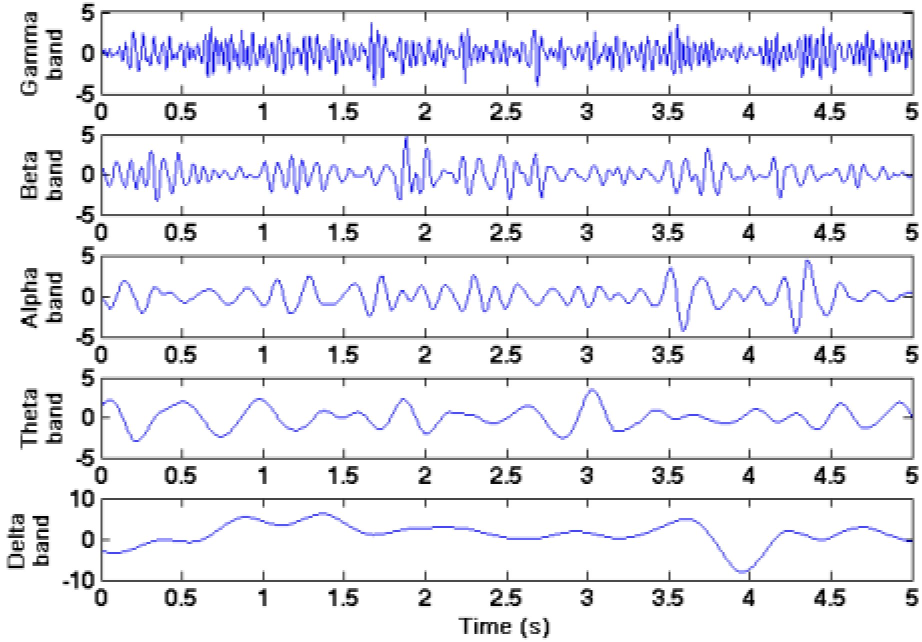


Figure 1: The five frequency bands of EEG signals [5]

Quantitatively measuring neuro-physiological signals using brain-computer interfaces (BCI) can be a potential solution to this problem. BCI is a system that can interpret brain activity by measuring brain waves of different frequencies, which are produced when neurons are activated and generate electric pulses in synchronisation [6]. These brain waves are classified into 5 different waves: alpha[8 - 14 Hz], beta[14 - 30 Hz], theta[4 - 8 Hz], delta[0.5 - 4 Hz], and gamma[>30 Hz] as shown in Figure 1. Gamma waves are detected during moments of high concentration or problem-solving; beta waves are detected when the brain is awake and active; alpha waves, during a relaxed or tired state; theta, when drowsy or during light sleep; and finally, delta waves are the slowest, and are detected during deep sleep [7].

According to Jamil *et al.* [6], learning is one of the most effective brain processes, but can still be enhanced through strengthening the relationship between brain cells. This can be facilitated by BCI, through measuring the brain waves of a student and analysing them, as brain waves can reflect the mental states of the student. Hence, developing a system that can measure aforementioned electrical brain signals and translate them into a computer, can give insight into the learning progress and provide real-time feedback to the student.

So far, a substantial amount of research that relates EEG with human cognitive tasks focus on quantifying performance in terms of mental fatigue, workload, effort, emotion, and stress [8]. However, Ismail and Karwowski [8] also found out that a majority of them also focus on driving a vehicle, or other complex cognitive tasks, such as aircraft control systems, power plants, or maritime activities. They found that out of 143 selected studies that link EEG with cognitive performance, less than 25 studies focus on simple cognitive tasks, such as colour matching, short-term memory, or arithmetic tasks. The studies do not link the activity of "learning" to EEG, but other states or indicators that can be measured short-term instead. Therefore, as mentioned above, these studies do not contribute in the direction of enhancing the learning experience. However, from these findings, this project can obtain information about the said indicators for states of concentration and fatigue and how to detect it, then link it to improving the learning environment to boost the learning efficiency.

The intended system of the project uses neuro-physiological signals to monitor the concentration of the students during the self-study phase and provide personalised feedback that enhances the learning experience. Specifically, the main goal of this graduation project is to develop a system that can detect when a student is losing focus or distracted by reading their brain waves using a wearable, non-intrusive headset, then remind the student about their learning state and adapt the environment through the use of visuals or sound in real-time, in order to alert and guide the student back to a concentrated state of mind. The major challenge expected to encounter during this project is identifying the specific aspects that are critical for effective self-study and the corresponding neurophysiological signals. Furthermore, it is essential to design a feedback system that is not intrusive but enhances learning performance without causing any negative impact. Ultimately, this system shall improve the effectiveness of the self-regulated study of students and enrich the learning experience, especially for those who struggle to keep themselves well concentrated and can be anticipated to even develop good learning habits for the students and improve their studying efficiency by reducing time wasted while distracted.

1.2 Research Question

To find the solution to the problem statement, lack of research and developments done regarding the BCI integrated self-regulated study assistant, the following research questions need to be answered:

Main research question:

- How can neuro-physiological computing systems be implemented to monitor the level of concentration and give real-time feedback in order to improve the self-regulated learning experience?

Sub-research questions:

- What are the factors and aspects of self-study that constructive feedback can be given on, that can be: identified or measured, and when received, can be improved upon?
- Which neuro-physiological signals, especially regarding EEG, are related to those factors?
- How can those neuro-physiological signals be measured, processed, and analysed, to elicit a meaningful interpretation?
- How can a feedback system be designed that is not intrusive and help users enhance their performance in a self-study setting, regarding the aspects mentioned above?

CHAPTER 2: Background Research

Before any actual progress on this project can be made, pre-knowledge about the types of electrodes that are used to measure EEG and the possible implementations of the BCI system is required in order to figure out in which direction this project should be conducted and which aspects of BCI this project should be focused on. Therefore, background research has been conducted through the form of a literature review, and the information obtained is described in this chapter. This includes not only information about the EEG electrodes, as they are critical in obtaining the raw data, but also information about the methods of processing the obtained neuro-physiological signals, the current BCI technology in the market, and how the BCI system can be implemented in education. This information will help with getting an idea of how a BCI system can be used and developed.

An overview of different types of EEG electrodes will be discussed in section 2.1; followed by the current implementation of the BCI system in education, and areas of potential application in section 2.2; section 2.3 describes the methods of neuro-physiological signal processing; section 2.4 outlines the state-of-the-art BCI technology that is currently in the market; and finally, in section 2.5, a conclusion on how neuro-physiological computing systems can be used to improve the learning experience during self-study will be drawn.

2.1 Types of EEG Electrodes

For this research, it is important to learn about the different types of electrodes that can measure the electrical signals generated by the neurons in the brain, especially in how they are set up and used. This shall help in determining what type of electrode would be best suited for the project's goal, as each type of electrode has their own strengths and weaknesses. As the signals can be diminutive and noisy, investigations on electrodes that are easily implemented with reasonable performance are in need; for example, despite providing a detailed result, the setup for a standard 24 channel EEG cap can take between 20 to 40 minutes [9].

Conventional lab-based EEG measurements use disc electrodes, flat and metal plates, with conductive media such as a gel [4, 10-11]. While the method allows reliable, stable, and repeatable EEG recordings [12], the electrode and the conductive media must make contact directly with the skin or scalp, and the skin needs to be prepared with processes such as cleaning before the attachment of the electrodes for better acquisition of data [4, 10-11]. Most of the time, the electrodes and conductive media are disposable, which makes the measurement expensive and not environmentally friendly.

Regarding that the aim of the research is to integrate a BCI system into self-regulated learning, this type of electrode is not suitable for its difficulty in usage as the preparation takes much effort and the application of electrodes is not aimed at non-professionals. The attention is on the application of EEG not only in clinical settings but other real-world applications with user-friendliness.

With advanced technology, diverse electrodes such as quasi-dry electrodes, semi-dry electrodes, dry electrodes, multiple types of active dry electrodes, and non-contact electrodes have been introduced. Quasi-dry electrodes, in the middle of wet and dry electrodes, use a small amount of fluid that is triggered by the movement of the electrode and scalp [13]. The quasi-electrodes are easier to apply on the user than the conventional wet electrodes and can be used reliably to record the EEG signals [13]. However, such electrodes require uniform pressure inside the electrodes for the moisturising agent to be reliably applied and electrode failure and non-uniform pressure will result in unstable signal acquisition [14].

Li *et al.* [14] argue that the semi-dry electrodes made of passive ceramic can be the solution as they release the saline in a systematic way that avoids failure of the signal acquisition. Although it can be applied to the user quicker and easier than the wet electrodes, it still requires saline to be refilled by the users and might cause signal disruption if the user forgot to do so.

Multiple studies suggested that the use of dry electrodes, which uses no conductive medium such as conductive gel or glue, may take the place of wet electrodes and optimise the measuring procedure by removing skin or scalp preparation [12, 15]. Dry electrodes that are made of an insulated rubber layer and a conductive rubber layer with shielding measure low-noise EEG signals and with the use of a high input impedance amplifier, the EEG measurements resulted similarly compared to conventional wet electrodes [12, 15]. Even though the use of a high input impedance amplifier has been suggested, the high impedance in the electrodes that is caused by the absence of a conductive medium can be problematic, as the high electrode impedances result into increased noise [16].

Furthermore, flat-shaped electrodes that are dry might not be suitable for hairy areas which will cause more impedance and noise as it may not make firm contact with the scalp. Active dry electrodes suggest pre-amplifying the impedance and decreasing noise at the collection level. Pourahmad and Mahnam [17] suggest two methods of active dry electrodes, the method of using a simple unity-gain buffer amplifier that converts the high impedance of the electrode and the method of amplifying and filtering the signals at the electrodes before sending them to the main system.

As for the first method, Fonseca *et al.* [18] also show the possibility of a dry active electrode with buffers that reliably replace the wet electrode with the use of a conventional rubber head-cap to plug the electrode. However, by using the conventional rubber head-cap, the application on hairy areas such as the scalp remains troublesome. In the research, the multipin dry active electrode was proposed [17]. The gold-coated silver pins attached to the electrode ensured better contact in hairy areas, however, the limitation was that it was not comfortable for the users depending on the displacement [17].

In another study, Chen *et al.* [19] suggest the use of soft and comfortable conductive polymer dry active electrodes consisting of operational amplifiers. Their research shows the experimental results of the new electrode corresponds with the wet electrode and argues that increasing carbon in polymer ensures reliable signal acquisitions while making it less elastic and causing discomfort to the user. Huang *et al. [20]* also suggest the use of comb-shaped dry active electrodes but with thin metal pins in their study. They mention that the active CSDE circuit it uses reduces the pressure needed to attach the electrode, therefore it reduces the discomfort of users and the experiments and questionnaire have proven that it is an acceptable level of pressure and pain. However, checking the pressure of each electrode might not be convenient.

Lee *et al.* [21] propose the use of active spring-loaded dry electrodes. The proposed electrode is a combination of spring-loaded probes with active buffer circuits which allows maximised physical contact between the electrode and the skin/scalp and reliable electrical signals acquisition [21]. To maximise the usability of the product, a non-contact type of electrode was considered. Non-contact electrodes are proposed by multiple researchers [22-24]. As the non-contact electrodes are a trade-off between usability, signal quality, and sensor complexity [22], the results show that the non-contact electrodes have the potential to be implemented, however, it is not yet at a reliable level to replace the wet electrodes [22-24].

2.2 Implementation of the BCI System

Due to the increased attention on Brain-Computer Interfaces systems, BCI systems have been applied to multiple fields. With a priority on its possible application in education, this research will examine the current state of implementation of the BCI systems.

As the focus is on enhancing self-regulated learning without the aid of an external educator, the implementation of wet electrodes was excluded for its complexity of application outside the laboratory. The In-ear EEG device with dry contact electrode for emotion monitoring was proposed [25]. The silver-adhesive fabric electrode was attached to the earphone rubber and the collected signals were used to determine the emotional changes of the users, and as it compromises the looking of earphones, the users were familiar with the shape of the electrode, therefore increasing the wearability and compatibility [25].

The research results from the prototype shows the potential of the product, however, the emotion classification results are unsatisfactory, as the accuracy for the classification of four emotions was under 60%. Jeong and Jeong [26] showed around 80% accuracy for attention state classification using in-ear EEG with silver-painted in-ear electrodes which made more contact with the skin but less comfortable. Therefore, it can be considered that the in-ear EEG has the potential to be successfully implemented and used, but there must be a trade-off between usability and sensor accuracy.

Larocco *et al.* [27] suggest the use of low-cost EEG headsets such as Emotiv Epoc, Neurosky Mindwave, InterAxon Muse, and OpenBCI for drowsiness detection. Most of the commercial headsets mentioned are non-contact but considering them low-cost might be controversial as their price range starts from €300 to above €3000. However, it has the possibility to be integrated into education as it can detect drowsiness and it can be cost-effective.

Although Larocco *et al.* only mentioned drowsiness, the EEG data can also be used to predict the attention of the students during online learning [28] or to measure and monitor the engagement of students [29]. The classification of the attention level using EEG data can be done using machine learning models such as RF models [29]. The measurement of both cognitive and emotional engagement consists of 8 dry electrodes and processing signals using machine learning techniques [29].

2.3 Neuro-physiological Signal Processing

2.3.1 EEG signal frequency bands

The human EEG can be classified into five categories: alpha, beta, theta, delta, and gamma, distinguished by their frequency bands as shown in figure 1 [5] in Chapter 1. According to Abo-Zahhad *et al.* [5], the frequency of each band and corresponding states of the human brain is as follows:

	Frequency	State
Alpha (α)	8-14 Hz	Relaxation (still awake)
Beta (β)	14-30 Hz	Normal consciousness, active concentration
Theta (θ)	4-8 Hz	Some states of sleep, quiet focus
Delta (𝛿)	0.5-4 Hz	Deep and unconscious sleep
Gamma (γ)	>30 Hz	Visual stimulation

Table 1: The five frequency bands of EEG signals and the states [5]

As each band has a distinct frequency and state of the brain, EEG signals reflect the brain activity and can be analysed to classify different mental states such as engagement, alertness, and concentration. Alpha activity decreases as the students are engaged in learning while beta activity increases with consciousness and alertness [30]. Also, [31-32] stated that higher beta activity is associated with increased concentration, memory activation and increased memory performance results in lower alpha activity.

Based on the data from [31-33], table 2 was created to show the engagement of each band for four states, alertness, concentration, engagement, and drowsiness.

	Alertness	Concentration	Engagement	Drowsiness
Alpha (α)	Decrease	Decrease	Decrease	
Beta (β)	Increase	Increase	Increase	
Theta (θ)			Increase (frontal)	Increase
Delta (𝛿)				Increase
Gamma (γ)				

Table 2: EEG signal bands for different states

2.3.2 EEG signal processing

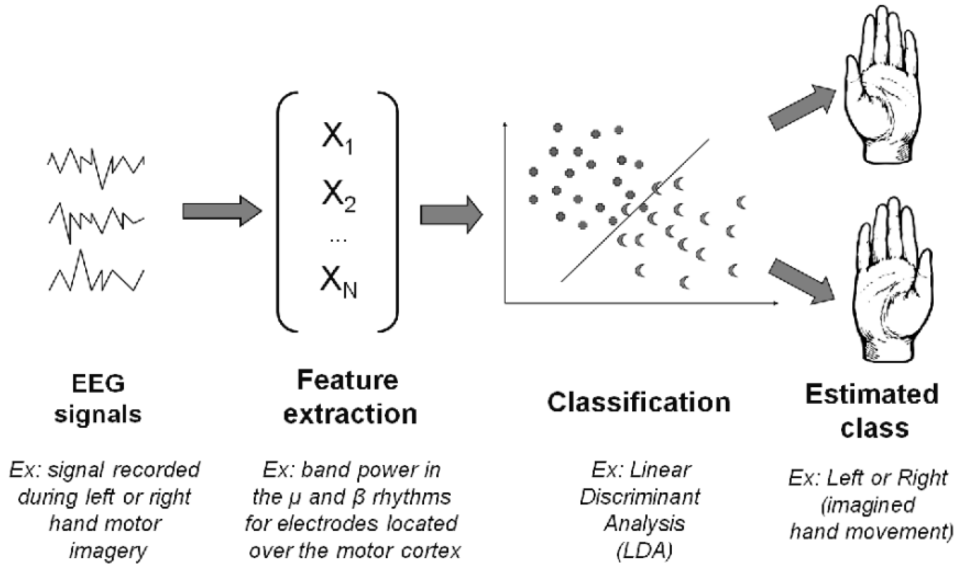


Figure 2: A classical EEG signal processing pipeline for BCI, in context of imagined movements [34]

As shown in Figure 2, a classical EEG signal processing pipeline consists of 4 parts: recording of the raw EEG signals, feature extraction, classification, and estimated class [34]. The feature extraction can be done after processing the raw signals into the frequency bands shown in Table 1 and describing the relevant values of the signals to classify the estimated class [34]. The classification of the signals into estimated classes such as level of attention, concentration, and engagement can be done using algorithms such as K-Nearest Neighbors (KNN), Random Forest (RF), Support Vector Machine (SVM), Artificial Neural Networks (ANN) [28-29].

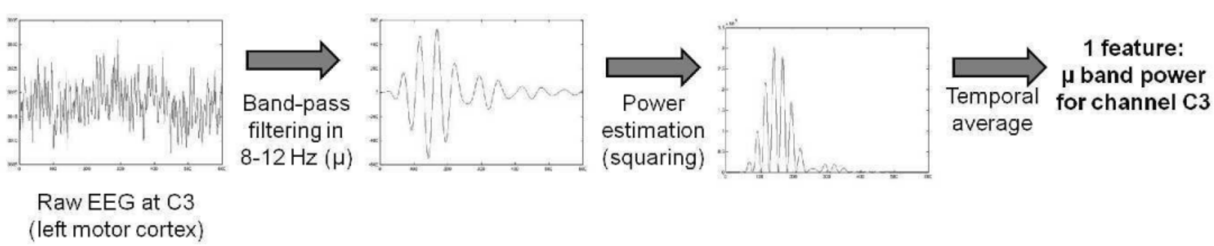


Figure 3: Signal processing steps [34]

A demonstration of the signal processing steps to extract the band power from the raw EEG signals is illustrated in Figure 3; albeit the steps show the processing of EEG of a left motor cortex, the same steps can be taken for the EEG required for this project. Among various ways to retrieve the band power from the raw EEG signals, a simple yet popular and efficient method is to use band-pass filtering [34].

For simpler analysis, instead of the machine learning techniques, indexes calculated based on the band power of each frequency band can be used.

$$Theta - to - beta\ Index = \theta / \beta$$
$$Engagement\ Index = \beta / (\theta + \alpha)$$

Theta-to-beta index is known to be decreased in concentration state [35]. Engagement index known to increase in engaged states [36]. Although the engagement in definition might differ from concentration, in this research the engagement index will also be treated to determine the concentrated state regarding that the engaged state only applies to the study environment in this research..

2.4 State-of-the-Art BCI Technology

2.4.1 OpenBCI

OpenBCI is an open-source BCI platform that provides low-cost and programmable hardware [37] for a wide range of customers such as institutions, researchers, and amateurs. There is abundant research done with the use of OpenBCI hardware including electrodes and boards. The software, OpenBCI GUI is provided, which enables the connection to the OpenBCI software, to retrieve and visualise the data. The EEG hardware is mostly provided in many options for Do-It-Yourself (DIY) and there is a lot of freedom to tinker from the device, consequently, the devices are more likely to be a prototype rather than a complete product as shown in the below figure.

Figure 4: Ultracortex EEG headset [38]

The Ultracortex EEG headset shown in Figure 4 is one of the products from OpenBCI, comes in two options for the number of channels, 8 or 16, and in various sizes and purchasing options with wire connection. The price ranges from $399.99 - 1149.99, depending on the assembly status and whether the customer chooses to 3D-print the parts oneself. The device includes dry electrodes and does not include the biosensing board that processes the signals using amplifiers or filters and is not intended for medical use.

Figure 5: EEG Headband Kit [39]

Another shape of the EEG measuring device from OpenBCI is an EEG headband that provides up to 8 channels, sold for $299.99, excluding the biosensing board [39].

2.4.2 Emotiv

Figure 6: Emotiv Epoc X [40]

Emotiv products are also intended for research and personal use and are not open-source. Unlike the OpenBCI, Emotiv devices are sold as complete products and licences must be purchased to obtain raw data from the device. Emotiv Epoc X, shown in Figure 6, is one of their products with 14-channel enabled with saline-based semi-dry electrodes and has wireless connectivity via Bluetooth Low Energy. The price of the device is $849. Data can be streamed using their software EmotivBCI with a “Brain control” feature which reacts to the cognitive state of the brain and enables the control of machines.

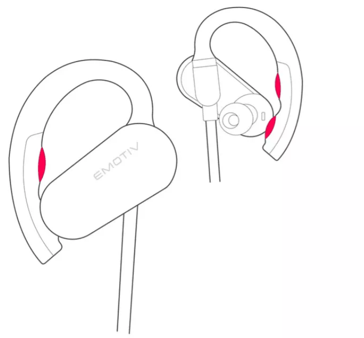


Figure 7: Emotiv MN8 [40]

Emotiv MN8 is a new product from Emotiv, which are 2-channel EEG earbuds and is not commercially available yet. As it only has two channels, it cannot read the thoughts or emotions but is limited to levels of stress and attention. [40]

2.4.3 Muse

Figure 8: Muse 2 [41]

Figure 9: Muse S [41]

Muse is an EEG-measuring headband enabled with five dry EEG sensors attached to the forehead. The aim is to help users with the meditation, to stay focused and calm, by sensing stress, cognition, and sleep and give audio feedback. The easiest setup is installing the Muse app on the smartphone and connecting the device via Bluetooth. The placement of five sensors is the same for both Muse 2 and Muse S devices, however, the usability was improved in Muse S by using comfortable fabric. The Muse S device costs $399.99 and Muse 2 is not sold on the official website anymore. [41]

2.4.4 Mindo

Figure 10: Mindo [42]

Mindo is a wireless 4-channel EEG-measuring headband with a Bluetooth connection. spring-loaded dry electrodes are used to measure brain activity, the associated mobile application provides audio feedback for relaxation, concentration, stress reduction, sleep and anxiety. Unlike previous devices, Mindo collects data from the hairy area, T3, T4, O1, and O2 located above the ears and back of the head, and it uses spring-loaded electrodes. The cost of the device is $399 and various development support to configure and receive data is available including Python, web, and mobile. [42]

2.4.5 BrainLink

Figure 11: BrainLink Pro [43]

Figure 12: BrainLink Tune [43]

BrainLink Pro is an EEG-measuring headband associated with its own mental health application. It also gives instant feedback for three states, focus, calm, and zone, by changing the colour of the light of the device. The measuring is done using three electrodes, two allocated at the forehead and one near the ear lobe. BrainLink Tune, EEG-measuring Bluetooth earbuds, has one semi-dry in-ear electrode to collect data. BrainLink Pro costs $259 and BrainLink Tune costs $199 while raw EEG data can be only collected from BrainLink Pro. [43]

2.5 Conclusion

The first part of this chapter focused on different categories of electrodes, wet and dry, and discovered more about different types of dry electrodes and compared the pros and cons. As the results of multiple studies show, there must be a trade-off between usability, sensor accuracy, and sensor complexity which is also directly related to the cost of the sensors. It clearly shows that the conventional wet electrodes cannot be integrated into a device that supports self-regulated learning without the aid of an external educator. While non-contact electrodes are to be discovered more in a later phase, the alteration of semi-dry electrodes might be promising to be developed during the project. The second part of the research discussed two implementations, in-ear EEG and EEG headsets. While multiple EEG headsets are available, it is costly to be widely accessible for every student. In-ear EEG is still in the early phase and needs to be further developed for accuracy. Implementation of the BCI system into education can be done in both cognitive and emotional engagement and attention.

