Nap Control: A Novel System For Precisely Controlling Nap Duration

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Declaration

This work has not been previously accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

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Statement 1

This thesis is the result of my own investigations, except where otherwise stated. Other sources are acknowledged by footnotes giving explicit references. A bibliography is appended.

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Abstract

Lack of sleep costs the UK economy £40 billion per year [1]. However, this is unsurprising considering that over third of UK adults struggle to get to sleep at least once a week and of this group 46% say that their poor sleep 'severely' or 'very severely' impacts their focus levels at work [2] [3].

This dissertation details the planning and development of a prototype device that is able to combat the UK's, along with other countries', issues resulting from a lack of sleep amongst their populations.

The device created encourages napping through providing more control and certainty to users over their nap duration and therefore helps to mitigate the impact of a lack of sleep.

Contents

Chapter 1

Introduction

The average human spends 26 years of their lifetime asleep [4], yet a study conducted in the Netherlands concluded that 43% of the sample subjects experienced insufficient sleep [5]. Lack of sleep not only has a huge impact on personal life, as discussed in section 2.1 of this document, but also has a dramatic effect on our economy. Lack of sleep among workers in the UK is costing the economy a reported £40 billion a year, which is roughly 1.86% of GDP [1].

Napping is one solution to recover lost sleep and comes with a plethora of health benefits such as boosting our immune cells [6] which is vital now more than ever before as we experience our first pandemic of the last century. This project demonstrates one solution to the underutilisation of napping, offering an intuitive way to claw back some of the missed hours of shut eye by providing a user-friendly way to take controlled naps in order for positive napping to become a more accepted part of our lives.

A possible application of this project would be for lorry drivers. When lorry drivers take their mandatory rest breaks, they need to rest for a specific amount of time. This device could offer an accurate nap time in order to maximise their nap length. The possibility of napping for an accurate amount of time could increase the likelihood of lorry drivers taking these naps. In turn, this will help to reduce tiredness and ultimately reduce road incidents involving tired drivers. One study found that in the USA 17% of road accidents are sleep related [7] which demonstrates how important this system could be in saving lives.

This project demonstrates such products should become commercially available as there is a nationwide and arguably global need to catch up on missed sleep. Our society preys on our attention yet our bodies are simply not able to fight the evolutionary need for 8 hours of sleep a night. Therefore, this project provides one way of getting the necessary sleep while maintaining strict control over our lives.

1.1 Project Aims

This section succinctly discusses the project aims. It also describes the reach of the project which looks at how broad an area was covered, and the impact the project may have.

1. Design a physical system that uses inexpensive hardware modules to read relevant data

related to sleep from the human body.

2. Create a bespoke piece of processing software that takes in data from the hardware sensors and produces probability of the user being asleep.

3. Produce a prototype piece of software that demonstrates functionality of the system, allowing the user to set a specific sleep duration after which time an alarm is played.

4. Provide a solution to those who regularly get insufficient sleep and regular nappers to increase the usage and acceptance of positive napping throughout the day.

1.2 Objective

The objective of this project is to demonstrate one possible solution to those who are regular nappers or those who suffer with sleep and want greater control over their nap length. The project draws from multiple areas of existing research and focuses on the hardware and functionality of the system rather than providing a visually appealing piece of software – although, the software will still provide the functionality described above.

By extension, this solution could contribute to increasing the acceptance and use of positive napping in our culture and demonstrate that napping could become an accepted part of our lives. It could also demonstrate economic benefits such as the potential to add up to £24 billion lost as a caused by workers often getting less than 6 hours sleep per night [1].

It is important to define what this project was not aiming to show This project does not aim to demonstrate a new method of processing and analysing electroencephalogram (EEG) data. Methods of processing EEG data are hugely complex and require deep knowledge of advanced mathematics and statistics as well as years of experience in algorithm design. For this reason, it would be naive to propose a new method of EEG or ECG data processing. In addition, this project does not demonstrate a method of sleep stage classification, although at the beginning of the project this was hoped to be an additional outcome it quickly became apparent that the hardware necessary was not available and was therefore not feasible.

This project does not show the optimal system solution however it can be a benchmark to show that a useful system is achievable at relatively low cost.