To conclude, the level of alertness, concentration, engagement, and drowsiness of the students can be used to give feedback during the self-regulated learning process. These four states can be classified from the neurophysiological signals acquired from electroencephalogram (EEG) measurements. The band power of raw EEG signals can be extracted into five categories, alpha, beta, theta, delta and gamma, which can be observed in different states of brain activities. This processing can be done by filtering the raw EEG signals for designated frequency bands. Analysis of alpha, beta, theta, and delta activity can indicate the different levels of alertness, concentration, engagement, and drowsiness.

CHAPTER 3: Approach

In this chapter, the approach to planning and handling the thought process and design process for this project will be described. Various methods have been used on the path to realising this project, such as stakeholder analysis, brainstorming technique, and creating a storyboard. However, the "Design Thinking Process" design method in particular will be described and explained in detail in this chapter, as it was the method that acted as the backbone during the entire design process.

In this chapter, the method itself and how it can be done will be described, however, the actual application of these methods to this project will be explained in detail in Chapter 4: Ideation instead, to avoid confusion.

3.1 Design Thinking Process (Design Method)

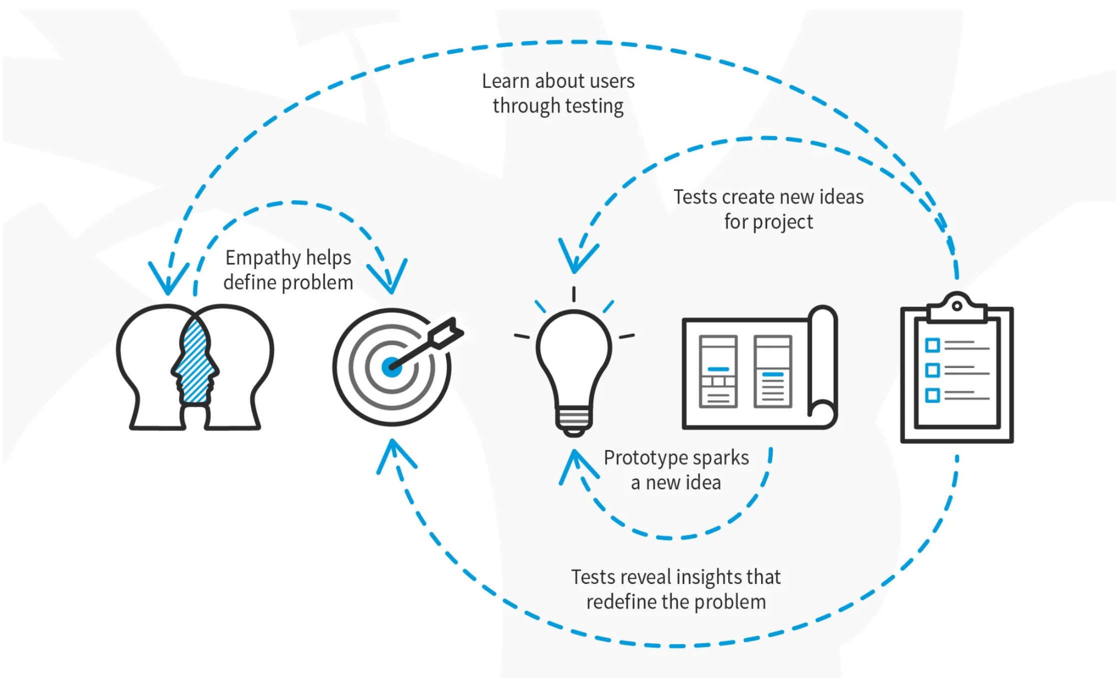


Figure 13: Design Thinking Process Diagram [44]

The "Design Thinking Process" originated from Stanford D(design) school and has been chosen to be applied in this project. This approach is a non-linear process that includes iteration of empathise, define, ideate, prototype, and test stages [44].

This design method was selected as it helps to think outside the box and leads to deeper problem-solving with more creative solutions. Moreover, part of the process includes user-centric research, which is necessary for this project as the project aims at voluntary daily use of the final product from its users.

The empathise stage includes understanding the user and researching their needs; the define stage consists of defining their needs and problems; the ideate stage is for creating ideas and identifying the challenge; and the prototype stage consists of creating solutions and developing the prototype that will be used in the test stage [44]. The application of this method to the project will be explained in detail as follows.

3.1.1 Empathise

The empathise stage is user-centric research, "understanding the users' perspective by seeing their world, understanding their feelings, appreciating them as human beings, and communicating the understanding [45]." This stage includes observations, interviews, and engaging with users. In this project, observations and interviews of the user domain will be conducted, especially regarding the bachelor students of University of Twente. During this stage, information about the users related to the self-regulated study will be gathered. For this stage, conducting a stakeholder analysis is also important, which is identifying the potential stakeholders and how important they are for this project. This clarifies for whom the project is being designed for, so that the design of the project does not deviate from the target audience.

3.1.2 Define

The needs and problems of the users will be defined during the define stage based on the information gathered during the empathise stage. And with that information, the stakeholder requirements will be identified. The needs and problems of the users during the self-regulated study will be defined using the MoSCoW method [46]. This is a technique to manage requirements, sorting them into different priorities, such as "Must have", "Should have", "Could have", and "Will not have" [46]. This stage will be the basis of the ideation in the next stage.

3.1.3 Ideate

The ideate stage is where the ideas are generated to solve the problems defined in the define stage that also fulfil the needs of the users. The brainstorming will be done during the stage and a concept map will be created. The outcome will be the ideas on potential feedback that will be given to the users during their self-regulated learning sessions.

3.1.4 Prototype

The solution will be created during the prototype stage. The possible solutions will be identified during the stage and implemented in the prototype. The prototype will be first created as a lo-fi version with limited functionality and disposable materials to check the limitations of the solution itself and to be improved before the creation of the actual prototype, so-called hi-fi prototypes. The lo-fi version of the prototype will go through the iteration process of the prototype stage and the test stage.

3.1.5 Test

The lo-fi and hi-fi prototypes will be tested on the potential users that are recruited for user testing. During the user testing, observations will be done and the follow-up questions can be asked afterwards in order to evaluate the solution and the prototype. Depending on the results of the test, the refinement of the problem statement and solutions or recreation of the prototype will be done.

CHAPTER 4: Ideation

In this chapter, the ideation of the graduation project will be described, based on the method explained in Chapter 3: Approach. Among the five steps of the Design Thinking Process, the three first steps, “Empathise”, “Define”, and “Ideate”, that are tailored to this project, will be explained in detail. The two later steps of “Prototype” and “Test” do not fit the ideation chapter, and hence they will be detailed in later chapters.

4.1 Empathise: Stakeholder Analysis

The students are the potential users of this product, and hence they are the main stakeholder and the target audience for this project. They are the main actors in the self-regulated learning process, and the easiest in accessibility in terms of observation, interview, and testing. They are familiar with the latest technology which will make the ideation process more efficient and open to more ideas that can be implemented with fewer restrictions. They are the major stakeholder for this project, as they are the target audience, and the system is designed to be used by the students.

There are three other stakeholders in this project. The first one is the developer for this project, who also designs and develops the system to meet the goal of the project. Another stakeholder is the supervisor, Mannes Poel, and the critical observer, Max Slutter, of this project, as they oversee and guide the developer and by doing so, influence the project. The last stakeholder is the University of Twente, who supply equipment and tools to the developer to conduct the project with high potential of having interest in promoting the system or product.

For the stakeholder analysis, the major focus will be cast on the students, as they are the target audience of this project, as mentioned above. The other three stakeholders’ interests are that the project is conducted and developed safely, smoothly, and successfully; however, this does not essentially guide the project to success. Hence, to find out the needs of the students, the steps of the design thinking process addressed in the previous chapter shall be conducted. The observation and interview of the students were conducted in the library, where the self-regulated study is performed most. The specific target is the bachelor students as they are the most accessible among the students as they are the peers of the researcher.

4.1.1 Observation

The goal of the observation was to gain a better understanding of the users. Their behaviour during the self-regulated study will be observed to understand the context and identify their needs. The observation will be unstructured and information regarding the distraction and general behaviour will be collected. The information will be used to generate the interview questions for deeper understanding.

For a week, from 11th of April to the 17th of April 2023, an observational study was conducted in the Vrijhof library. The length of the observation was approximately 5 - 10 minutes each day. The first part of the observation includes the students sitting in an open space, and the observation could not only include the target students, bachelor students, but such as master students and others as the library is open to everyone. The observation shows that most of the students are leaving once in a while for a break such as a coffee break or taking a walk. The library offers noise-cancelling headphones and it was observed that most students in the open place are wearing headphones and earphones. The second part of the observation was on three to five bachelor students that were sitting inside a project room. They were a group of friends in different bachelor courses and were studying individually. They were often distracted from studying due to chatting, and they were also wearing headphones or earphones while they were concentrating or watching online lectures. They also left for a break altogether when one suggested.

The outcome of the observation suggests that most of the students wear headphones or earphones while studying. They seemed to use the equipment to avoid distractions such as conversations near them. Students are taking breaks, sometimes it can be the result of peer pressure if they are studying with their peers in the same place.

4.1.2 Interview

Based on the observations, three interview questions were generated, and four Bachelor students were interviewed.

Questions	Interviewee 1	Interviewee 2	Interviewee 3	Interviewee 4
Do you listen to music during self-regulated learning?	Yes, if studying outside.	Yes, to block the noise.	Yes, but sometimes stop or skip the music if it becomes a distraction.	Yes, most of the time.
Do you wear headphones or earphones?	Yes, earphones.	Yes, headphones.	Yes, headphones.	Yes, whatever is available around me at that moment.

Do you have a specific preference for music (such as genre, tempo, key, etc.) while studying?	Yes, jazz or low-tempo music.	Yes, but it changes with the study progress and mood of that day.	Yes.	Yes, but it depends on my mood and concentration level.

Table 3: Interview questions asked and the responses obtained from three Bachelor students

They were asked if they listen to music during self-regulated learning and if they are wearing headphones and earphones and their preferences. They all answered that they listen to music during self-regulated learning and mostly wear headphones or earphones (depending on their availability) outside. The preferences were more on the headphones. They were also asked if they have specific preferences for the music they listen to when they study and the answer was that all of them have specific music preferences, such as different genres of music or musical atmosphere, to maintain their concentration levels.

The outcome of the interviews suggests that, for students, the wearing of headphones or earphones during a self-regulated study is to prevent distractions from auditory noise and that there is a specific preference for the music they listen to in order to maintain concentration, but this may differ for each person. However, listening to music can also become distracting and there might be a need to change the music during the self-study process which can be a cause of disturbance.

4.2 Define (Stakeholder Requirements)

Based on the empathise stage, the stakeholder's or user's problems and needs are defined. The problem is that the selection of the music can cause distractions while the aim of wearing the headphones and listening to the music is to avoid the disturbances caused by noise and to increase immersion and concentration. Therefore, the automation of selecting the music that helps the users to concentrate without active engagement or continuous control of the user is in need. In addition, real-time feedback is important, so that the student will be aware and their environment can be adapted as soon as they lose focus; providing feedback after a self-study session is less effective and does not fit the project's aim. Requirements are generated based on the information gathered during empathise and define stage.

Must have requirements:

- Must not distract the students by itself.

- Must keep students concentrated.
- Must provide real-time feedback to prevent confusion.
- Must take into account the neuro-physiological signals of the students.
- Must be non-intrusive.

Should have requirements:
- Should be easy to use and user-friendly.
- Should have multiple music options.

Could have requirements:
- Could have abundant music options.
- Could have a dashboard where students can get an overview of their learning performance.

4.3 Ideate

4.2.1 Brainstorming

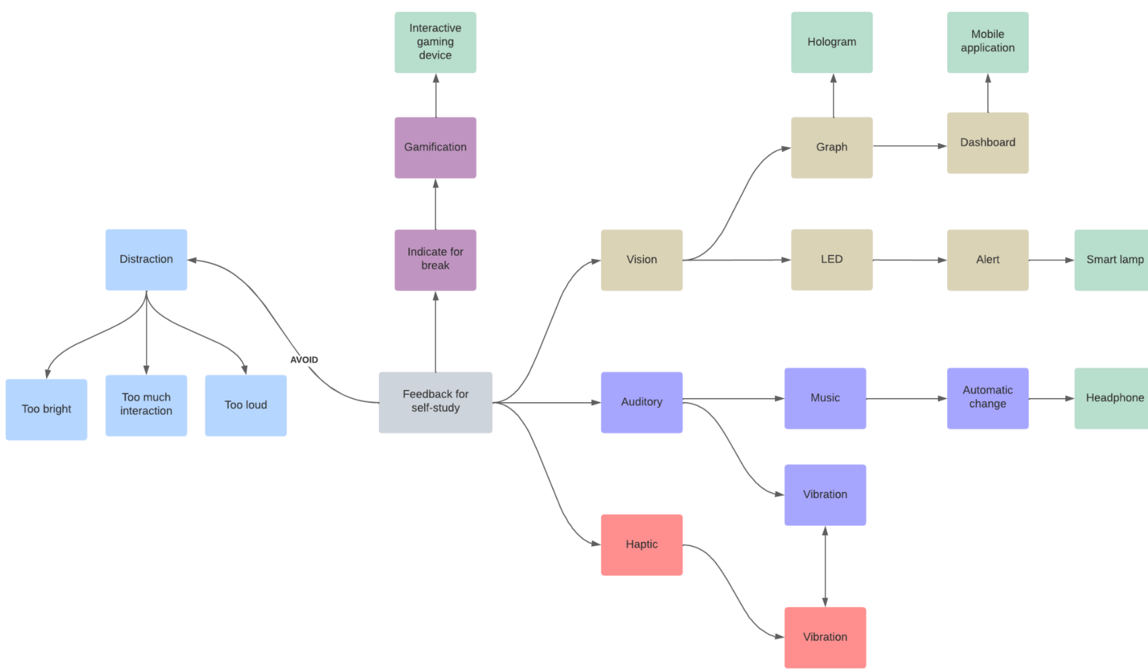


Figure 14: A concept map on self-study feedback options

I. Interactive gaming device
The idea of an interactive gaming device is to give feedback when there is a need to take a break during self-regulated learning. The device consists of a photoresistor and accelerometer for the students to solve the quests such as moving to a brighter

place or walking around to refresh. However, the idea requires too much interaction between the device and the users which may cause disturbance to the users.

II. Hologram
The idea is to provide visuals to the users on their concentration level. A prism cube can be implemented to the device with a screen such as OLED to create a 3D visual of the concentration level graph. The idea can be a more interesting way of representing the graph instead of using a flat screen with minimal physical components and technical difficulties.

III. Mobile application
Developing a mobile application is a typical way of giving an overview to the users. A dashboard of the concentration level of the students that might be sorted by time, date or customised filters can be shown on websites that can be easily accessed by the students with their phones. However, a dashboard of the mobile application is not suitable for real-time feedback and the use of mobile phones can lead to distraction of the students.

IV. Smart lamp
The idea is to change the colour of the lights based on the concentration level of the students. By changing the light, the students can notice that there is a change in their concentration level and then can escape from the distractions. If the use of different colours causes distractions, it can only change the colour when the concentration of the student is very low and an alert is in need.

V. Headphone
The idea is to automatically select and change the background music based on the concentration level of the students. Also, a lot of students already wear headphones and earphones and listen to music during self-regulated learning, which makes the system more familiar to the students than other feedback options above, and decreases the chances of the feedback option itself being a distraction. Therefore, it has been decided that this option will be the most effective among the five ideas generated during the ideate stage. The idea will be explained in detail in the next section.

4.2.2 Initial concept

The initial concept includes the components shown in Figure 15 below. Each component will be explained in depth in three parts, data acquisition, data processing, and feedback.

Figure 15: Initial concept (dry electrodes[47])

I. Data acquisition
The brain activity signals will be collected and recorded using the electrodes that are attached to the headphones. The electrodes will ideally be in the form of semi-dry or dry electrodes that make natural contact with the skin and scalp as wearing the headphones.

II. Data processing
The machine learning model can be trained with the collected data with a public dataset available online to predict the level of concentration of the user based on the brain activity signals, however, regarding the difficulty of realisation within time span, rather simpler method of different frequency band activation comparisons such as engagement index and theta-to-beta index as mentioned in Chapter 2 will be explored.

III. Feedback
The real-time data will be transmitted to the microcontroller and mini-computers such as Arduino and Raspberry Pi. The formula to calculate the index of concentration will be implemented in the Raspberry Pi to make calculations on the concentration level of the user. Based on the level of concentration, different music, regarding the bpm, will be played to increase or maintain the concentration level.

4.2.3 Final concept

During the iteration of the design thinking process, several factors such as technical difficulties and time limitations of the research were considered. A trade-off of the needs of the users and also a trade-off of the aforementioned factors were done to realise the project. Through this process, it was decided to focus more on the processing of data, comparing the frequency bands activation, rather than focusing on the electrodes and electronics. The system consists of three parts as shown in Figure 16. Muse is connected to the mini computer, measures EEG and sends the data packet to the computer. The mini-computer receives the EEG data, records and processes the data, determines the concentration level, and changes the music when necessary. The final concept is described in detail in the following sectors.

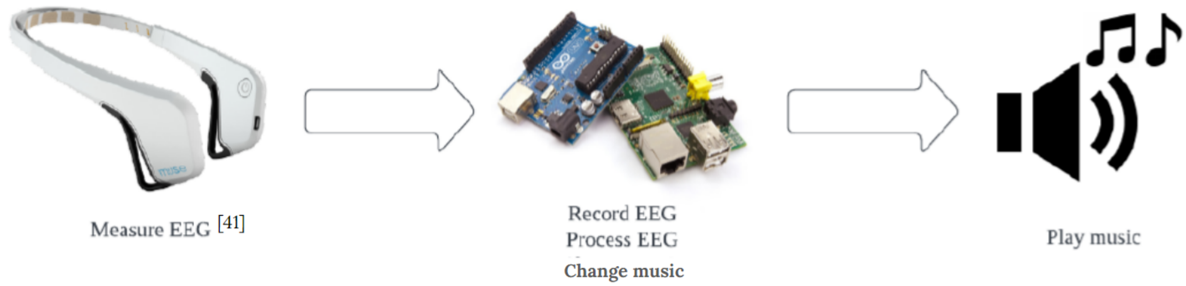


Figure 16: Final global concept of system

I. Data acquisition

Figure 17: Muse [41]

With the use of the public dataset used in the research [28] mentioned in the literature review, instead of developing the headphone with the electrodes, a commercially available EEG measuring device, the Muse will be used to record the EEG data. As addressed in the state-of-the-art in chapter 2.4.3, Muse is a headband with 4 EEG sensors that are attached to the forehead of the users.

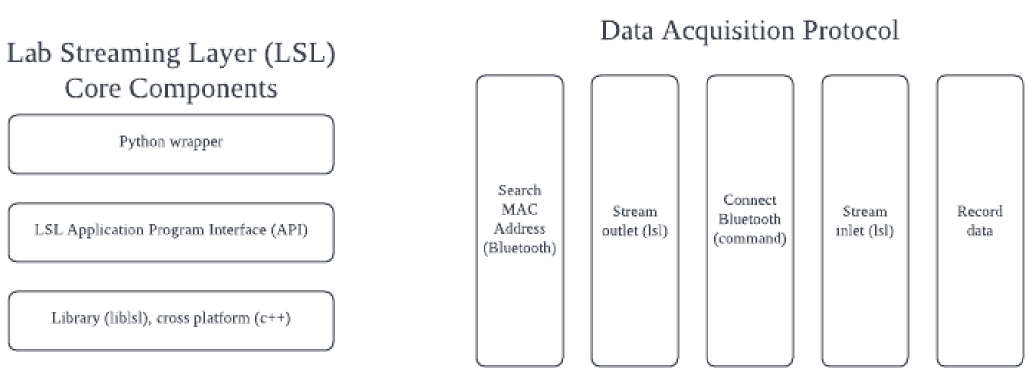


Figure 18: LSL and the data acquisition protocol

Raw data from the muse can be acquired by adopting Lab Streaming Layer (LSL) which allows streaming data from the muse to the computer. The core components of the LSL are shown in Figure 18. The PyLSL, Muse LSL, and UVic Muse are the existing Python libraries enabling communication between the muse and the computer. The protocol of the data acquisition is shown in Figure 18. The MAC address of the muse can be found by searching Bluetooth devices from the computer and by refining it by name that contains the string 'Muse'. By using the LSL library, the stream of the outlet can start, and the muse and the computer will be connected via Bluetooth to give commands to the muse device to send the required data. The EEG data can be retrieved by streaming inlet and then it can be recorded into CSV files.

II. Data processing

The *mne.preprocessing* and *mne.filter* submodules of the MNE library support the various approaches of preprocessing of the raw data with techniques such as maxwell filtering, filtering, and downsampling. The extraction of band power from the raw EEG data collected can be done with the use of the Python library, Magnetoencephalography and Electroencephalography in Python (MNE) [48]. The indexes that can be used to represent the concentration level of the users will be tested and implemented. Such indexes include engagement index and theta-to-beta index as discussed in more details in Chapter 2.

III. Feedback

As the headband is implemented instead of headphones, instead of streaming the music via headphones, a speaker will be implemented. The initial plan is to connect a Bluetooth speaker to the Raspberry Pi, however, if the Bluetooth connection is unstable due to the Bluetooth connection of Muse, the earphones will be connected to the audio jack or USB.

CHAPTER 5: Lo-fi Prototype

The final concept generated in the last chapter is further specified using a variety of prototyping methods such as user persona, storyboard, and low fidelity prototype in this chapter. Furthermore, the brief requirements defined in chapter 4.2 will be revised and discussed in more detail. The requirements mentioned in chapter 4.2 are below.

Must have requirements:

- Must not distract the students.
- Must keep students concentrated.
- Must provide real-time feedback to prevent confusion.
- Must take into account the neuro-physiological signals of the students.
- Must be non-intrusive.

Should have requirements:

- Should be easy to use and user-friendly.
- Should have multiple music options.

Could have requirements:

- Could be customisable.
- Could have abundant music options.
- Could have a dashboard where students can get an overview of their learning performance.

Each prototype method will be presented in sub-chapters, followed by the requirements resulting from the prototype.

5.1 User Persona

User persona is a fictional representation of the stakeholders, which can help the understanding of user needs and to gain insights to generate requirements of the product. A user persona of character Jane has been produced using tool *Miro* as illustrated in figure 19. The character is set to be bachelor students studying engineering with a high workload from the study.

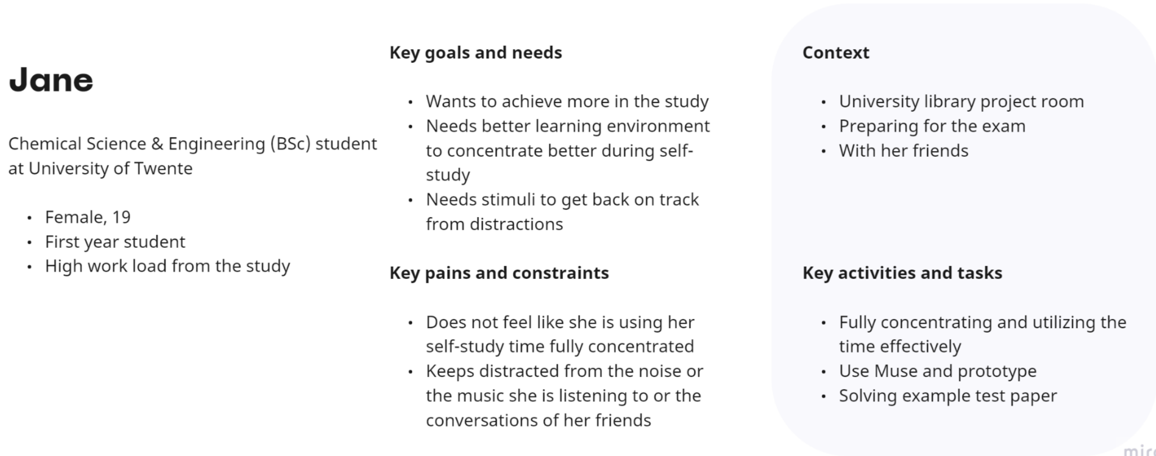


Figure 19: User Persona, student

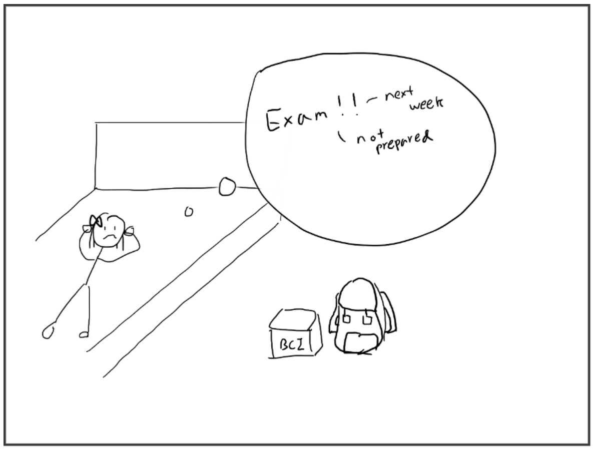
The additional requirements evaluated from the user persona in figure 19 are as follows.

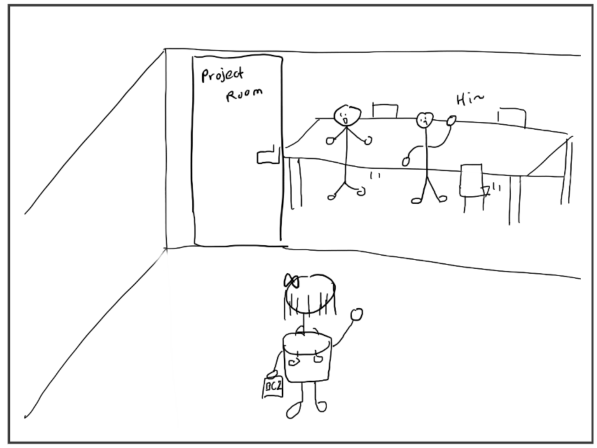
a. Providing stimuli to get back on track from distraction
b. The system and product should be usable in the library or project room
    i. Needs to be personal and not too loud
    ii. Compact in size

5.2 Storyboard

The user persona has identified key goals, needs, pains, constraints, activities and tasks and the brief context to deepen the empathy. However, the user persona lacks the step-by-step interaction between the user and the system and events in time-domain such as users' journey. By using storyboards, a visual narrative in time-domain can be acquired, which can detect the missing components of the system in order to create flawless interaction flow.

The storyboard includes 8 scenes, a day of Jane, the fictional character created in user persona, awakes in busy exam preparation week. Additional requirements will be presented after explaining each scene in more detail.





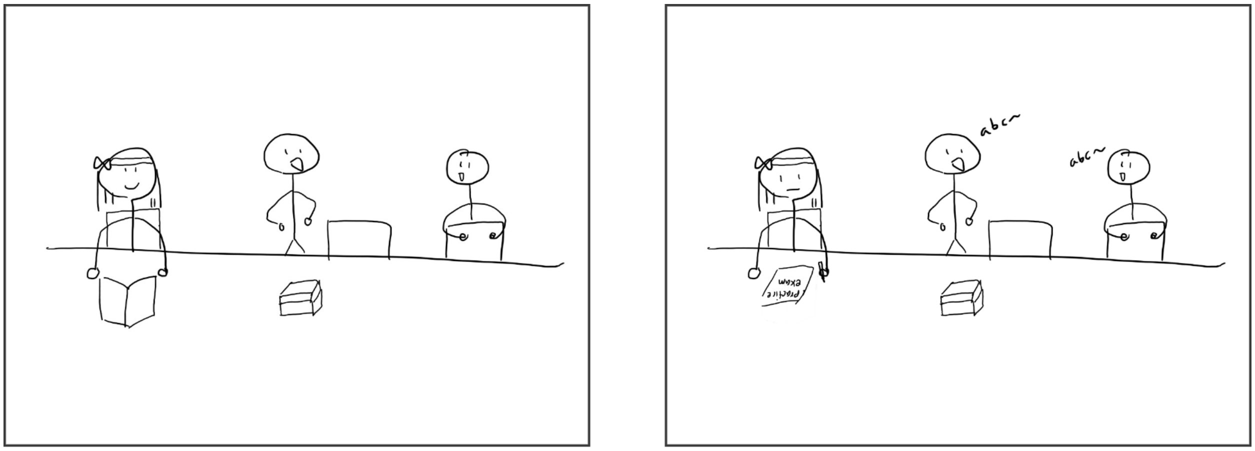
# 1	
Jane is feeling frustrated and overwhelmed as her exam is only a week away, and she does not believe that she is prepared for it, so she decides to go to the library with BCI device.	
Who	Jane
Where	Home
What	1. Frustrated for the exam next week 2. Goes to the library with BCI

# 2	
Jane arrives at the library, finds her friends in the project room and enters the project room.	
Who	Jane
Where	University library
What	1. Arrive at the library 2. Finds her friends 3. Enters the project room

miro

Figure 20: Storyboard scene 1 and 2

The first two scenes of the storyboard illustrate Jane going to the library in stress to prepare for the exam in the week after. She has to take the BCI device from home to the library. It indicates that the device must be portable and compact in size, the system should not be loud so that it can be used in public places, and it should not interfere with people inside the project room.



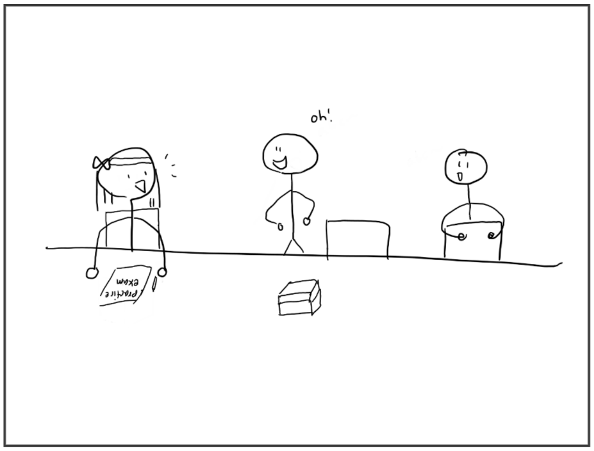
# 3	
Jane quickly prepare the study material and connect the BCI device while having conversation with friends.	
Who	Jane
Where	Project room in the library
What	1. Prepare the study material 2. Connect the BCI device

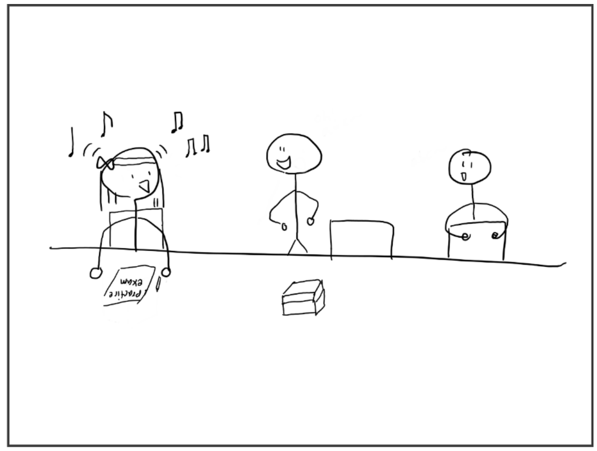
# 4	
Jane tries to solve the example question but her friends are still having conversion.	
Who	Jane
Where	Project room in the library
What	1. Solves the example question 2. Gets distracted

miro

Figure 21: Storyboard scene 3 and 4

The next two scenes, figure 21, illustrate the preparation step before starting the self-study and the early phase of the self- study. The device should be connected to the system, there must be some indication to the user that it has been connected and the system is ready to be used. Scene No.4 shows that there can be external distractions present during the self-study. In this scene, Jane is not yet fully distracted nor stopped from the learning process.



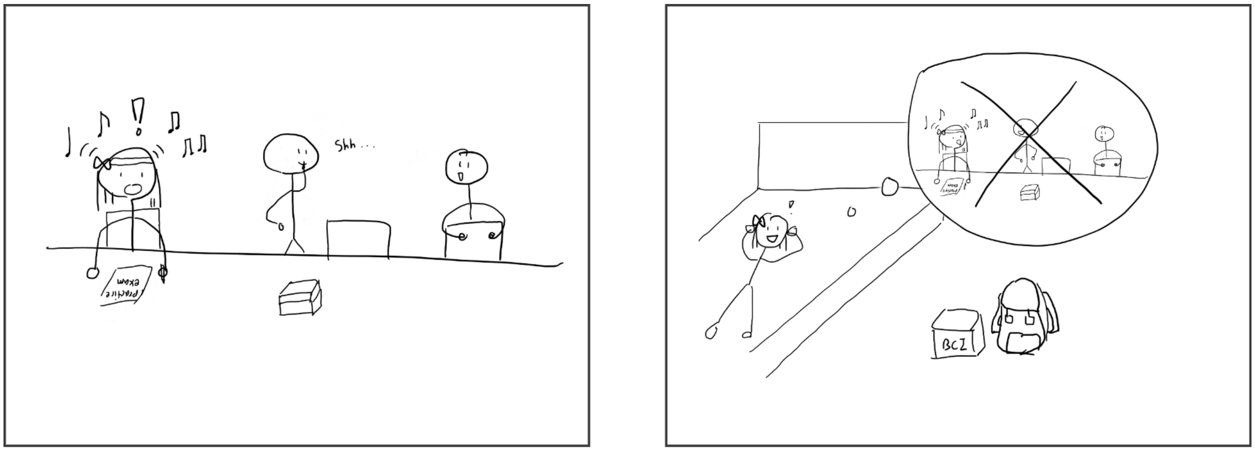


# 5	
Jane gets distracted and stops solving question.	
Who	Jane
Where	Project room in the library
What	1. Gets distracted 2. Stops solving question

# 6	
The system recognise that Jane has stopped studying, and notify her by changing the music.	
Who	Jane
Where	Project room in the library
What	1. Gets notification that she has stopped concentrating

Figure 22: Storyboard scene 5 and 6

Scene No.5 in figure 22 illustrates Jane getting distracted and stopping from studying and losing her focus in study. As a consequence, the system that recognised the loss of focus notifies Jane that she has lower concentration by changing the music. The requirement generated from these scenes is that the feedback from the system must be enough to catch the attention of distracted users.



# 7	
Jane realises that she got distracted and gets back to work.	
Who	Jane
Where	Project room in the library
What	1. Realises that she got distracted 2. Reconcentrates

# 8	
Jane checks her performance today and decide not to go inside the project room with her friends.	
Who	Jane
Where	Home
What	1. Checks her performance 2. Revise her study place and environment

Figure 23: Storyboard scene 7 and 8

In the next scene, scene No.7 in figure 23, Jane realises that she got distracted and she has to concentrate in her study. Eventually she concentrates and the peers also notice that they have been distracting her and stop the conversation. In the last scene, scene No.8 in figure 23, Jane checks her daily performance and revises her study environment. The suggested requirements from these scenes are support to reconcentrate and report on the daily performance based on the concentration.

5.3 Lo-fi Prototype

5.3.1 Lo-fi Prototype Version 1

I. Wireframe

As evaluated from the previous prototypes, supporting users to connect the BCI device to the system is in need. Furthermore, for the baseline correction purpose, there must be an indication of collection of data for the baseline correction, and when the system is ready to be used for feedback based on the concentration. Therefore, a wireframe was created using

Figma, which has the essential interface to connect the device to the system and to start/stop the collection and recording of EEG data.

Figure 24: Wireframe of settings page (search device and list the available device)

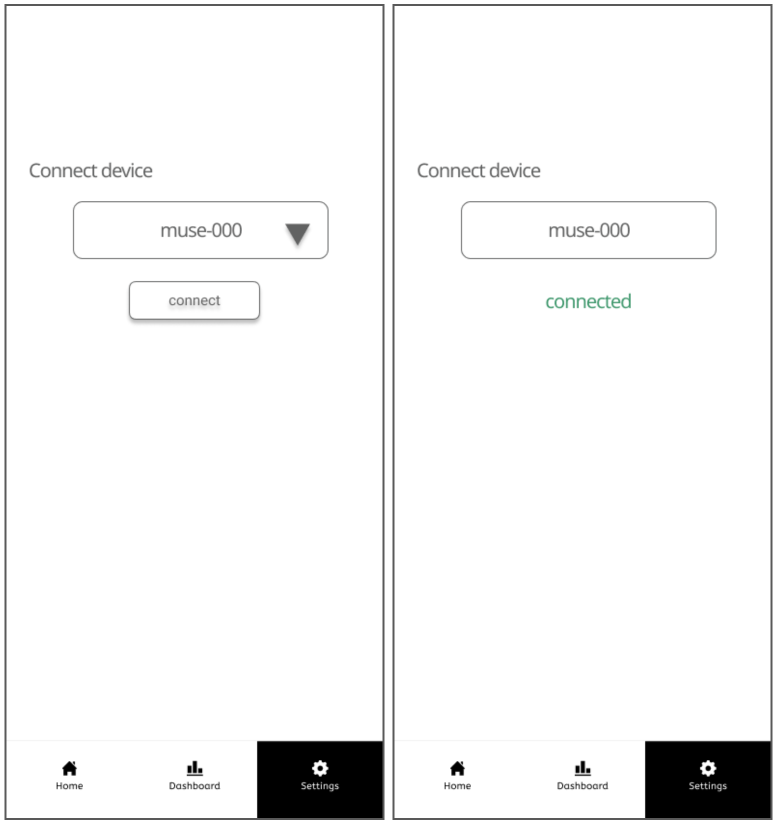


Figure 25: Wireframe of settings page (select device and notify on connection)

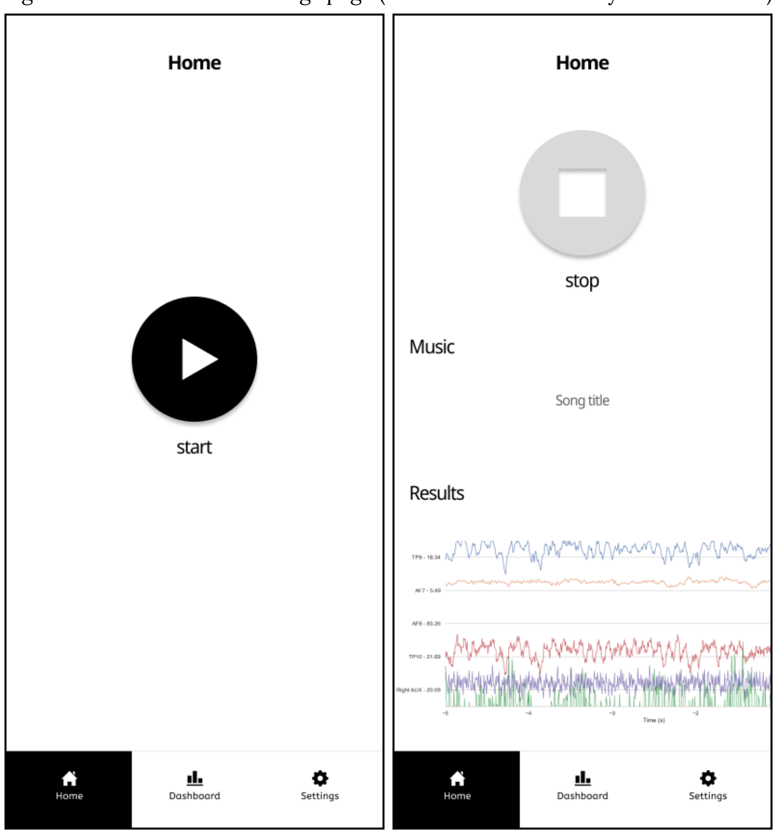


Figure 26: Wireframe of home page (start/stop recording and show real time results)

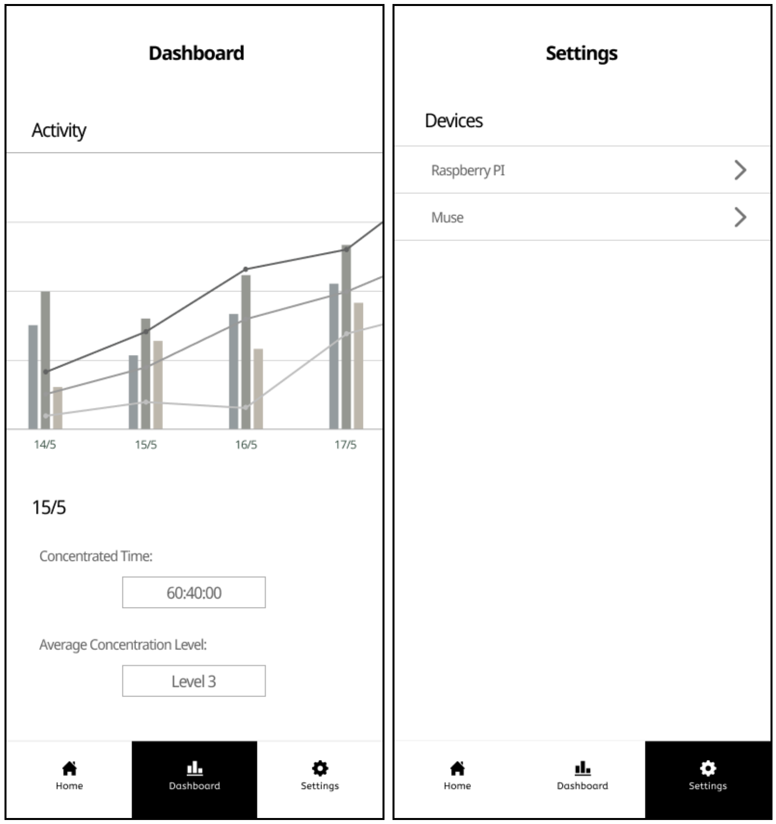


Figure 27: Wireframe of dashboard and settings page

The figure 24 and 25 represent the essential pages for connection of devices. Figure 26 contains the start/stop button for the user to do the concentration session. The music and real time results section are additional features that need to be tested if they are necessary. Figure 27 illustrates the dashboard and additional settings page that might be beneficial to the users.

II. Hardware

The Muse was used to give users the feelings of their brain waves being measured. The EEG signals were not being collected nor observed in the lo-fi prototype version 1 test. The laptop was to play different music to the user when their distractions were being observed.

III. Software

There was no software developed in the lo-fi prototype version 1. *Youtube Music* was used to play different music.

IV. Test

There were two separate tests for lo-fi prototype version 1 evaluation as the wireframe was developed later than the hardware version test.

a. Goal

i. Test whether the participants finds it difficult or unpleasant to use Muse (hardware, test 1)
ii. Test whether the changing the music disturbs the participants (software, test 1)
iii. Test whether the design of the wireframe is intuitive (wireframe, test 2)
iv. Test whether the real-time feedback and music sections helps users to concentrate (wireframe, test 2)

b. Methods
   I. Test 1
      A. (participants) Wear Muse
      B. (participants) Study own materials
      C. (researcher) Observe the participants and change the music as the participants seems to be distracted or their concentration level decreases by taking note if the participants stop working or roll their eyes or move their eyes
      D. (participants) Answer the questions
         1. Was the device comfortable to wear?
         2. Do you have any other remarks?
   II. Test 2
      A. (participants) Freely explore the designs
      B. (researcher) Observe the participants
      C. (participants) Answer the questions
         1. Was the design intuitive?
         2. Do you think the real-time section of the home page would help you to concentrate?

c. Results
Below is the summary of the results from the lo-fi version 1 user testing conducted with four participants and the full test results can be found in Appendix B.
   i. All participants were comfortable wearing Muse.
   ii. There was no sign of losing focus (wandering, stopping from writing/typing, starting conversations) when the background music (classical music, piano) changes.
   iii. When the music changes when they are distracted, they have noticed that it is telling them to get back on track
   iv. Other remarks:
      1. Smoother transitions in between the music would be nice
      2. Would like to check the overview/results

v. Design of the wireframe was intuitive for all participants
   1. It took some time to the participants to observe and understand the results section of the home page

vi. Real-time results section of the home page is distracting
   1. Participants takes about 1 minutes to understand what it is about with additional explanation from the researcher
   2. Participants constantly check on the results section

5.3.2 Lo-fi Prototype Version 2

In lo-fi prototype version 2, the actual EEG signals of the participants were measured and the theta-to-beta index as the representation of the concentration level was being observed. The feedback, turning on the music when the participants are distracted according to the EEG signals, was being implemented. No personal data including both EEG and demographic data was being collected.

I. Hardware

Figure 29: Hardware used for lo-fi prototype version 2 (muse [41], raspberry PI, earphones, and laptop)

II. Software

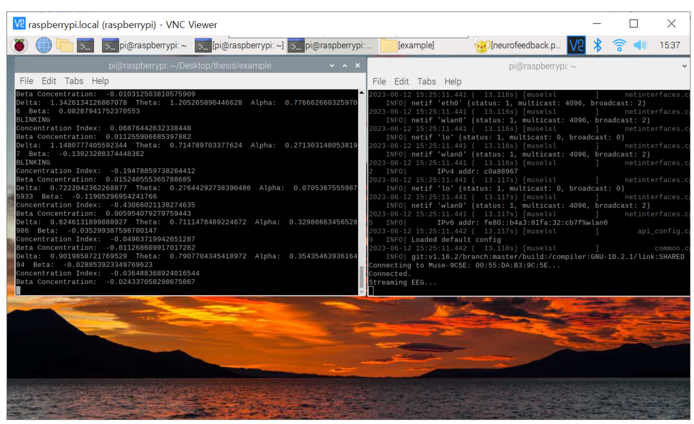


Figure 30: Screenshot of LSL stream and EEG feedback program

Python libraries MuseLSL[49] and PyGame[50] were used to develop the prototype. The MuseLSL was used to connect Muse to the Raspberry Pi and to calculate the index, while the Pygame was used to load, play and stop the music.

III. Test

   A. Goal

Test whether the index working to detect the loss of focus
Test changing the music accordingly to the index would help the participants to keep focus

B. Methods
    1. (researcher) Connect the Muse
    2. (participants) Wear Muse
    3. (researcher) Check the connection by visually inspecting the signals
    4. (researcher) Check the connection by asking participants to blink their eyes and observing the delta signals
    5. (participants) Start with the self-study
    6. (researcher) Check the index and observe the environment and participants. If the participant does not get distracted for a few minutes, interrupt the participant on purpose to check the feedback action.

C. Results

Below is the summary of the results from the lo-fi version 2 user testing conducted with four participants and the full test results can be found in Appendix C.

    1. While 5 participants started the user testing, one participant requested to stop the experiment as the sensor connection was bad and therefore the feedback did not match the concentration state. Another participant had good sensor connection and the concentration level was normal without the feedback, however, listening to the feedback gave her anxiety and pressure of “what if her concentration is not normal”. One participant mentioned that the feedback was not correct for once. (i.e. alarming the participant when fully concentrated)
    2. 2 participants suggested that the constant play of the music with change into white noise on loss of focus would help them to concentrate better while 1 participant mentioned that turning it to an alarm may help. Overally, participants were satisfied with the accuracy of the feedback.
    3. Theta-to-beta index worked most accurately, however, taking different frequency bands and comparing per the placement of electrodes may be considered in later research.

CHAPTER 6: Realisation

During realisation, the prototype for the project is developed in accordance with the requirements listed in the specialisation chapter. Firstly, a hi-fi prototype will be created and implemented. Then, with the data obtained through real-life testing, the prototype design and model will be evaluated through feedback and retrospect for any improvements.

6.1 Hi-fi Prototype

Figure 31: System architecture of hi-fi prototype

The system architecture of the hi-fi prototype is illustrated in the figure above. Muse collects the data, Raspberry Pi processes data and calculates the theta-to-beta index to turn on the music when the user is being distracted. The music will turn off as the user regains the concentration which will be determined by theta-to-beta index.

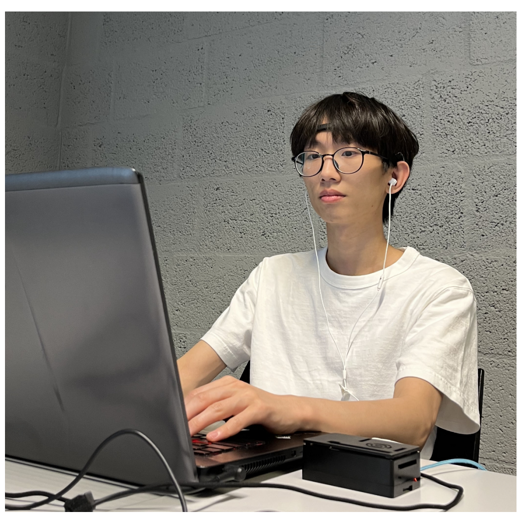


Figure 32: Photo of the prototype being used

Full setup of the hi-fi prototype can be found in Figure 32. The user will wear Muse and earphones that are connected to the Raspberry Pi and will be conducting self-regulated study.

6.2 Evaluation Plan

The evaluation of the hi-fi prototype will be placed in the project room in the Vrijhof building. Eight participants will be recruited for the evaluation, and they may come individually and stay in the room only with the research, or participate as peers and stay in the same room to give the reality of the learning environment. Each session will last 50 minutes.

6.2.1 Methods

5 mins	Introduction to the graduation project, signing informed consent, answering demographic questions	
8 mins	Connecting Muse and preparing the system	
1 min	Record and observe index of distracted state	
1 min	Record and observe index of concentrated state	
5 mins	session 1	self-study with the feedback
5 mins	session 2	self-study without the feedback
5 mins	session 3	self-study with the feedback
5 mins	session 4	self-study without the feedback
5 mins	session 5	self-study with the feedback
5 mins	session 6	self-study without the feedback
5 mins	Questionnaire and closing	

Table 4: Evaluation methods with time

6.2.2 Evaluation

From the EEG data recorded during the session, each interval will be analysed with the power spectral density and the multiple indexes such as theta-to-beta and engagement index. The performance of the participants with and without the feedback will be compared with the answer from the participants. The rest of the questionnaire is to investigate the improvement plan.

6.3 Results

While the full hi-fi prototype evaluation results of the first three participants can be found in Appendix F, the results showed the limitation of the evaluation method as well as the room for improvement of the accuracy of the timing of the feedback and the type of the feedback. Given the freedom of working on own materials, it was hard for the research to compare between the participants. During the experiment, all three participants were staying in the same project room in the library, however, the participants tended to be too aware of the experiments and the behaviours were abnormal, such as not talking to each other during the experiment while in between the sessions they were freely chatting with each other. Also the demographic questions being asked at the beginning of the experiments were meaningless in evaluation. Therefore, the improvement of the hi-fi prototype and conduction of the new evaluation method were essential.

CHAPTER 7: Realisation Iteration

During the realisation iteration, hi-fi prototype was improved with better signal processing and the new concrete evaluation plan was developed. The baselining to remove the drift of the signals were applied as highpass filter at 0.1 Hz [51]. To reject the artefact, signals containing absolute value above 200µV were removed [52]. The power spectral density was replaced with multitaper methods, for better performance against the noise [53].

7.1 Improved Hi-fi Prototype

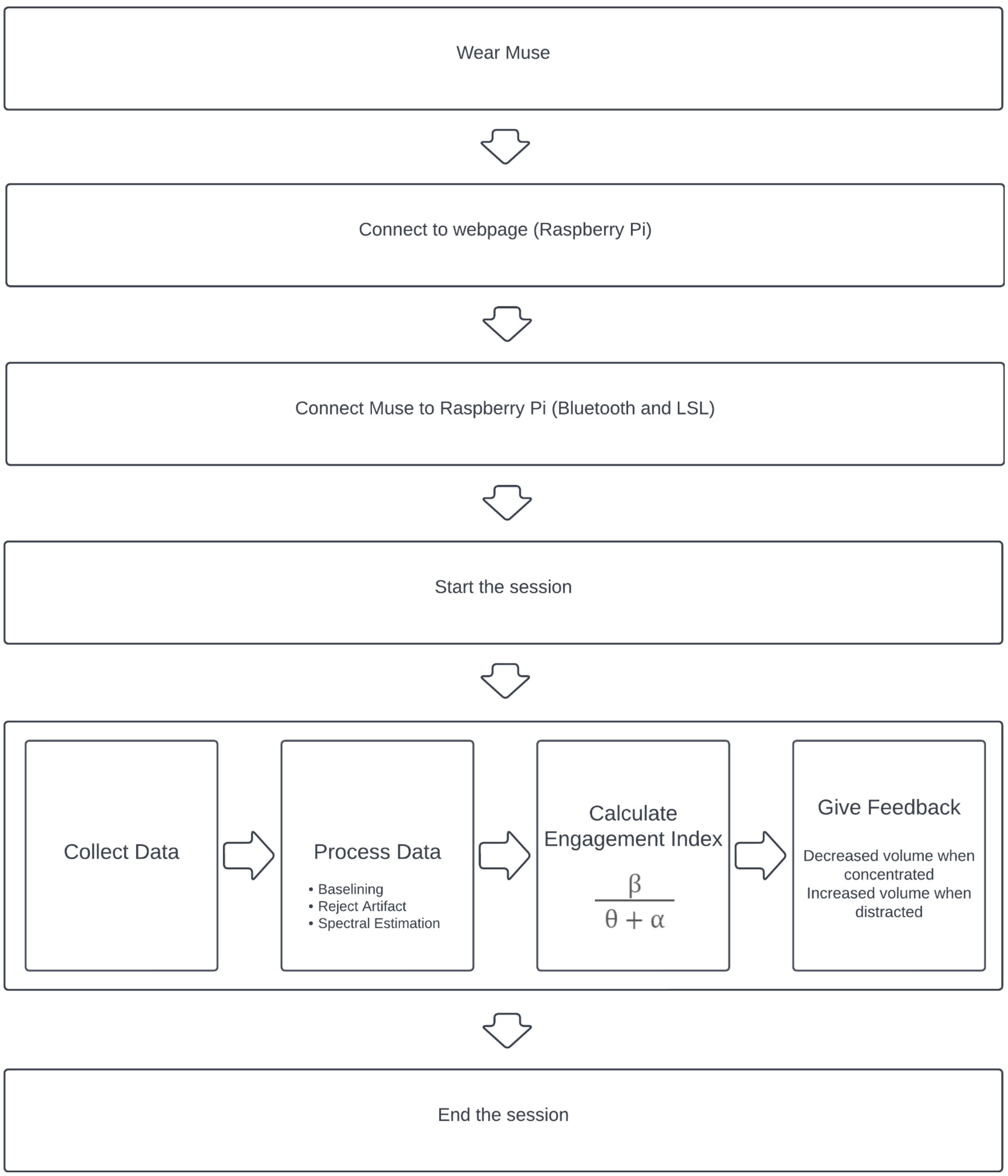


Figure 33: Use cycle of improved hi-fi prototype

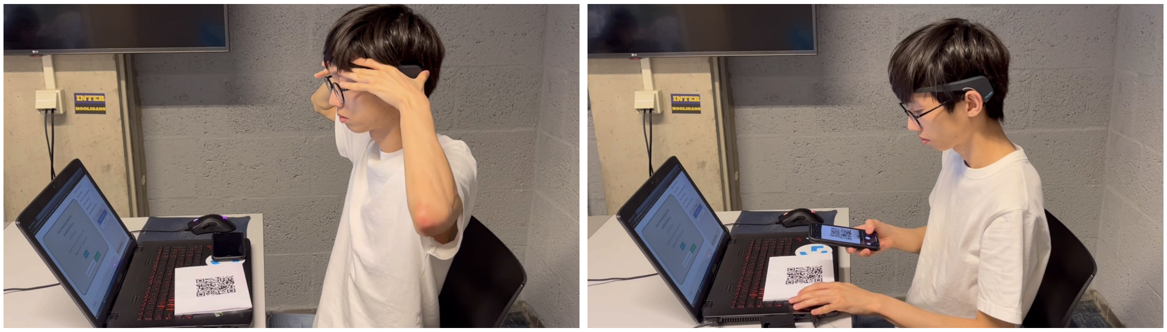


Figure 34: Step-by-step photo of the use of hi-fi prototype - wearing Muse and redirect to the webpage

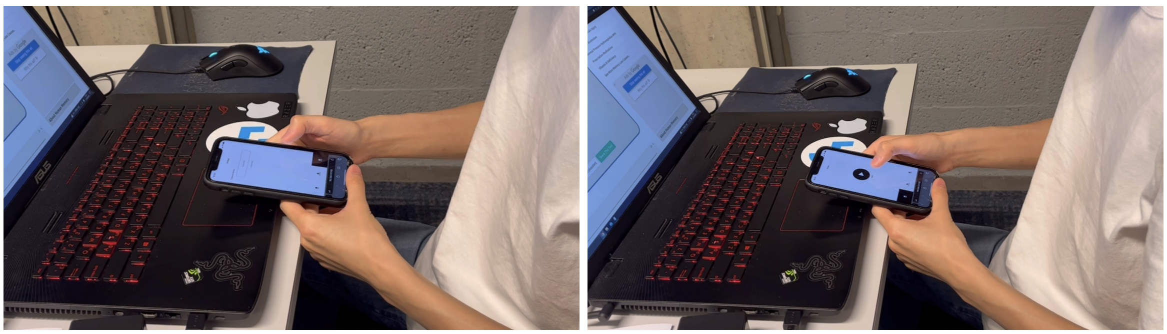


Figure 35: Step-by-step photo of the use of hi-fi prototype -connect Muse and start the session

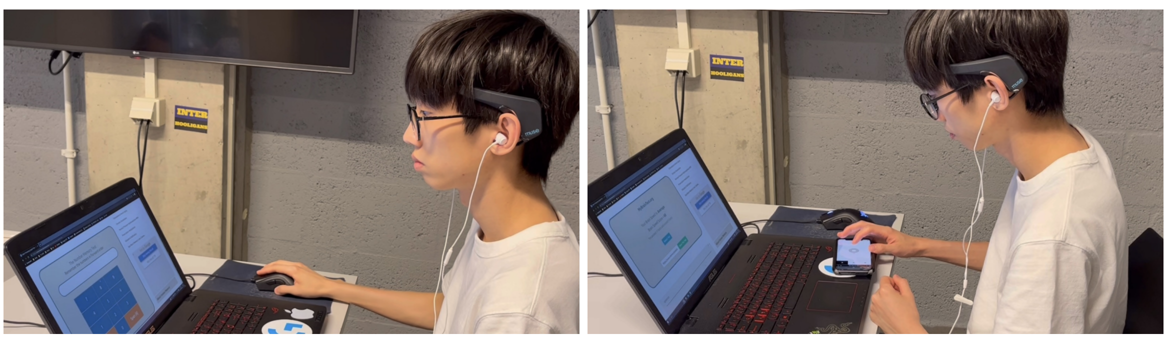


Figure 36: Step-by-step photo of the use of hi-fi prototype -connect Muse and start the session

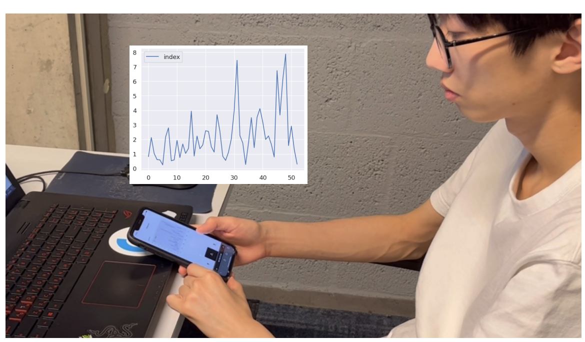


Figure 37: Step-by-step photo of the use of hi-fi prototype - check engagement index over time for the session

The improved design and system architecture can be found in Figure 36. As mentioned, the data processing was further developed to include baselining, rejecting artefacts for increased accuracy of the index. As the process of data is expected to be more reliable, alpha bands became usable, therefore the theta-to-beta index was replaced by engagement index for increased accuracy of the feedback.

The step-by-step usage of the prototype is illustrated in Figure 34 - 37. As shown in according figures, the cycle in Figure 36 has been realised.

7.2 Improved Evaluation Plan

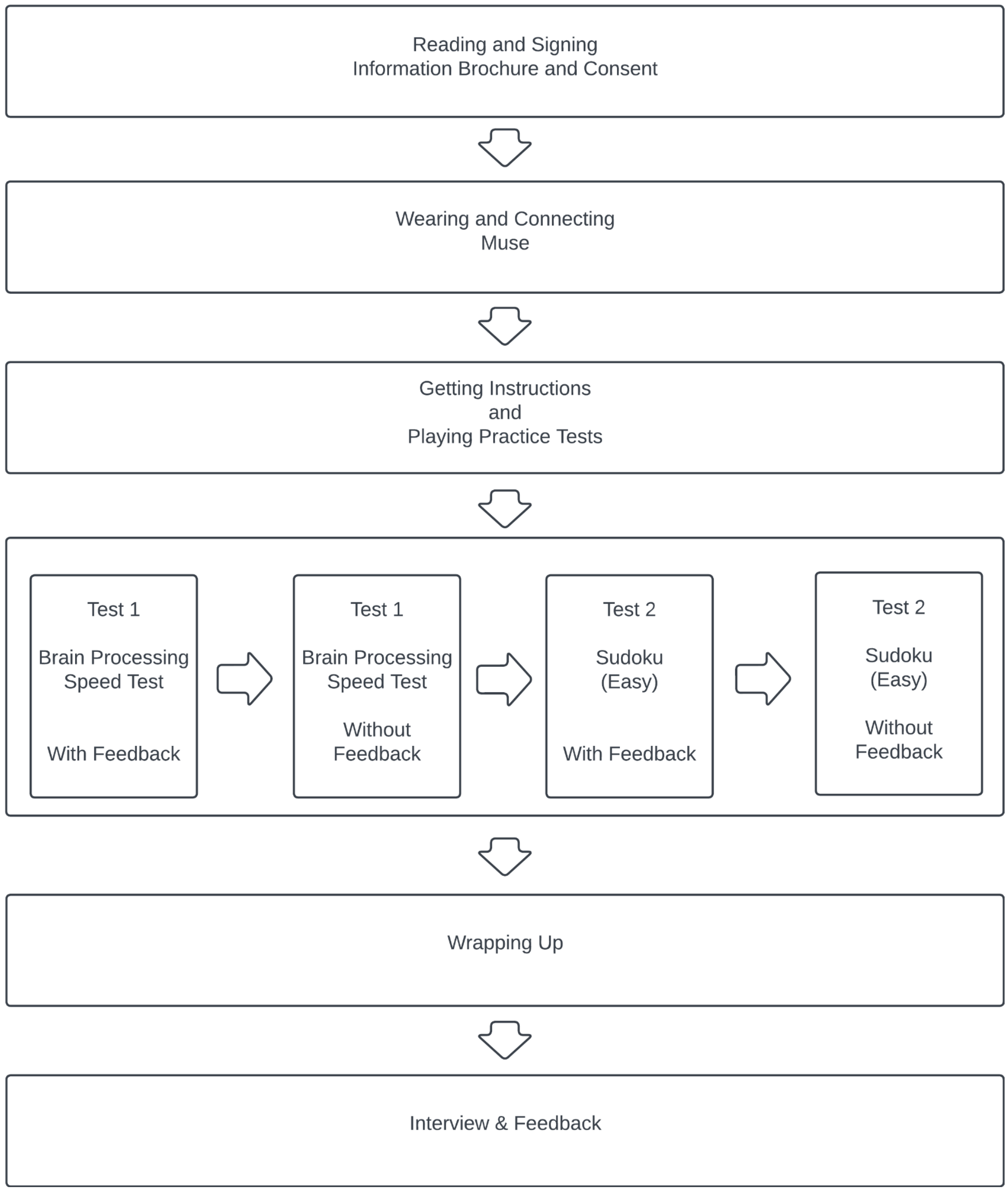


Figure 38: Improved evaluation plan

The improved evaluation plan as illustrated in Figure 38, consists of two types of tests. The first test is the brain processing speed test including 8 tasks where the participant repeats random 4-digits to 6-digits numbers that were being shown both forward and reversed order, and repeat the location of the four to six objects in 4 x 4 grid in both forward and reversed order []. The second test is solving a well-known puzzle called Sudoku, where the number from 1 to 9 must be in every row, column and 3 x 3 grid without overwrapping in a 9 x 9 grid. The second test was conducted via Sukoku.com []. Even though the tests do not perfectly reflect the self-regulated study environment it is expected to give comparable results. Connection of the Muse and starting/ending each session will be done by researchers to minimise the burden and confusion of the participants.

CHAPTER 8: Evaluation

The final prototype was tested with five main stakeholders. As planned in the previous chapter, each participant was given the instructions and opportunity to go through the practice tests to reduce the biassed results created from the order of the tests. The full results of the evaluation can be found in Appendix G. The feedback from the participants acquired from the semi-structured interviews were analysed in below figures.

Figure 39: Word cloud based on the feedback of the participants

As shown in Figure 39, the most frequent feedback received from the participants was uncomfortable usability of Muse. It was reported that it is too tight leading to pain near ears and leaving marks on forehead. The other most frequent feedback was that the timing of the feedback was accurate and helpful. The breakdowns of each component are in the pie charts below.

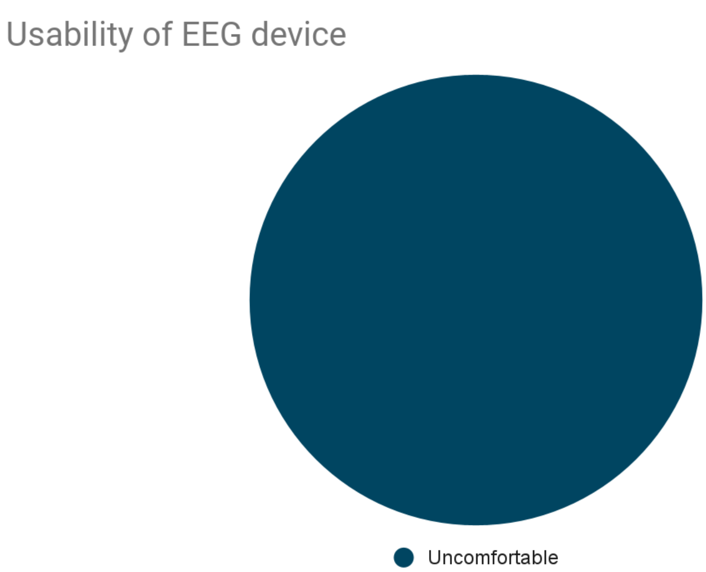


Figure 40: Pie chart based on the feedback of the participants on the usability of EEG device

As shown in Figure 40, all of the participants reported that they had an unpleasant experience with Muse. It was mostly due to the tight connection between the device and the skin of the users, leading to tension at the back of the ears.

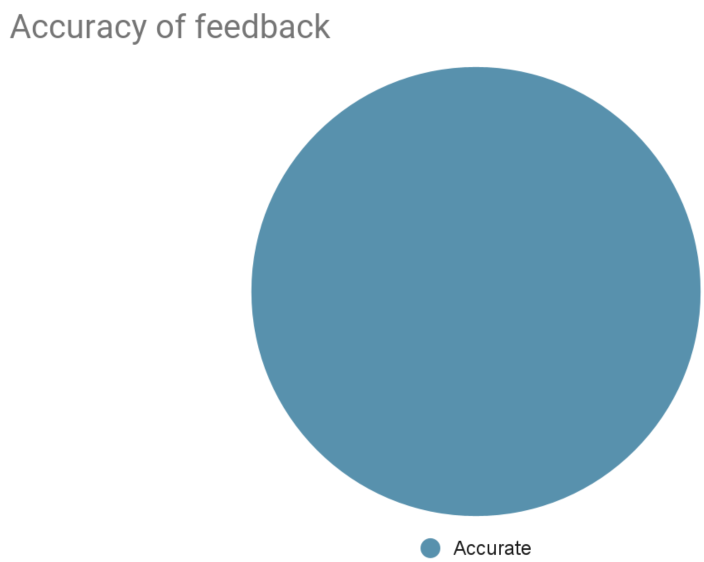


Figure 41: Pie chart based on the feedback of the participants on the accuracy of feedback

As shown in Figure 41, all the participants answered that the timing of the feedback was accurate, meaning that the volume of the music decreased as they were engaged in the test and the volume increased as they got distracted or lost focus.

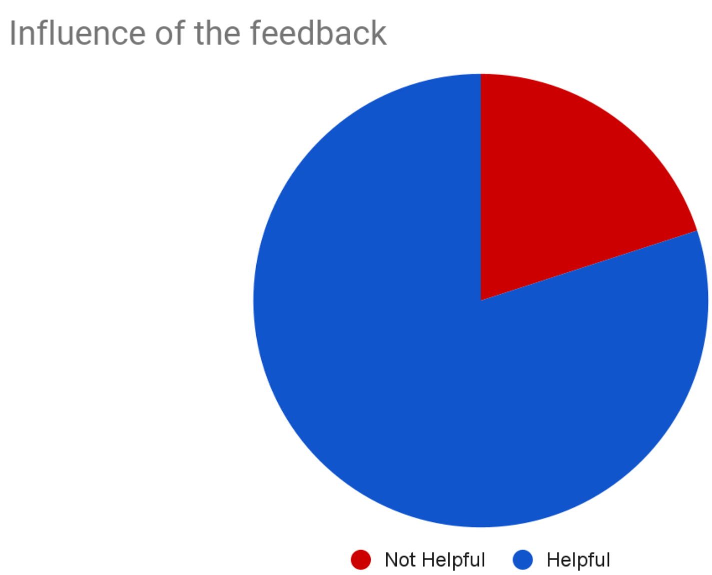


Figure 42: Pie chart based on the feedback of the participants on the influence of the feedback

As shown in Figure 42, four participants indicated that the feedback had influence on the performance and concentration, however, one participant indicated that the feedback was not helpful as the participant simply does not care about the audio while concentrating.

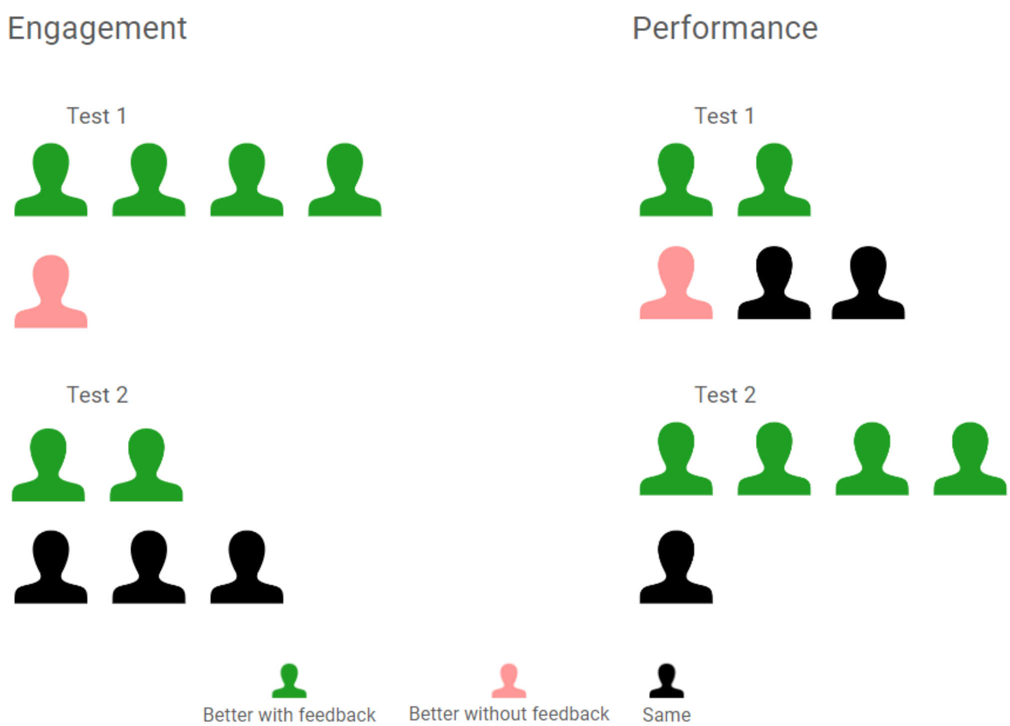


Figure 43: Pictogram representing the engagement and performance difference based on the feedback

The trendline of each session was observed to check the increased engagement over time of the participant. The participants with increased engagement over time with feedback are indicated as green pictograms in Figure 43. The participants with decreased performance with feedback are marked as pink and the participants with the same results were indicated with black. The performance of the participants were measured firstly with the results of the tests. The time duration and speed of resolving were looked at when the results of both circumstances are the same.

As the results provided, the overall engagement of the participants were increased with the feedback. The performance of a relatively long-term test, regarding that test 1 consists of a maximum of 3 minutes while test 2 had a minimum of 2 minutes 30 seconds up to 10 minutes, seems to have been positively influenced by the feedback. The results also show that the participant who answered that the feedback had no influence during the interview actually was not influenced by feedback.

CHAPTER 9: Discussion and Conclusion

9.1 Discussion

The results of the evaluation on the last chapter shows the potential in the project that it can improve the self-regulated learning experience of the students. The results show that giving feedback, changing the volume of the music depending on the engagement index of the students, lead to the improved engagement of the students while increasing relatively long-term performance of the students. However, the research has limitations in various approaches. Most importantly, the evaluation of the final prototype only consists of five participants which makes it difficult to conduct any statistical analysis, therefore, only assumptions can be made on the impact of the project. The test method is arguable for its relation with the self-regulated learning environment, while it was the best way for the evaluation under current conditions.

The other major consideration is on the usability of the EEG device. To acquire the meaningful signals from the EEG device, the tight contact of the device and the skin of the user is critical. However, many users complained about the pain of wearing the device, especially the ear pain.

The last consideration is the effectiveness of the feedback. Different auditory feedbacks were tested during the project and it showed the different needs of the users. Some may prefer non-intrusive feedback while others demand for stronger treatments. Furthermore, there is a need for further investigation on the types of the music that can effectively encourage the users to be focused. Therefore, there is a need for personalization of the feedback and further research and development.

9.2 Conclusion

To conclude, the research aimed at discovering the neuro-physiological computing systems that can be implemented to monitor the level of concentration and give real-time feedback in order to improve the self-regulated learning experience. The constructive feedback on the engagement index of the students, calculated based on the theta, beta, and alpha bands of the EEG signals were given to the users. To create the non-intrusive feedback system, the background music with reduced volume on engaged or concentrated states of the brain and increased volume on distracted, lowered engagement index, was adapted to the system. The evaluation of the system indicated increased engagement index and better performance of the majority of the participants while it is limited in small sample numbers.

CHAPTER 10: Future Work

The future research must be done on analysing the performance of the system with a bigger number of tested participants. With more user testing, statistical analysis can be done for better evaluation of the system. Furthermore, the different aspects of performance such as duration of concentration time, quality of concentration and the academic performance of the students. Test methods can also be developed to reflect more of the characteristics of long-term self-regulated learning.

To discover and include artefacts of EEG signals related to the self-regulated study, machine learning techniques mentioned in Chapter 2 can be worth studying in the future to give more insight to the users.

REFERENCES

[1] "Goal 4 | Department of Economic and Social Affairs," United Nations. [Online]. Available: https://sdgs.un.org/goals/goal4.

[2] S. Cassidy, "Self-regulated learning in higher education: Identifying key component processes," Studies in Higher Education, vol. 36, no. 8, pp. 989–1000, 2011.

[3] P. R. Pintrich, "The role of metacognitive knowledge in learning, teaching, and assessing," Theory Into Practice, vol. 41, no. 4, pp. 219–225, 2002.

[4] E. H. T. Shad, M. Molinas, and T. Ytterdal, "Impedance and Noise of Passive and Active Dry EEG Electrodes: A Review," IEEE Sensors Journal, vol. 20, no. 24, pp. 14565–14577, Dec. 2020, doi: 10.1109/jsen.2020.3012394.

[5] M. Abo-Zahhad, S. M. Ahmed, and S. N. Abbas, "A New EEG Acquisition Protocol for Biometric Identification Using Eye Blinking Signals," *IJISA*, vol. 7, no. 6, pp. 48-54, May. 2015, doi: 10.5815/ijisa.2015.06.05

[6] N. Jamil, A. N. Belkacem, S. Ouhbi and C. Guger, "Cognitive and Affective Brain–Computer Interfaces for Improving learning Strategies and Enhancing Student Capabilities: A Systematic Literature Review," in IEEE Access, vol. 9, pp. 134122-134147, 2021, doi: 10.1109/ACCESS.2021.3115263.

[7] P. A. Abhang, B. W. Gawali, and S. C. Mehrotra, "Chapter 2 - Technological Basics of EEG Recording and Operation of Apparatus", in *Introduction to EEG- and Speech-Based Emotion Recognition*, Academic Press, 2016, pp. 19-22.

[8] L. E. Ismail and W. Karwowski, "Applications of EEG indices for the quantification of human cognitive performance: A systematic review and bibliometric analysis", PLoS ONE, vol. 15, Dec 2020.

[9] "Electroencephalogram (EEG)," NHS. [Online]. Available: https://www.nhs.uk/conditions/electroencephalogram. Accessed: Jun. 12, 2023.

[10] K. E. Mathewson, T. R. Harrison, and S. a. D. Kizuk, "High and dry? Comparing active dry EEG electrodes to active and passive wet electrodes," Psychophysiology, vol. 54, no. 1, pp. 74–82, Jan. 2017, doi: 10.1111/psyp.12536.

[11] M. Teplan, "FUNDAMENTALS OF EEG MEASUREMENT," MEASUREMENT SCIENCE REVIEW, vol. 2, pp. 1–11, Jan. 2002, [Online]. Available: https://www.measurement.sk/2002/S2/Teplan.pdf

[12] G. Gargiulo et al., "A new EEG recording system for passive dry electrodes," Clinical Neurophysiology, vol. 121, no. 5, pp. 686–693, May 2010, doi: 10.1016/j.clinph.2009.12.025.

[13] A. R. Mota et al., "Development of a quasi-dry electrode for EEG recording," Sensors and Actuators A-physical, vol. 199, pp. 310–317, Sep. 2013, doi: 10.1016/j.sna.2013.06.013.

[14] G. Li, D. Zhang, S. Wang, and Y. Duan, "Novel passive ceramic based semi-dry electrodes for recording electroencephalography signals from the hairy scalp," Sensors and Actuators B-chemical, vol. 237, pp. 167–178, Dec. 2016, doi: 10.1016/j.snb.2016.06.045.

[15] G. Gargiulo, P. Bifulco, R. A. Calvo, M. Cesarelli, C. Jin, and A. Van Schaik, "A mobile EEG system with dry electrodes," Biomedical Circuits and Systems Conference, Nov. 2008, doi: 10.1109/biocas.2008.4696927.

[16] E. S. Kappenman and S. J. Luck, "The effects of electrode impedance on data quality and statistical significance in ERP recordings," *Psychophysiology*, 2010. doi:10.1111/j.1469-8986.2010.01009.x

[17] A. A. Pourahmad and A. Mahnam, “Evaluation of a low-cost and low-noise active dry electrode for long-term biopotential recording,” Journal of Medical Signals and Sensors, vol. 6, no. 4, p. 197, Oct. 2016, doi: 10.4103/2228-7477.195091.

[18] C. Fonseca et al., “A Novel Dry Active Electrode for EEG Recording,” IEEE Transactions on Biomedical Engineering, vol. 54, no. 1, pp. 162–165, Jan. 2007, doi: 10.1109/tbme.2006.884649.

[19] Y.-H. Chen et al., “Soft, Comfortable Polymer Dry Electrodes for High Quality ECG and EEG Recording,” Sensors, vol. 14, no. 12, pp. 23758–23780, Dec. 2014, doi: 10.3390/s141223758.

[20] Y. Huang, C.-Y. Wu, A. M. K. Wong, and B.-S. Lin, “Novel Active Comb-Shaped Dry Electrode for EEG Measurement in Hairy Site,” IEEE Transactions on Biomedical Engineering, vol. 62, no. 1, pp. 256–263, Jan. 2015, doi: 10.1109/tbme.2014.2347318.

[21] S.-C. Lee, Y. Shin, A. Kumar, K. Kim, and H.-N. Lee, “Two-Wired Active Spring-Loaded Dry Electrodes for EEG Measurements,” Sensors, vol. 19, no. 20, p. 4572, Oct. 2019, doi: 10.3390/s19204572.

[22] T. Sullivan, S. R. Deiss, and G. Cauwenberghs, “A Low-Noise, Non-Contact EEG/ECG Sensor,” Biomedical Circuits and Systems Conference, Nov. 2007, doi: 10.1109/biocas.2007.4463332.

[23] Y. M. Chi, Y.-T. Wang, Y. Wang, C. Maier, T.-P. Jung, and G. Cauwenberghs, “Dry and Noncontact EEG Sensors for Mobile Brain–Computer Interfaces,” IEEE Transactions on Neural Systems and Rehabilitation Engineering, vol. 20, no. 2, pp. 228–235, Mar. 2012, doi: 10.1109/tnsre.2011.2174652.

[24] Y. M. Chi and G. Cauwenberghs, “Wireless Non-contact EEG/ECG Electrodes for Body Sensor Networks,” Wearable and Implantable Body Sensor Networks, Jun. 2010, doi: 10.1109/bsn.2010.52.

[25] C. Athavipach, S. Pan-Ngum, and P. Israsena, “A Wearable In-Ear EEG Device for Emotion Monitoring,” Sensors, vol. 19, no. 18, p. 4014, Sep. 2019, doi: 10.3390/s19184014.

[26] D. Jeong and J. Jeong, “In-Ear EEG Based Attention State Classification Using Echo State Network,” Brain Sciences, vol. 10, no. 6, p. 321, May 2020, doi: 10.3390/brainsci10060321.

[27] J. LaRocco, M. D. Le, and D.-G. Paeng, “A Systemic Review of Available Low-Cost EEG Headsets Used for Drowsiness Detection,” Frontiers in Neuroinformatics, vol. 14, Oct. 2020, doi: 10.3389/fninf.2020.553352.

[28] A. Al-Nafjan and M. Aldayel, “Predict Students’ Attention in Online Learning Using EEG Data,” Sustainability, vol. 14, no. 11, p. 6553, May 2022, doi: 10.3390/su14116553.

[29] A. Apicella, P. Arpaia, M. Frosolone, G. Improta, N. Moccaldi, and A. Pollastro, “EEG-based measurement system for monitoring student engagement in learning 4.0,” Scientific Reports, vol. 12, no. 1, Apr. 2022, doi: 10.1038/s41598-022-09578-y.

[30] N.-H. Liu, C.-Y. Chiang, and H.-C. Chu, “Recognizing the Degree of Human Attention Using EEG Signals from Mobile Sensors,” Sensors, vol. 13, no. 8, pp. 10273–10286, Aug. 2013, doi: 10.3390/s130810273.

[31] K. Van Der Hiele et al., “EEG correlates in the spectrum of cognitive decline,” Clinical Neurophysiology, vol. 118, no. 9, pp. 1931–1939, Sep. 2007, doi: 10.1016/j.clinph.2007.05.070.

[32] P. Aricò, G. Borghini, G. Di Flumeri, A. Colosimo, S. Pozzi, and F. Babiloni, “A passive brain–computer interface application for the mental workload assessment on professional air traffic controllers during realistic

air traffic control tasks," in Progress in Brain Research, Elsevier BV, 2016, pp. 295–328. doi: 10.1016/bs.pbr.2016.04.021.

[33] B. Raufi and L. Longo, "An Evaluation of the EEG Alpha-to-Theta and Theta-to-Alpha Band Ratios as Indexes of Mental Workload," Frontiers in Neuroinformatics, vol. 16, May 2022, doi: 10.3389/fninf.2022.861967.

[34] F. Lotte, "A Tutorial on EEG Signal-processing Techniques for Mental-state Recognition in Brain–Computer Interfaces," in Springer eBooks, 2014, pp. 133–161. doi: 10.1007/978-1-4471-6584-2_7.

[35] S. Lim, M.-A. Yeo, and G. Yoon, "Comparison between Concentration and Immersion Based on EEG Analysis," *Sensors*, vol. 19, no. 7, p. 1669, Apr. 2019, doi: 10.3390/s19071669.

[36] T. McMahan, I. Parberry, and T. D. Parsons, "Evaluating Player Task Engagement and Arousal Using Electroencephalography," *Procedia Manufacturing*, vol. 3, pp. 2303–2310, Jan. 2015, doi: 10.1016/j.promfg.2015.07.376.

[37] "OpenBCI," OpenBCI. [Online]. Available: https://openbci.com. Accessed: Jun. 10, 2023.

[38] "Ultracortex "Mark IV" EEG Headset," OpenBCI Shop. [Online]. Available: https://shop.openbci.com/products/ultracortex-mark-iv. Accessed: Jun. 10, 2023.

[39] "Open Source Tools for Neuroscience." https://openbci.com/

[40] EMOTIV, "EMOTIV | Brain Data Measuring Hardware and Software Solutions," EMOTIV, Apr. 27, 2023. https://www.emotiv.com/

[41] "Muse: the brain sensing headband Store with Worldwide Shipping | MuseTM EEG-Powered Meditation & Sleep Headband," Muse: The Brain Sensing Headband, 2023. https://choosemuse.com/

[42] "Homepage," BrainBit. https://brainbit.com/

[43] "BrainLink by Macrotellect | Healthy Brainwaves for Everyone," BrainLink Official Website. https://o.macrotellect.com/

[44] Siang, T. Y., & DAM, R. (2018). Stages in the Design Thinking Process. The Interaction Design Foundation.

[45] "What is Empathize?", Interaction Design Foundation. https://www.interaction-design.org/literature/topics/empathize (accessed May. 8, 2023)

[46] "What is MoSCoW Prioritization?", Product Plan. [Online]. Available: https://www.productplan.com/glossary/moscow-prioritization.

[47] C. Guger, G. Krausz, B. Z. Allison, and G. Edlinger, "Comparison of Dry and Gel Based Electrodes for P300 Brain–Computer Interfaces," *Frontiers in Neuroscience*, vol. 6, Jan. 2012, doi: 10.3389/fnins.2012.00060.

[48] "Explore event-related dynamics for specific frequency bands — MNE 1.3.1 documentation," Apr. 24, 2023. https://mne.tools/stable/auto_examples/time_frequency/time_frequency_global_field_power.html

[49] Alexandrebarachant, "GitHub - alexandrebarachant/muse-lsl: Python script to stream EEG data from the muse 2016 headset," *GitHub*. https://github.com/alexandrebarachant/muse-lsl

[50] "Pygame Front Page — pygame v2.5.0 documentation." https://www.pygame.org/docs/

[51] “Order of processing steps — ERP Info,” *ERP Info*, Mar. 25, 2023. https://erpinfo.org/order-of-steps

[52] Alexandrebarachant, “EEG raw data from muse · Issue #11 · alexandrebarachant/muse-lsl,” *GitHub*. https://github.com/alexandrebarachant/muse-lsl/issues/11

[53] R. Vallat PhD, “Bandpower of an EEG signal.” https://raphaelvallat.com/bandpower.html

Appendix A - Lo-fi Prototype Version 1 User Testing Questionnaire

Test 1 Questions:

Question 1. Was the device comfortable to wear?
Question 2. Do you have any other remarks?

Test 2 Questions:

Question 1. Was the design intuitive?
Question 2. Do you think the real-time section of the home page would help you to concentrate?

Appendix B - Lo-fi Prototype Version 1 User Testing Results

Test 1 Results

	#1	#2	#3	#4
Q1	Yes, it was ok	Yes, but worried that it might look funny	Yes, but might have concern about the makeup	Yes
Q2	Nothing particular	Smooth transition between the music Wants to check the results	It felt strange to have music suddenly changes Some analysis on the concentration	Wants to check the results
Observation	Was distracted at the beginning but got back to concentration when the background music changed	Nothing peculiar	Was distracted twice but got back to concentration when the background music changed	Was bit loud outside but did not get distracted

Test 2 Results

	#1	#2	#3
Q1	Yes	Yes, but some graphs such in results and dashboard were hard to understand	Yes
Q2	No, it will be distracting if I can check it all the time	No, I think it is not necessary and as mentioned earlier, hard to know the meaning of the graph	No, but would like to see the results or summary at some point
Observation	Seemed bit confused	Spent longer time in	Constant check of

	with the dashboard page (Needed explanation) Constant check of results section	observing the dashboard page (Needed explanation)	results section

Appendix C - Lo-fi Prototype Version 2 User Testing Results

	#1	#2	#3	#4	#5
Observation	Coding for project Silence Threshold was increased on request of participant in the middle of session Index was abnormally increasing so stopped the session for two minutes Index increased as the participant get distracted (intentionally by research)	Reading materials on laptop, paper, and iPad AF8 electrode seemed not to be working Muse got disconnected due to Bluetooth error Participant requested to stop session	Index increased as the participant get distracted (intentionally by research) As the actual session starts, the participant seemed to be nervous as the feedback was given	Searching and reading materials on the internet Was interrupted by observer once and the index and feedback were working from the monitoring	Coding for project Was interrupted by observer once and the index and feedback were working from the monitoring
Feedback	The feedback was not given correctly in the middle and the threshold was not suitable at	It does not seem to work but it will be helpful if it works	Concentration goes to the music and lose concentration if the music suddenly stops	The feedback was not correct for few times but it was helpful to get notified Agree with	The feedback were seem to be correct but cannot really hear anything if fully concentrated anyway

	the beginning. The intent of system has potential to be really helpful Maybe have stronger alarming system			the previous participant that the white noise instead of the music might be more helpful	

Appendix D - Information Brochure and Consent Form

Consent Form for [Enhancing the Self-Regulated Learning Process Using a Brain-Computer Interface with Auditory Neurofeedback]

YOU WILL BE GIVEN A COPY OF THIS INFORMED CONSENT FORM

Dear participant,

In this brochure, you will find information about the research you have applied to participate in. The experiment will take place on _________, in ____________, University of Twente.

In the proposed research, titled 'Enhancing the Self-Regulated Learning Process Using a Brain-Computer Interface with Auditory Neurofeedback', auditory feedback will be given upon distraction or when a decrease in concentration of the user is detected, based on the measured electroencephalography (EEG) signals. This feedback is expected to enhance the learning process of the user by supporting them to remain concentrated and nudge the user to be back in focus. In order to evaluate the research, an experiment will be conducted to compare the user experience of self-regulated learning with and without the feedback. This research has been reviewed and approved by the BMS Ethics committee / domain Humanities & Social Sciences.

Firstly, the participants will be asked to sign the informed brochure and informed consent to take part in the research. Demographic questions will be asked to confirm the eligibility of the participants. The personal data collected will not be used to specify individuals.

Secondly, during the experiment, brain waves from 4 electrodes attached to the forehead and back of each ear will be collected using a commercially available brain sensing headband, "Muse". The equipment is not for a medical purpose and the collected data cannot be used to diagnose any neurological disorders (brain disease). The collected data will be locally stored in a mini-computer (Raspberry Pi) and the laptop of the researcher and will never be shared with any external parties. The data will be processed to determine the states of relaxation, neutral, distraction, and concentration. Both raw and processed data will not be used to specify individuals.

Thirdly, during the experiment, observation notes will be taken and photos of the experiment process may be taken that could be included in the report, which can be publicly accessed. The photos will not include the faces of the participants.

You can decide to stop the experiment at any point of the research and up to 24 hours thereafter without giving any reason nor having any consequences, and if so your data will be permanently deleted and will not be included in the research. Your data will be handled in a confidential manner with a guarantee of anonymity, and will never be disclosed to third parties without your permission.

The experiment lasts for a maximum of 1 (one) consecutive hour.

Please tick the appropriate boxes	**Yes**	**No**
Taking part in the study		
I have read and understood the study information dated [__/__/____], or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	□	□
I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	□	□
I understand that taking part in the study involves survey questionnaires, interviews, observations, and experiments, and that the information is captured by taking pictures, taking notes, and using a brain sensing headband.	□	□
Use of information in the study		
I understand that the information I provide will be used for evaluation of the project.	□	□
I consent that the EEG data and personal data that cannot identify me can be collected.	□	□

....

Name of participant *Signature* *Date*

Ari Lee

....

Name of researcher *Signature* *Date*

Study contact details for further information:

Ari Lee (a.lee@student.utwente.nl)

Contact Information for Questions about Your Rights as a Research Participant:

If you have any complaints about this research, please contact supervisor, dr. Mannes Poel (email: m.poel@utwente.nl)

If you have questions about your rights as a research participant, or wish to obtain information, ask questions, or discuss any concerns about this study with someone other than the researcher(s), please contact the Secretary of the Ethics Committee/domain Humanities & Social Sciences of the Faculty of Behavioural, Management and Social Sciences at the University of Twente by ethicscommittee-hss@utwente.nl.

Appendix E - Hi-fi Prototype Evaluation Questionnaire

Demographic Questions:

Question 1. What is your age?

Question 2. Which gender do you identify yourself with?

Question 3. How many times do you listen to music during self-study?

Question 4. Are you easily distracted during self-study?

Question 5. Is it difficult to get back on track once distracted?

Question 6. On a scale of 1 to 10, with 1 being extremely tired/sleepy/nervous and 10 being fully awake/relaxed/focused, how would you rate your current state in terms of being able to study effectively?

Question 7. For this experiment, what kind of 'self-study' are you going to proceed with?

Interview Questions:

Question 1. Were you both mentally and physically comfortable with the use of the device?

Question 2. Do you think the timing of the feedback was reasonable?

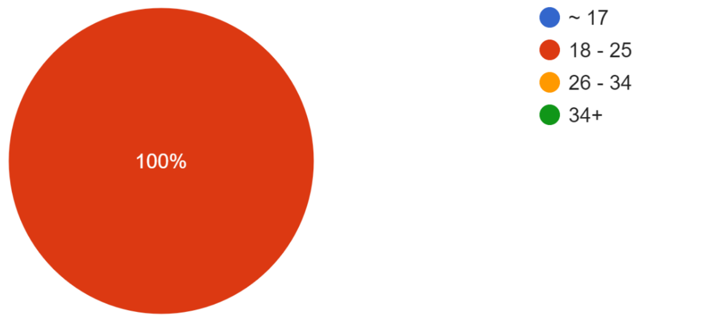
Question 3. Did the feedback help you to get back to focus?

Question 4. How was your learning performance during the session?

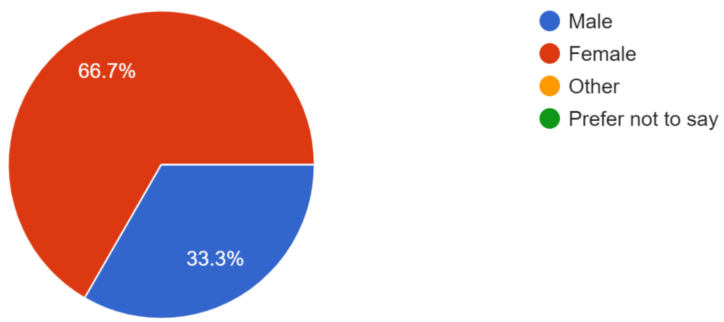
Question 5. Do you have any suggestions or remarks?

Appendix F - Hi-fi Prototype Evaluation Results

What is your age?
3 responses

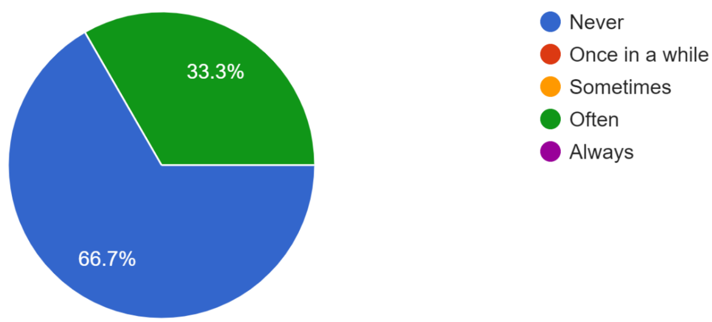


Which gender do you identify yourself with?
3 responses



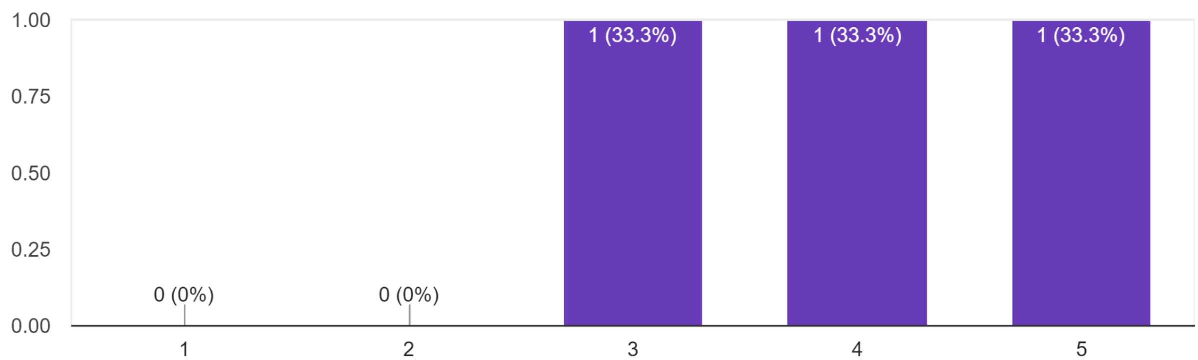
How many times do you listen to music during self-study

3 responses



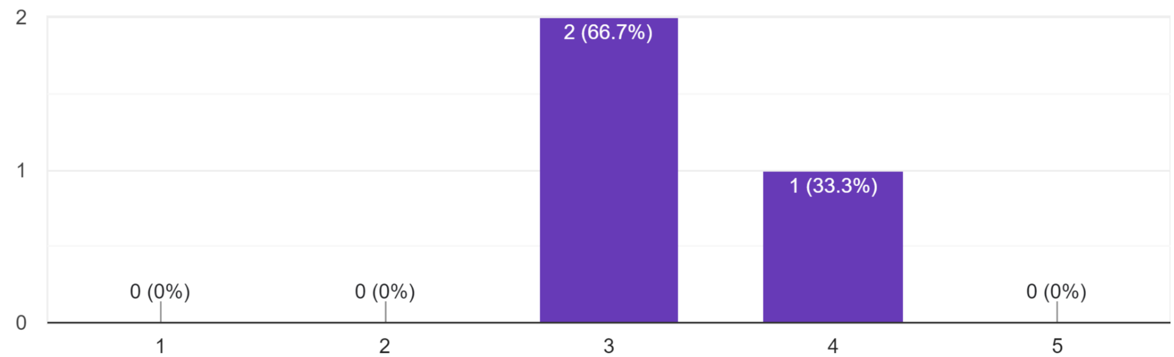
I am easily distracted during self-study

3 responses



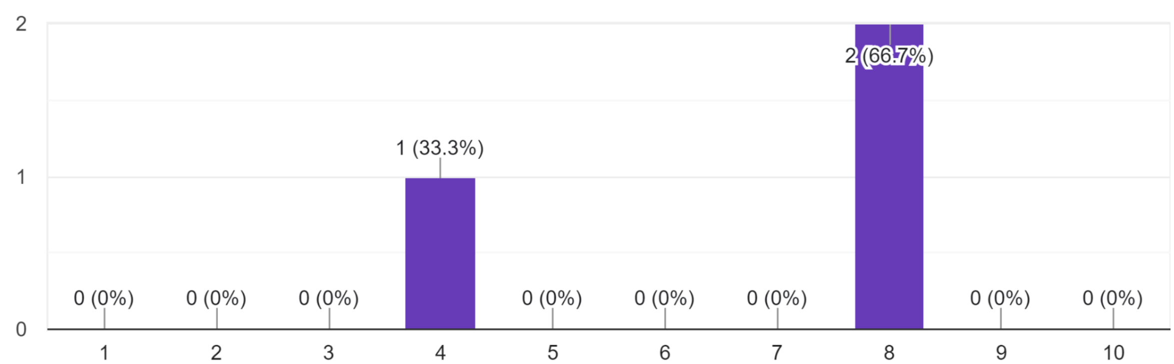
It is difficult to get back on track once distracted

3 responses

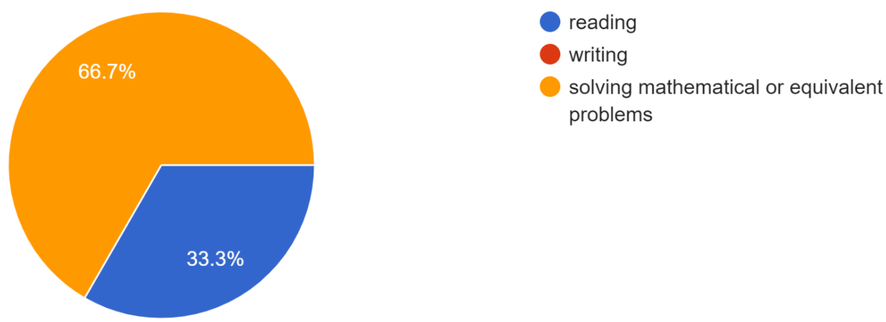


On a scale of 1 to 10, with 1 being extremely tired/sleepy/nervous and 10 being fully awake/relaxed/focused, how would you rate your curr...state in terms of being able to study effectively?

3 responses



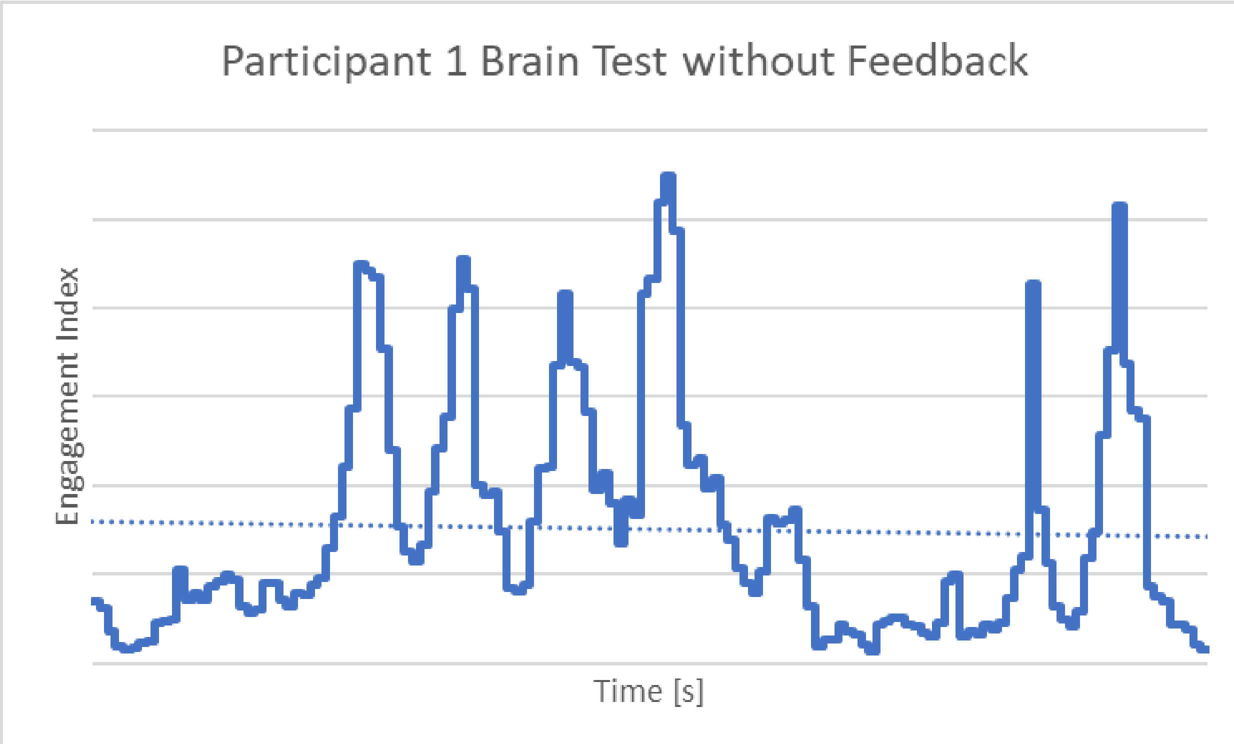
For this experiment, what kind of 'self-study' are you going to proceed?
3 responses

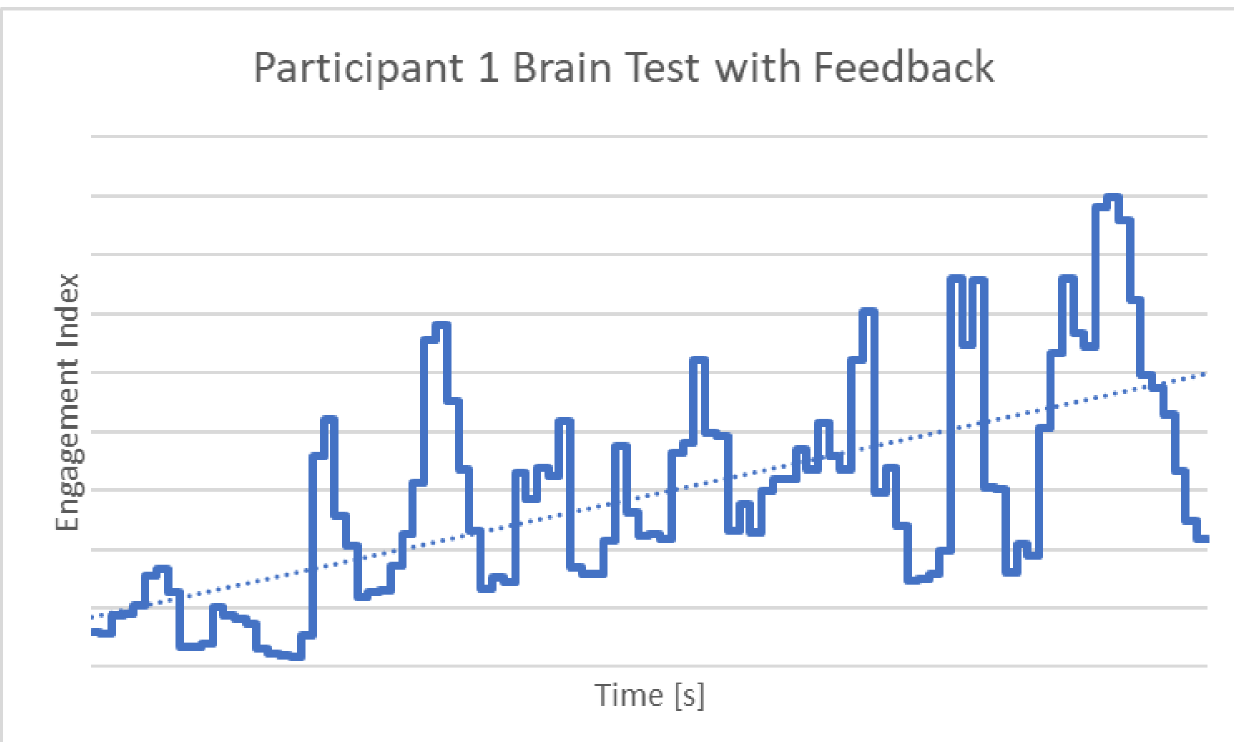


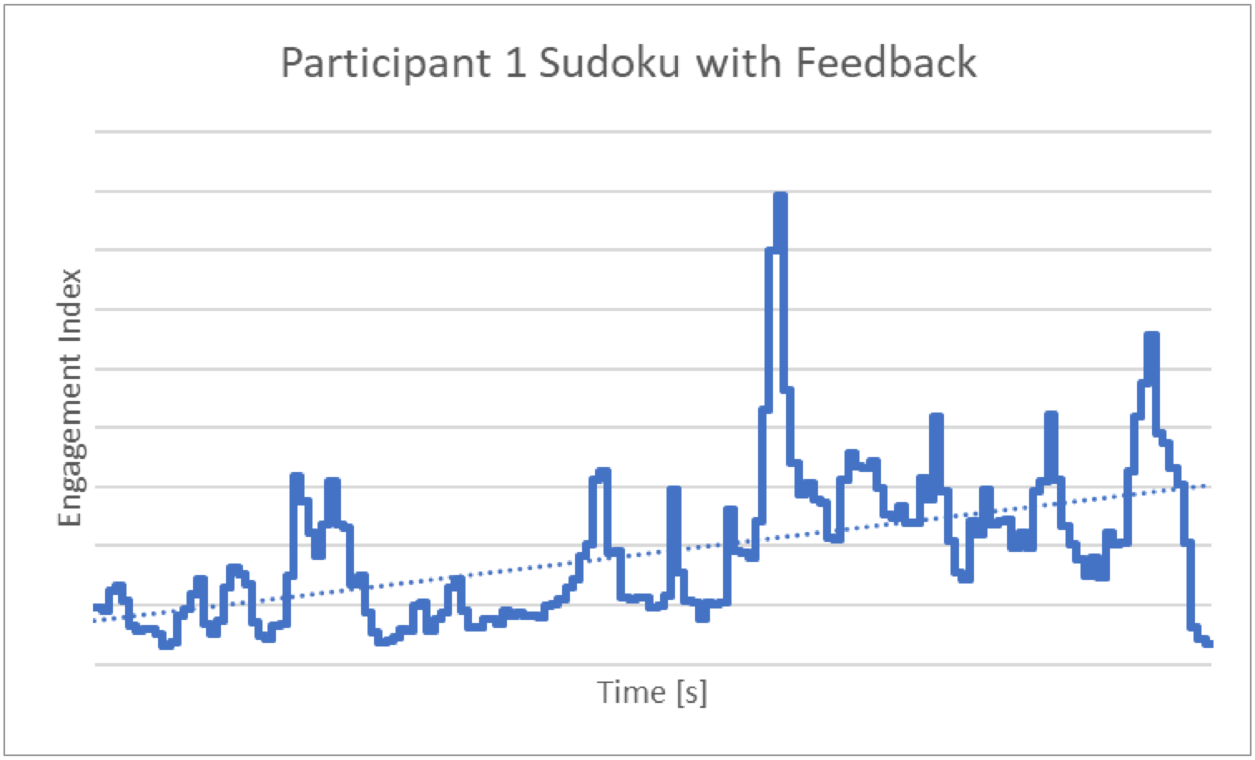
	#1	#2	#3
Q1	Ears hurt from Muse	Volume was too loud	Yes
Q2	Yes	Yes, but sometimes not	Yes
Q3	Once focused then yes	No	No, it is mostly the fact that it is an experiment and that the EEG is being recorded
Q4	It was good	Was reading book so not applicable	It was good, but sometimes the feedback was distracting
Q5	No	The feedback of turning on and off the music can be improved	The feedback of turning on and off the music is so distracting
Observation - Session 1	Medium noise from typing inside the room and the noise from the outside the room	Nothing peculiar	Nothing peculiar
Observation - Session 2	More noise from	Someone entered the	Nothing peculiar

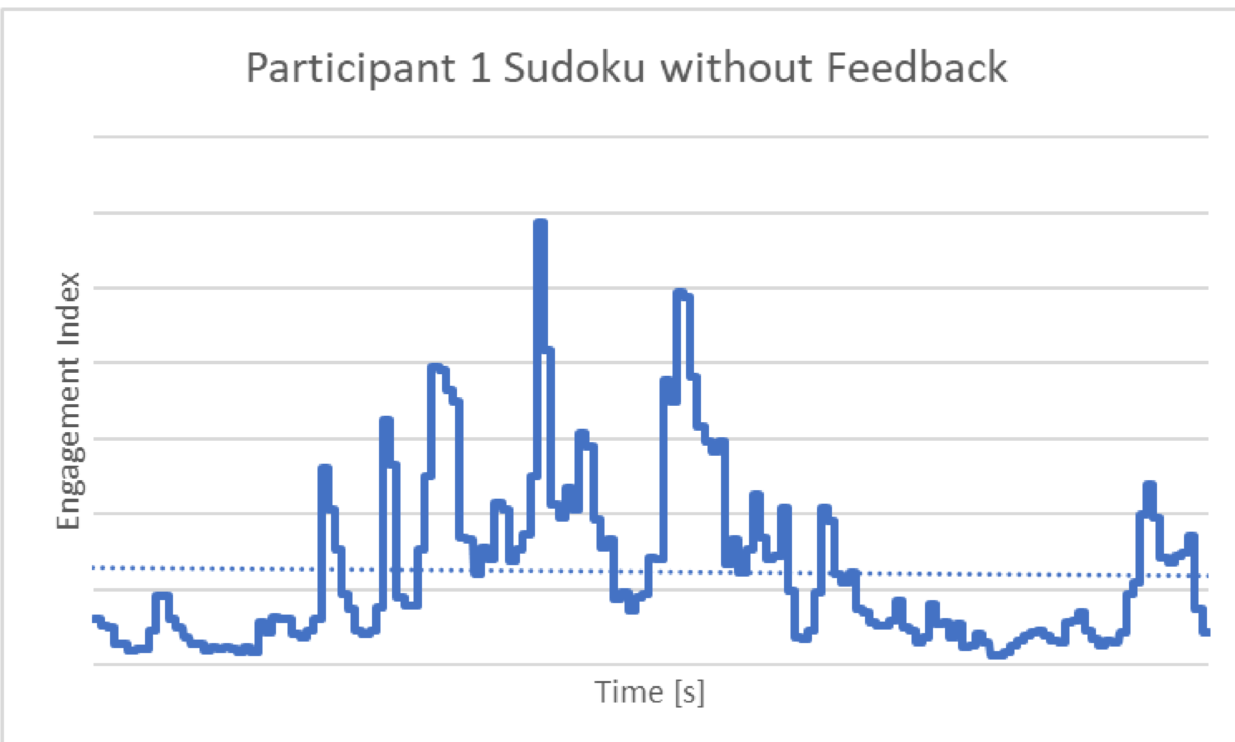
	outside	room and resulted in decreased index Continuous touch of the headband	
Observation - Session 3	Participant was talking to herself	Nothing peculiar	Nothing peculiar
Observation - Session 4	Less noise from outside Asked "what are you doing" to the other person in the room but eyes were still on the screen	Nothing peculiar	Nothing peculiar
Observation - Session 5	Nothing peculiar	Nothing peculiar	Nothing peculiar
Observation - Session 6	Nothing peculiar	Nothing peculiar	Nothing peculiar
Feedback	Barely got feedback	The experiment itself forced to focus rather than get affected by the feedback	Rather have constant music playing than turning on and off

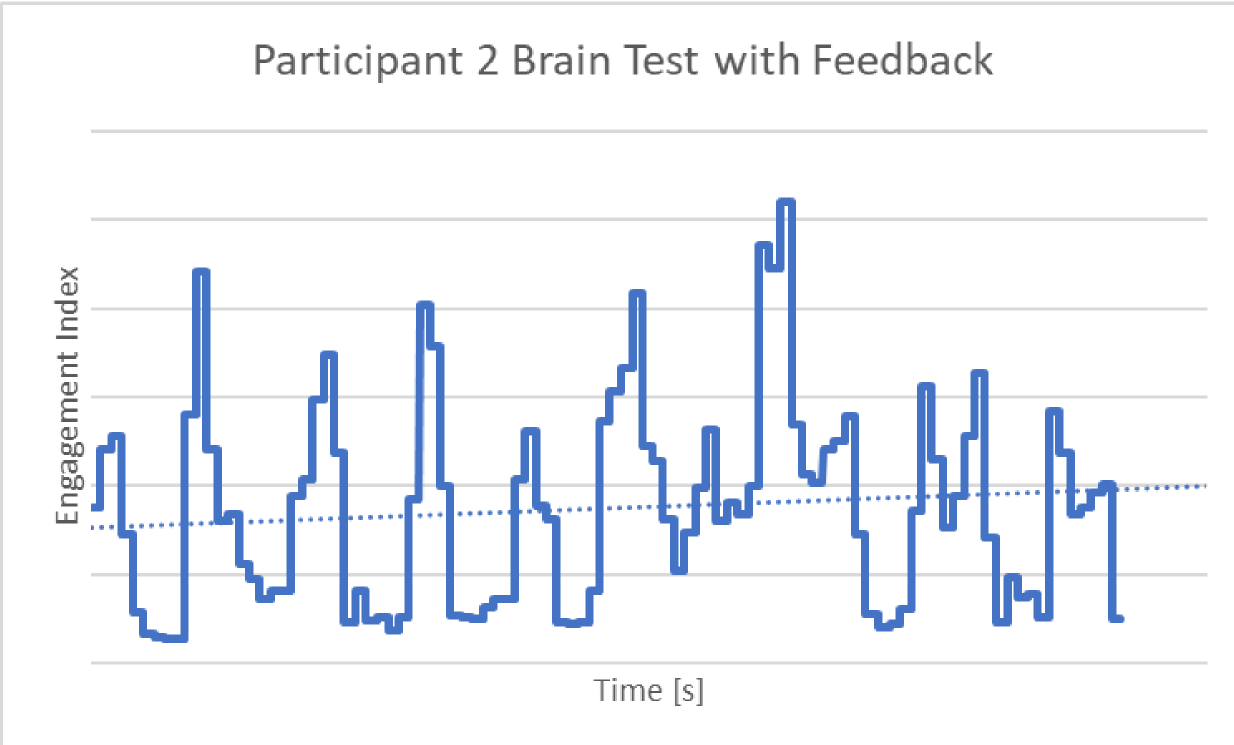
Appendix G - Revised Hi-fi Prototype Evaluation Results

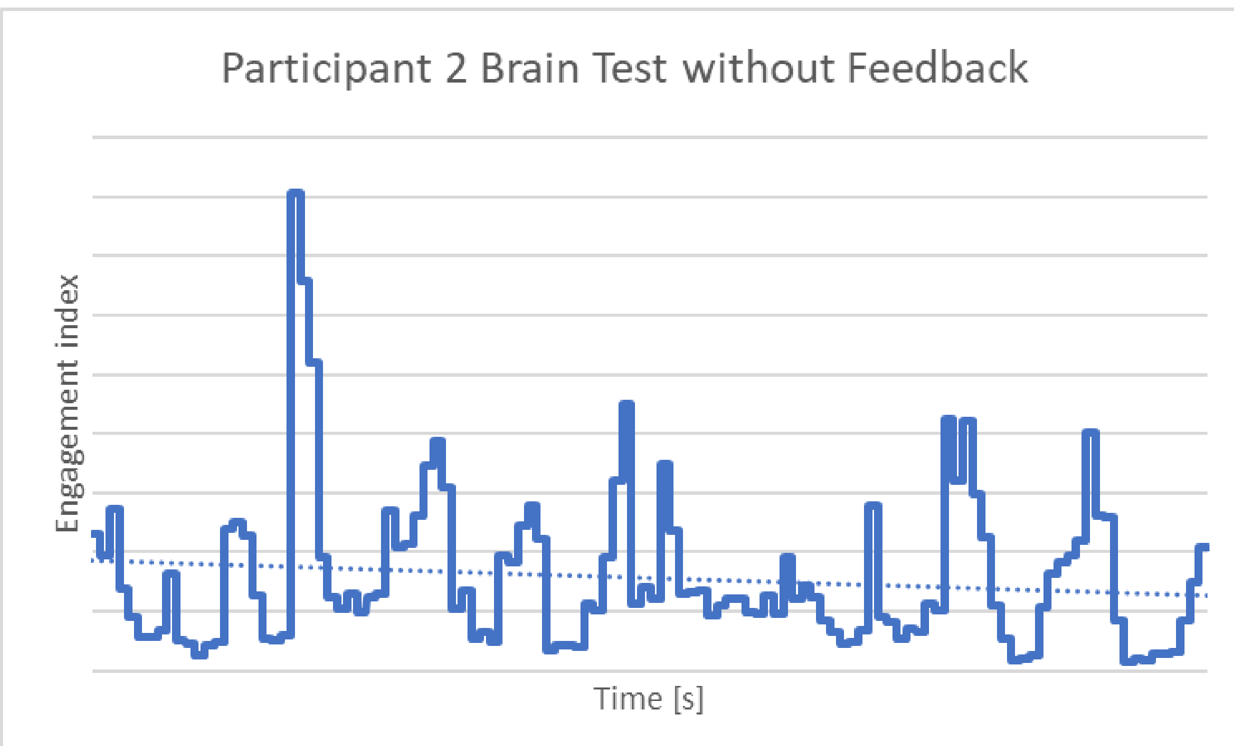


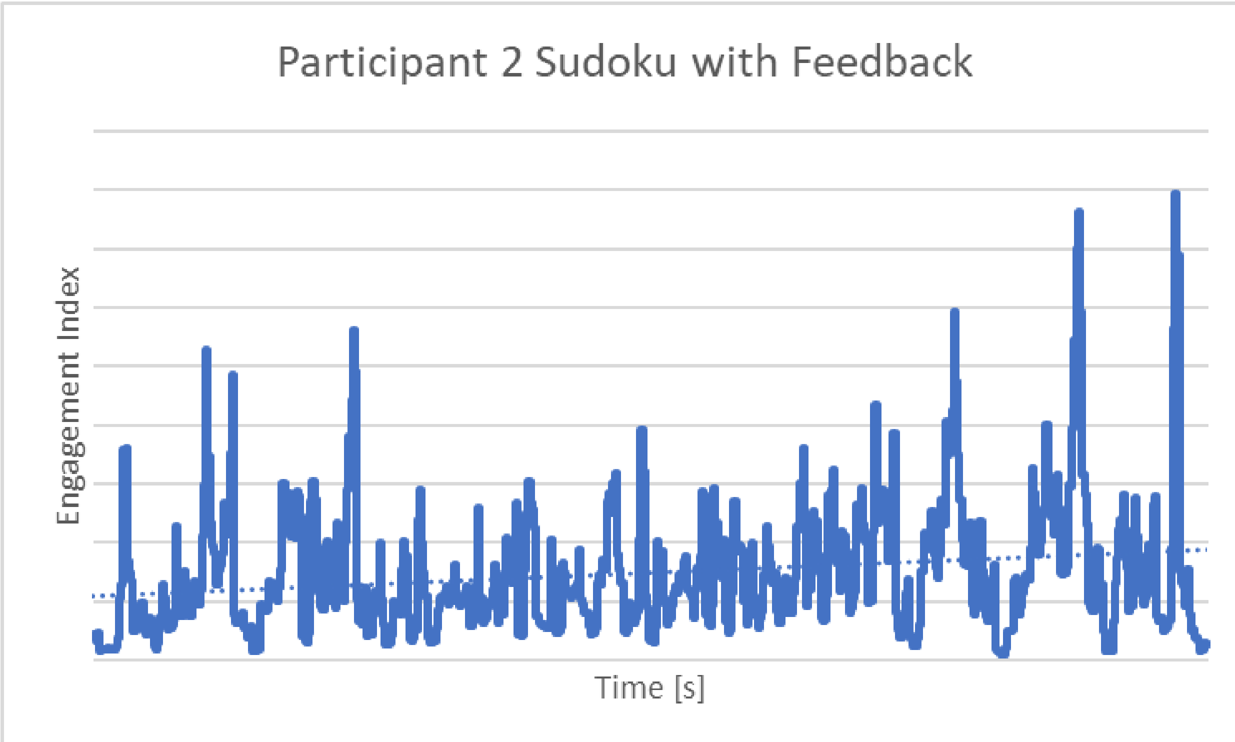


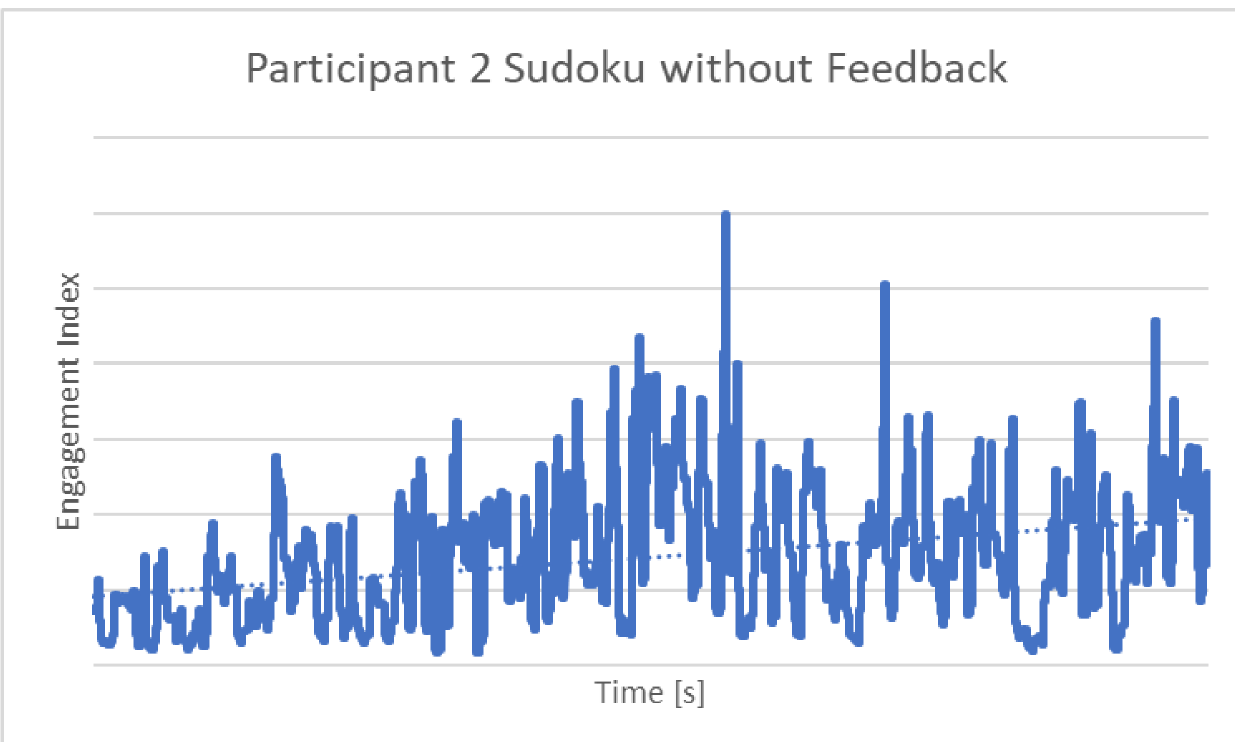

Participant 1 Sudoku with Feedback
Engagement Index
Time [s]

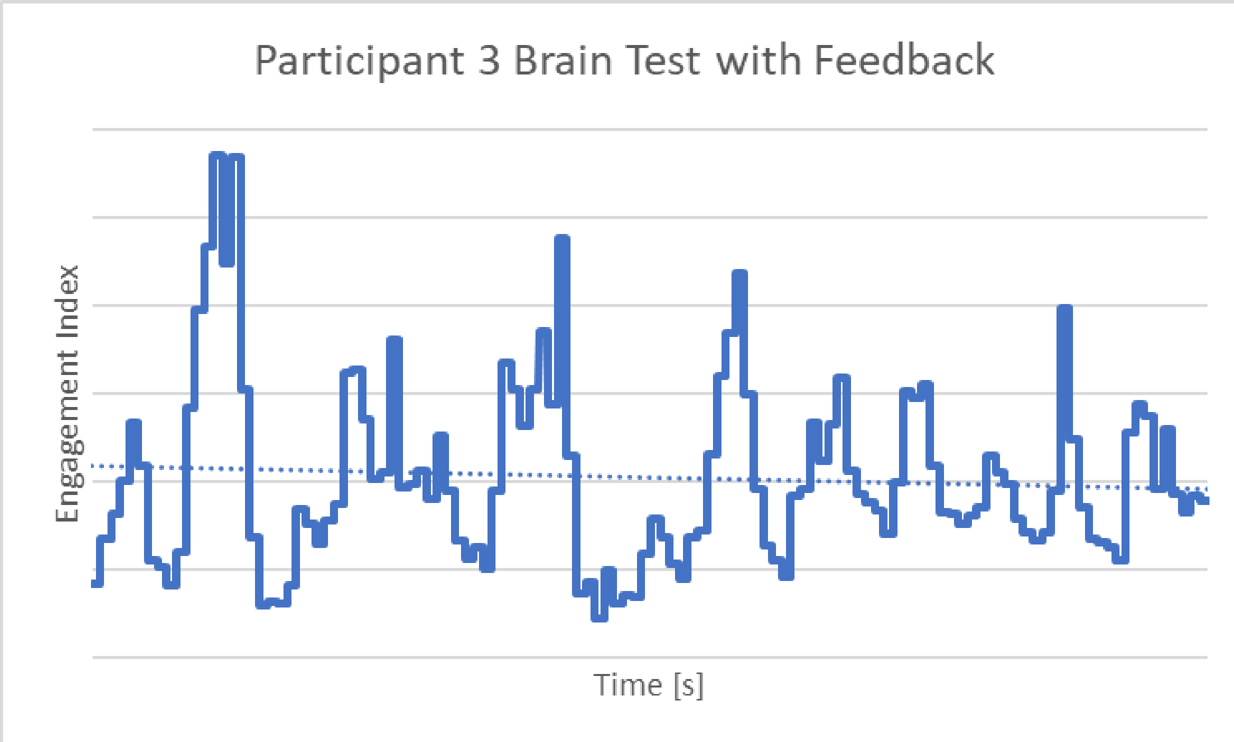

Participant 1 Sudoku without Feedback
Engagement Index
Time [s]

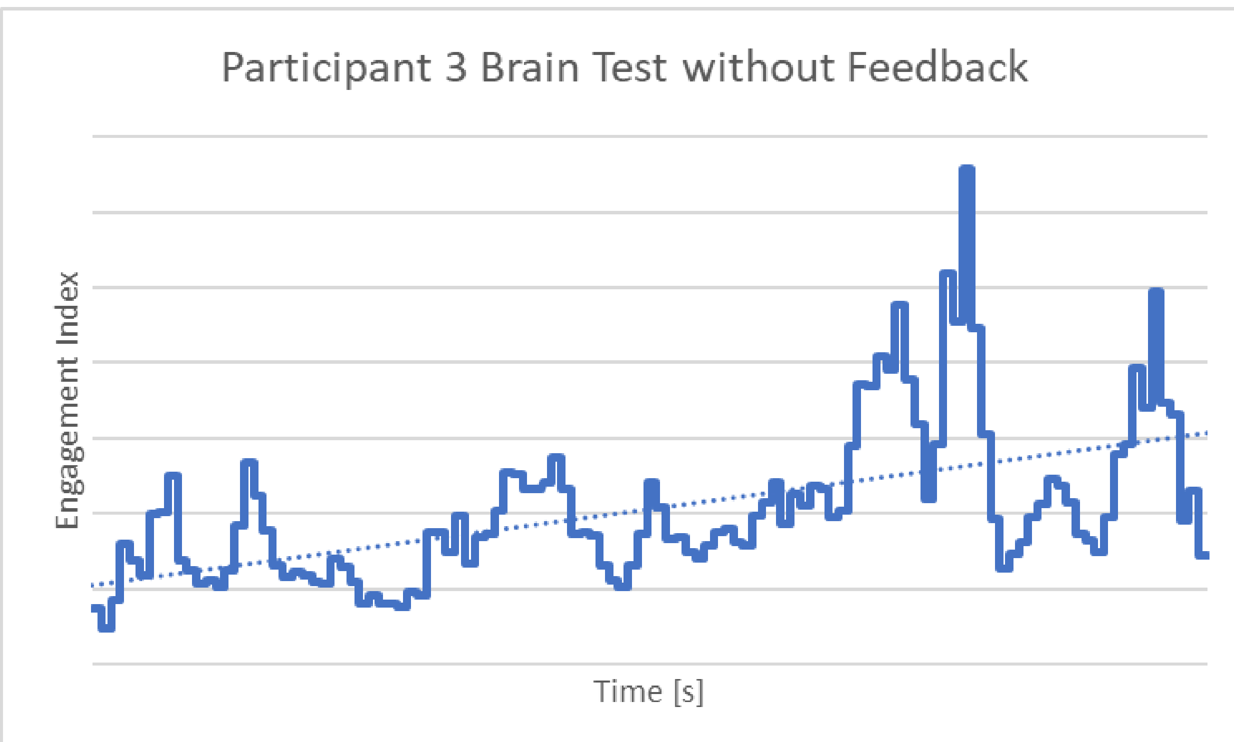

Participant 2 Brain Test with Feedback
Engagement Index
Time [s]

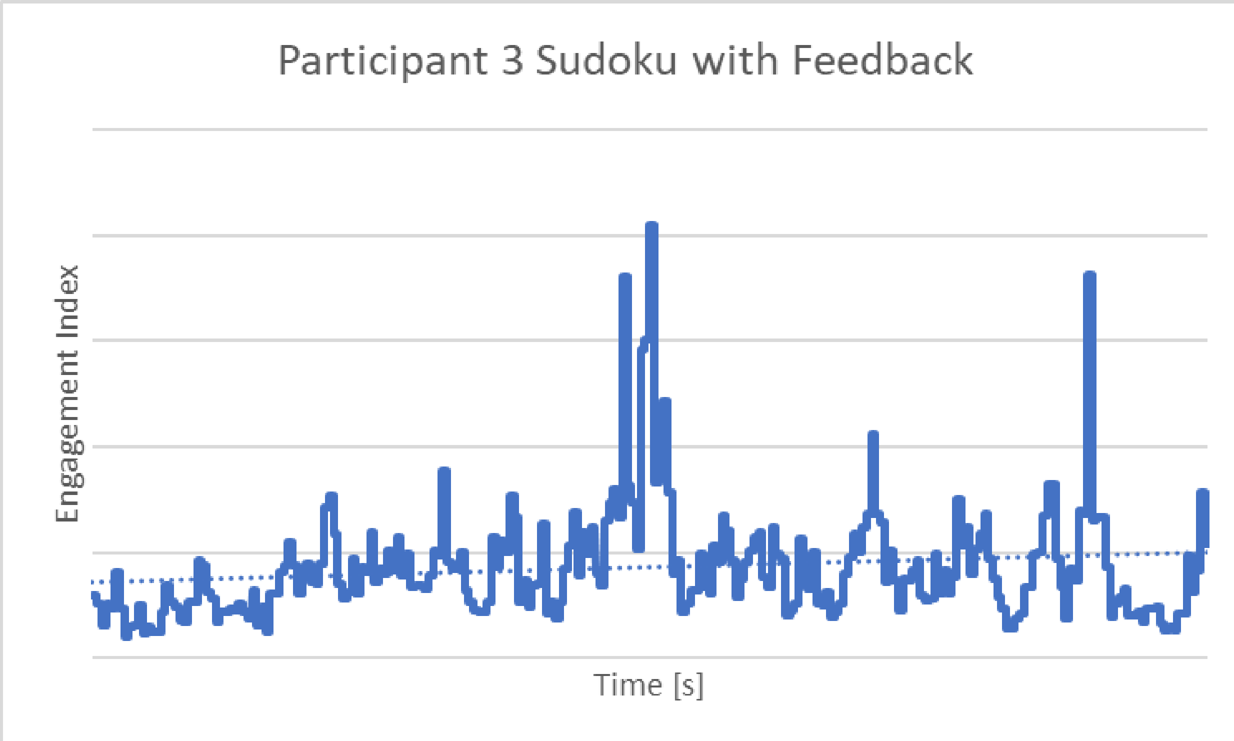

Participant 2 Brain Test without Feedback
Engagement index
Time [s]

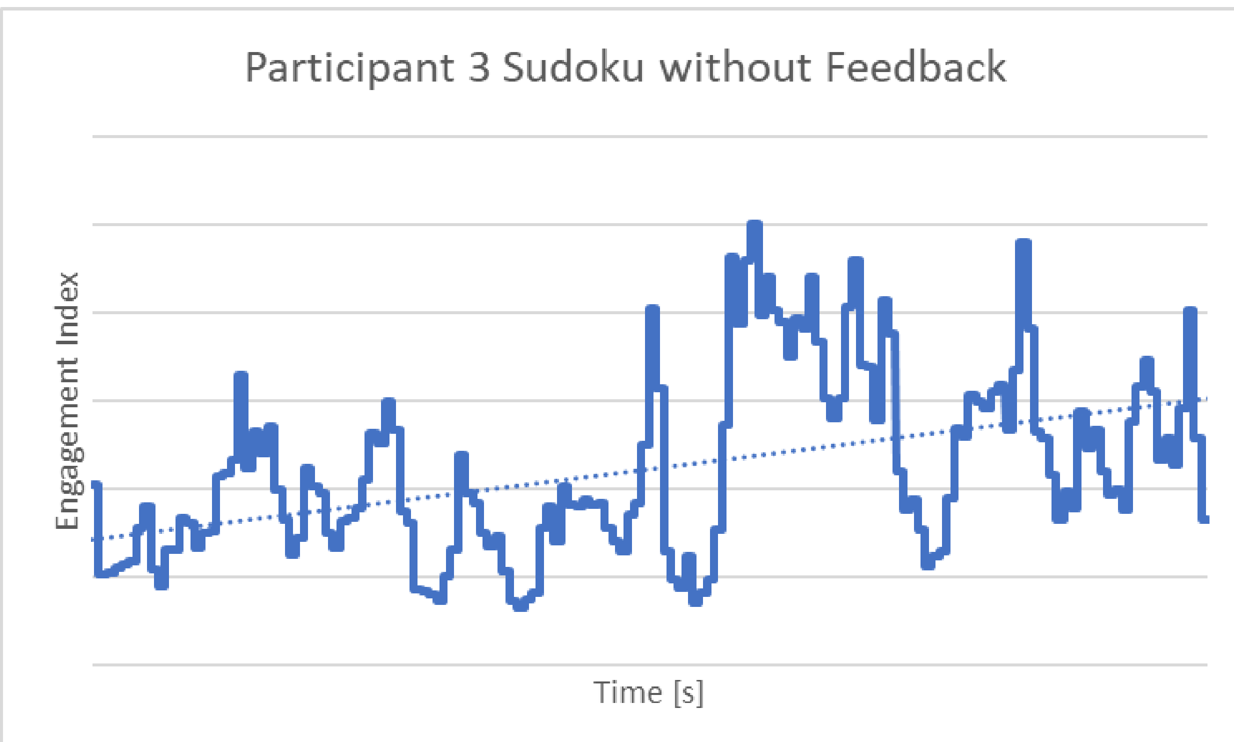

Participant 2 Sudoku with Feedback
Engagement Index
Time [s]

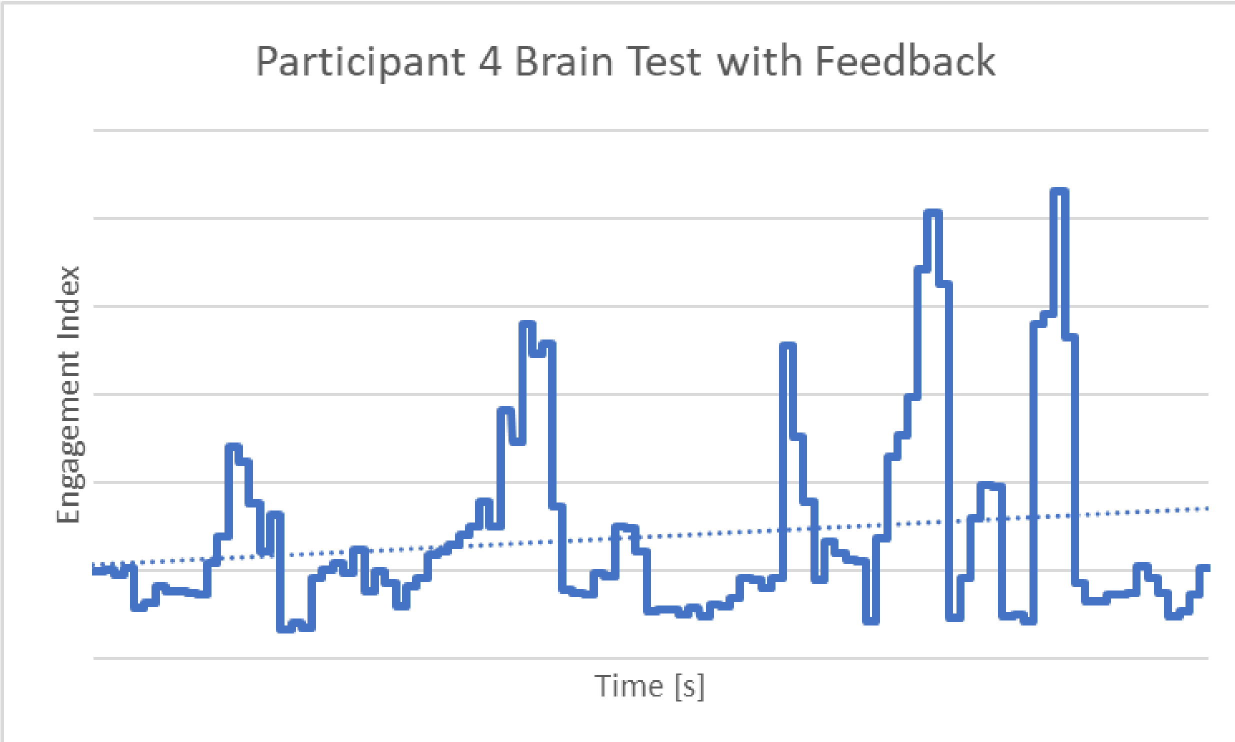

Participant 2 Sudoku without Feedback
Engagement Index
Time [s]

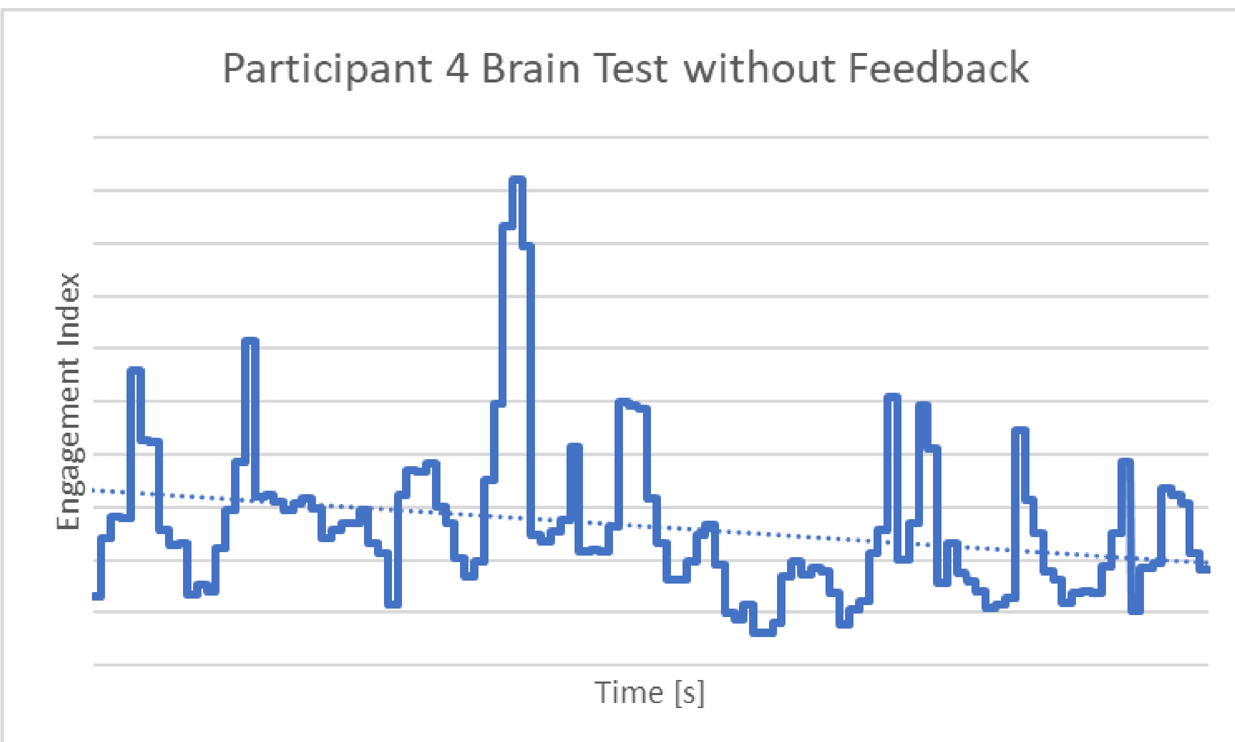

Participant 3 Brain Test with Feedback
Engagement Index
Time [s]

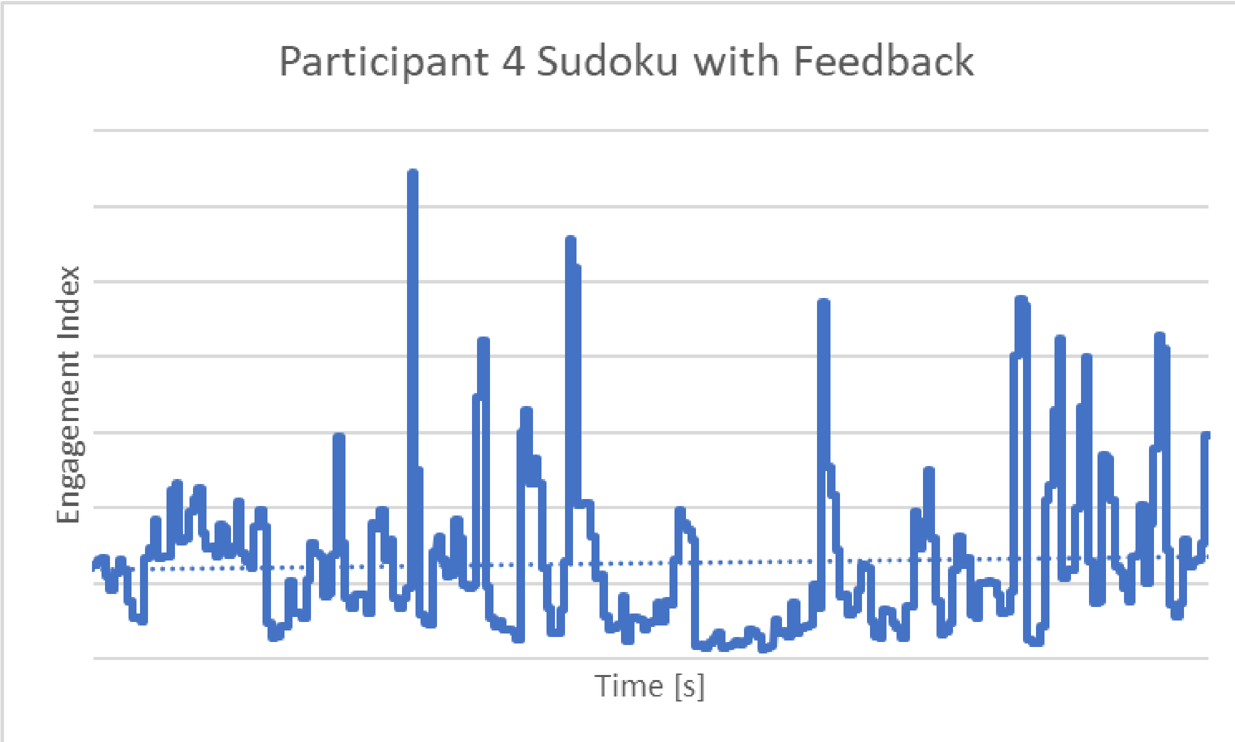

Participant 3 Brain Test without Feedback
Engagement Index
Time [s]

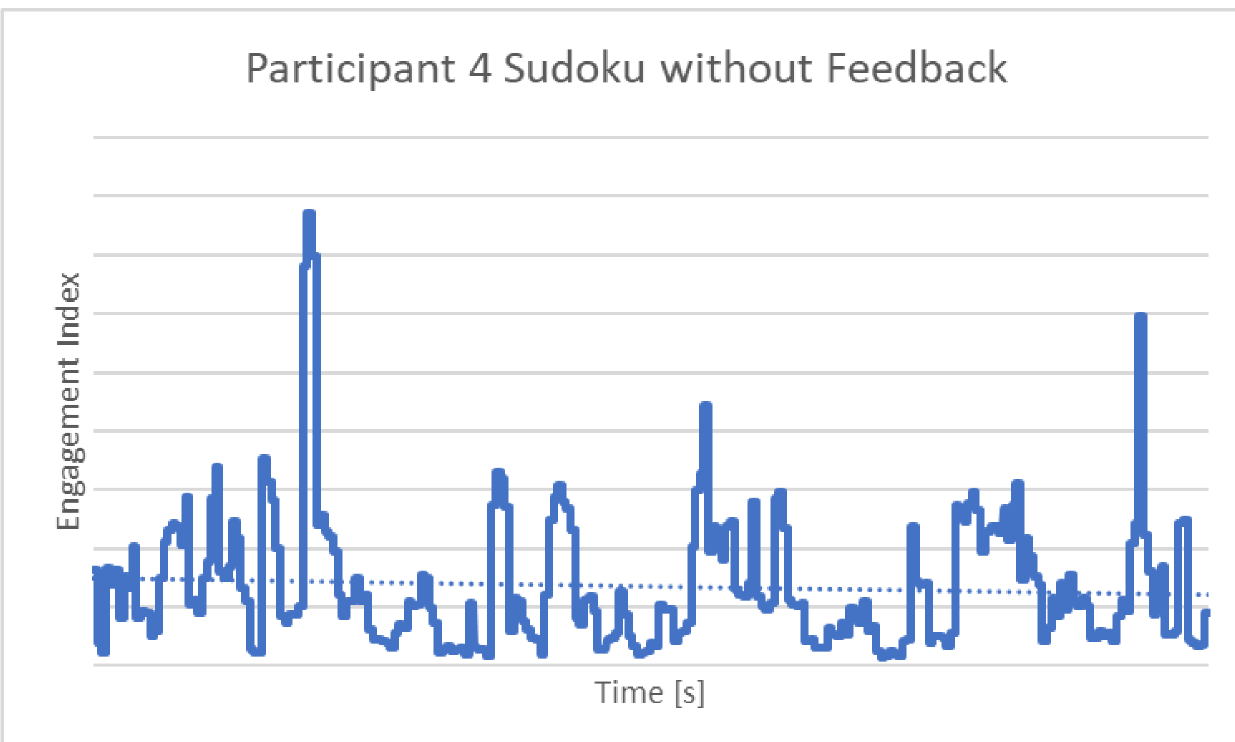

Participant 3 Sudoku with Feedback
Engagement Index
Time [s]

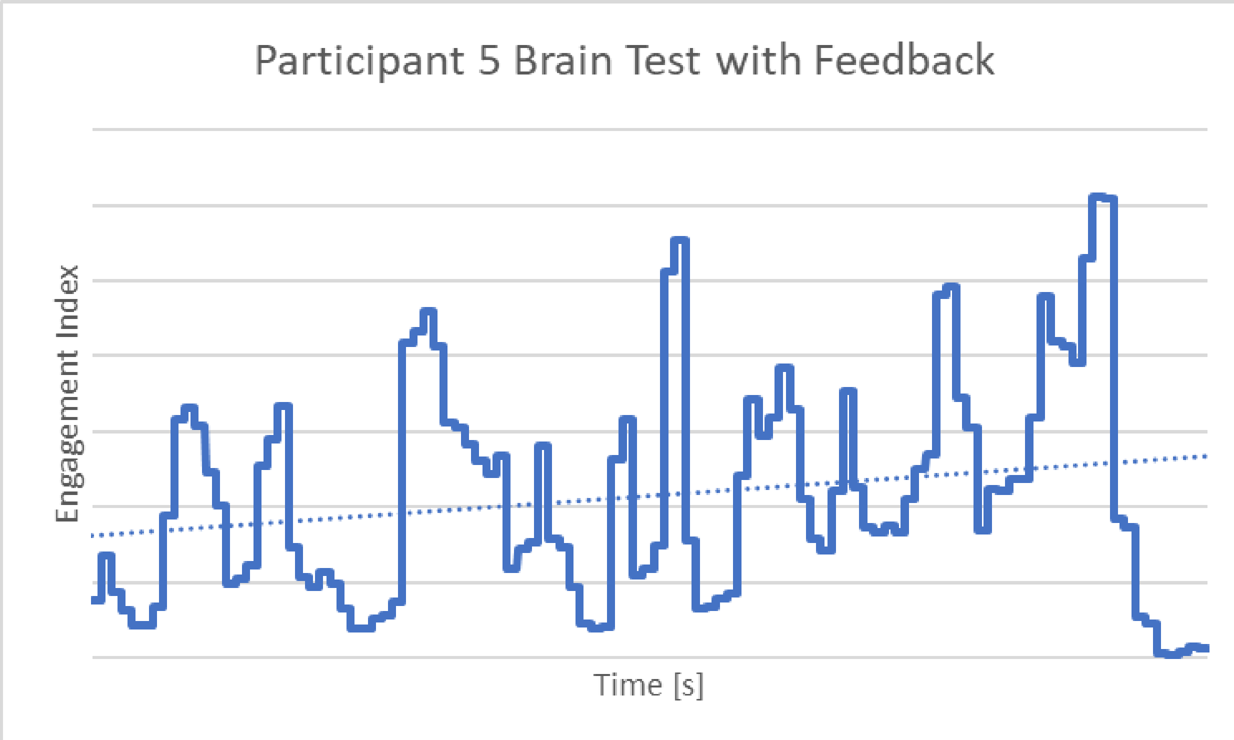

Participant 3 Sudoku without Feedback
Engagement Index
Time [s]

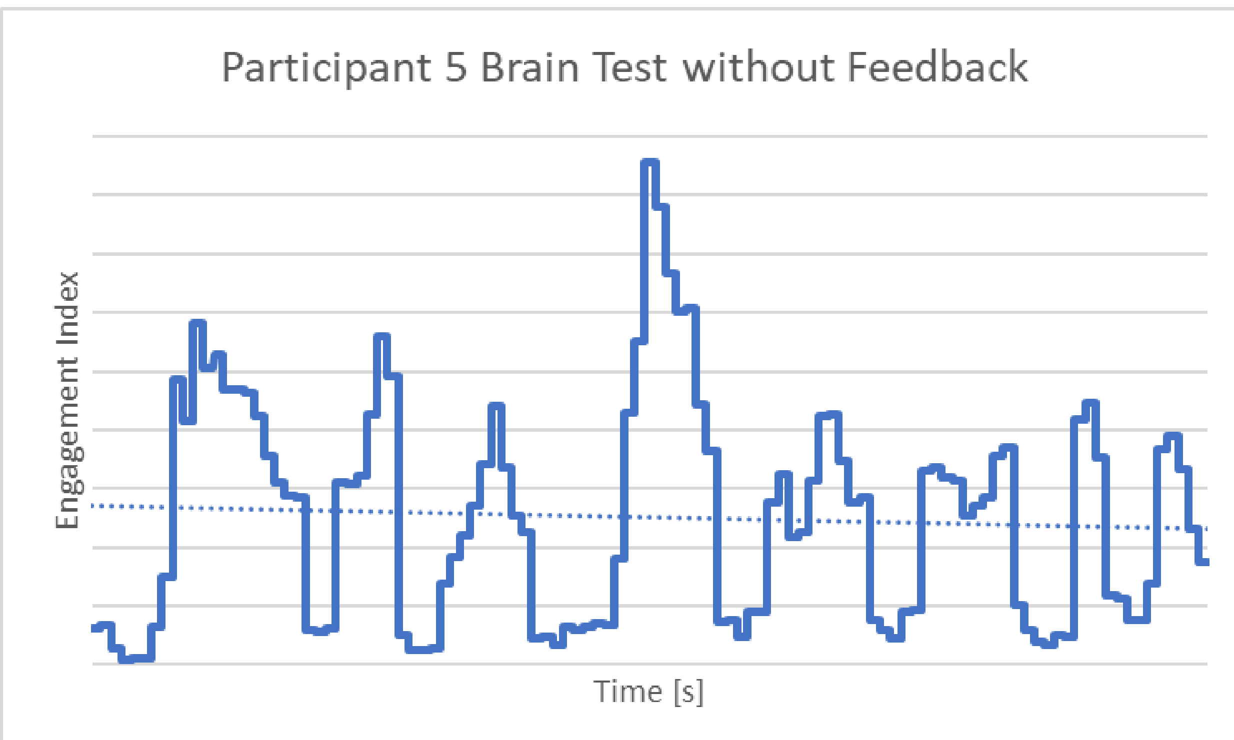

Participant 4 Brain Test with Feedback
Engagement Index
Time [s]

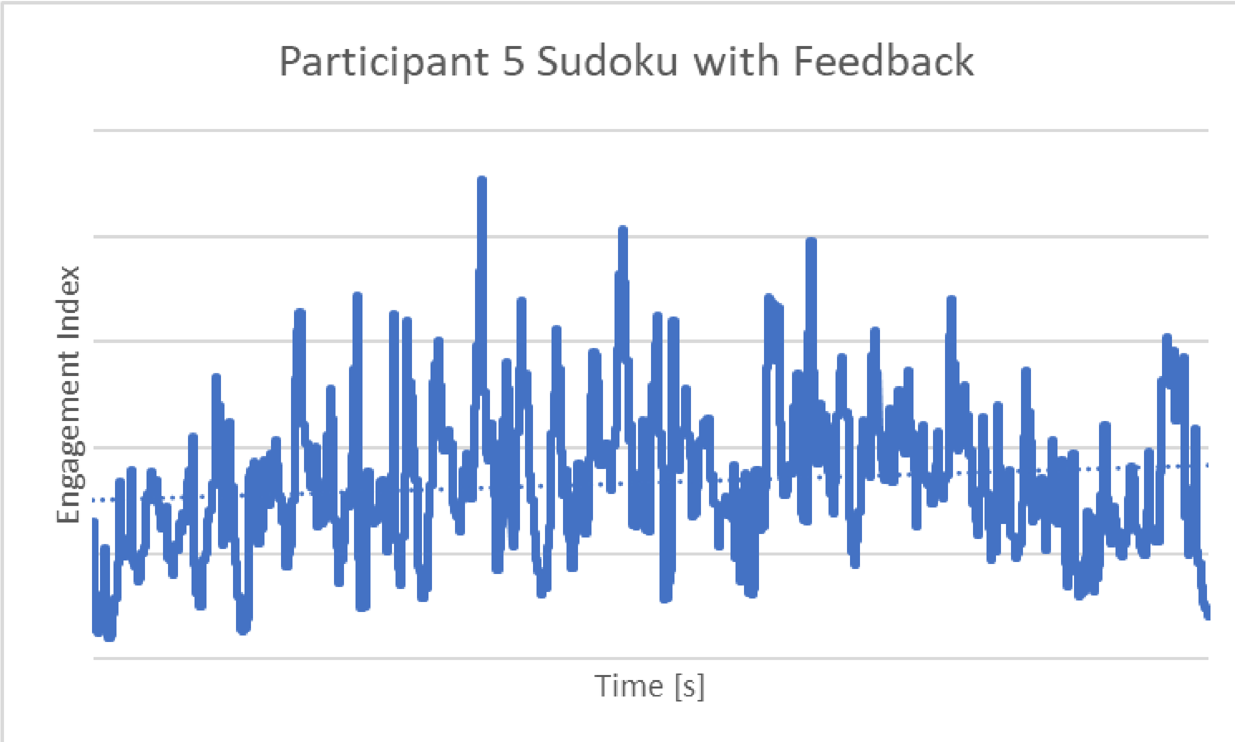

Participant 4 Brain Test without Feedback
Engagement Index
Time [s]

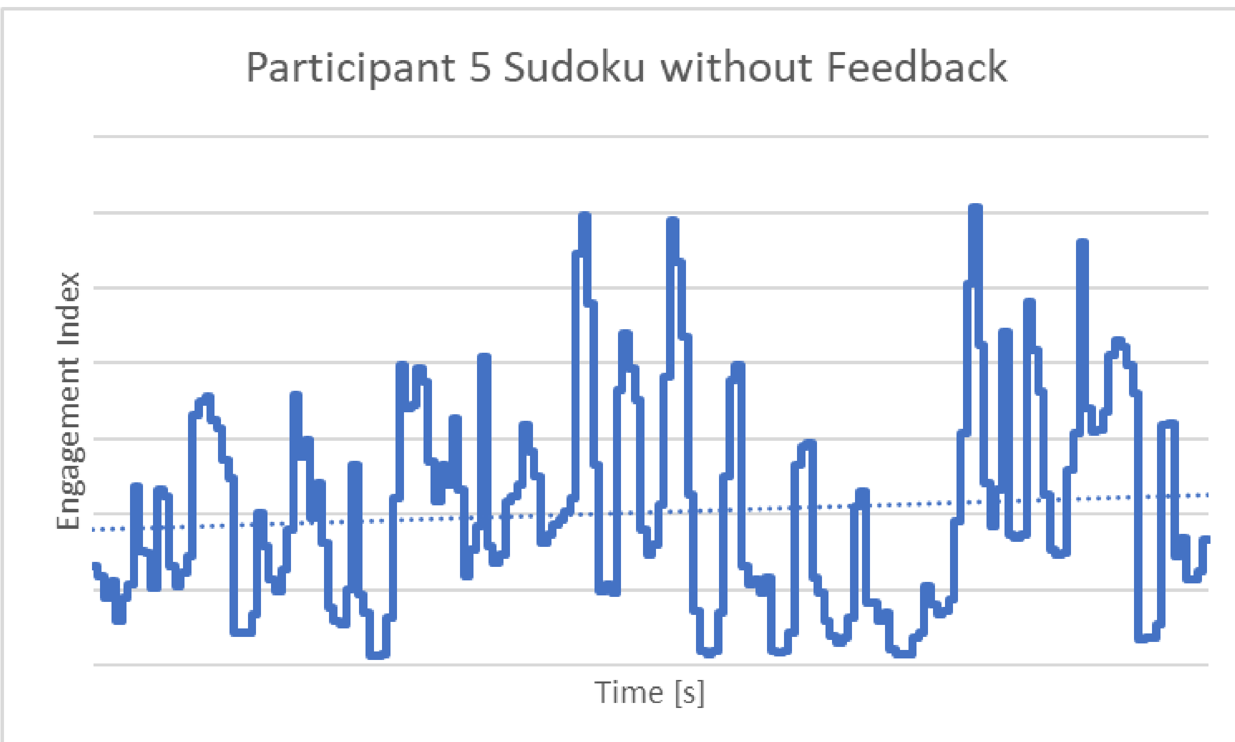

Participant 4 Sudoku with Feedback
Engagement Index
Time [s]


Participant 4 Sudoku without Feedback
Engagement Index
Time [s]


Participant 5 Brain Test with Feedback
Engagement Index
Time [s]


Participant 5 Brain Test without Feedback
Engagement Index
Time [s]


Participant 5 Sudoku with Feedback
Engagement Index
Time [s]


Participant 5 Sudoku without Feedback
Engagement Index
Time [s]

	#1	#2	#3	#4	#5
Feedback Usability of EEG device	Uncomfortable to wear Muse, too tight and mark on forehead	Uncomfortable to wear Muse, ears hurt and too tight that leaves mark on forehead	Uncomfortable to wear Muse, ears hurt	Uncomfortable to wear Muse, too tight and mark on forehead	Uncomfortable to wear Muse, mark on forehead
Feedback Accuracy of feedback	Accurate, but when the volume of the music decreases, the noise from the outside can be hear	Accurate, but when the volume of the music decreases, the noise from the outside can be hear	Accurate but does not really matter	Accurate	Accurate
Feedback Influence of the feedback	Helpful (wants stronger feedback, such that physically influences)	Helpful	No effect (Do not care)	Helpful	Helpful
Test 1 With feedback	Increased trendline in engagement index	Slightly increased trendline in engagement index	Slightly decreased trendline in engagement index	Decreased trendline in engagement index	Decreased trendline in engagement index
Test 1 Without feedback	Decreased trendline in engagement index	Decreased trendline in engagement index	Increased trendline in engagement index	Decreased trendline in engagement index	Decreased trendline in engagement index
Performance	Same performance (missing two questions)	Missed one with the feedback but that was on purpose (to check the	Misclicked twice with feedback	Missed one more without feedback	Missed three questions in both tests but scored higher in speed with

		feedback)			feedback
Test 2 With feedback	Increased trendline in engagement index	Decreased trendline in engagement index	Decreased trendline in engagement index	Decreased trendline in engagement index	Decreased trendline in engagement index
Test 2 Without feedback	Slightly decreased trendline in engagement index	Decreased trendline in engagement index	Decreased trendline in engagement index	Decreased trendline in engagement index	Decreased trendline in engagement index
Performance	Same performance (three errors)	45s faster completion time with one less mistake with feedback	Both game ended due to three mistakes, but held 2 minutes more with feedback	Completed both, 20s faster completion time with feedback	Both game ended due to three mistakes, however,almost finished with feedback while and took 6 minutes more