Chapter 2

Background Research and Related Work

2.1 Background

This project focuses on collecting and analysing sleep data. This section aims to provide a summary of existing research surrounding the process of analysing sleep data. This ranges from the initial discovery of individual sleep stages to the modern-day techniques used to analyse sleep. It will also detail the advantages of taking a well-timed nap. In addition, this section covers the medical aspect of sleep, the need for sleep and the devices used to take relevant bodily readings related to sleep. Overall, this section is designed to give context to the project and the areas of existing research the project draws from.

The study of sleep is a relatively new field in science, it wasn't until 1952 that Eugene Aserinksy and Nathaniel Kleitman at the University of Chicago discovered regular periods of rapid eye movement (REM) while observing test subjects sleep as published in 1953 in their paper titled 'Regularly Occurring Periods of Eye Motility, and Concomitant Phenomena During Sleep' [8]. Before this time sleep was viewed simply as a time when the brain shut down or rested [9]. After almost 70 years of research since this paper was published, we now know these preconceptions could not be further from the truth, the subconscious sleeping brain is often equally as active as the waking brain [10].

The REM sleep state they had observed would later be categorised as the last stage of sleep by Allan Rechtschaffen and Anthony Kales in what became the standard for sleep scoring. The process of analysing individual sleep stages that they developed became known as RK (Rechtschaffen Kales) scoring [11]. This method of sleep scoring divides a single sleep cycle (of which a person may have 4-5 in an ordinary night's sleep) [12]) into 7 distinct stages: wake, stage 1, stage 2, stage 3, stage 4, REM and Movement time [11]. Stages 1-4 are also commonly referred to as non-REM (NREM) phase. These stages are characterised by the unique actions the brain performs at each stage and can be individually identified by reading EEG data from the brain from the varying frequency of electrical waves emitted at each stage based on the action currently being carried out in the brain [13].

The RK method is a relatively old sleep scoring technique that has been criticised for its lack of regard to modern day automated sleep analysis systems [14]. Therefore, it has since been challenged by the American Academy of Sleep Medicine (AASM) to become the standard sleep scoring method. The AASM follows the RK method by retaining the 5-sleep stage standard [15]. Despite this change being significant for the sleep science field, it has little relevance to this project.

Individual sleep stages can be best identified using an EEG recording device [10]. These devices use small metal electrodes carefully placed on the scalp to listen in to the small electrical signals produced by the countless brain cells in the cerebral cortex, the outside layer of the brain [9]. This is one of the best methods of taking a general reading of the current state of the brain. However, it does not give readings of specific actions that the brain is carrying out [9]. Consequently, it is often referred to as a non-invasive way of taking brain activity readings.

Stage 1 of sleep lasts for only 1-7 minutes and is the stage where a subject begins to drift off to sleep, often characterised by dream-like thoughts similar to daydreaming called hypnogogic hallucinations [16] as well as involuntary bodily movements such as kicking a leg called hypnic jerks [17]. The waves emitted at this stage are slowing down from the initial alpha waves, which are observed soon after closing our eyes at 8-13Hz, towards low theta waves that occur in the 4-7Hz frequency range [13].

Stage 2 (or light sleep) produces a larger amount of theta waves in addition to Sleep Spindles and K-Complexes which are sudden bursts of brain activity [18] [13], this stage lasts from 10 to 25 minutes [19]. Whilst there is still a lot of ambiguity as to the reason for these burst events, they are a good identifier of Stage 2. This stage is often the best time to wake from a nap as it is just before stage 3 and 4 which if awoken in will likely cause the disorientated and sluggish feeling experienced by people when awakening in the morning. This was noted in a paper published called 'Effect of different nap opportunity on short-term maximal performance, attention, feeling, muscle soreness, fatigue, stress and sleep'. The paper found that a 25 - 35-minute nap, or a 45-minute nap, is optimal to minimise the feeling of fatigue while retaining the benefits of feeling refreshed [20].

Stage 3 and 4, the last stages of NREM sleep, are the deepest sleep stages that it is hardest to awaken someone from, this stage is characterised by the lowest type of EEG waves - delta waves at 1-3Hz [13]. This stage facilitates some of the most important functions of sleep such as the growth and restoration of body tissue, the consolidation of memories from the previous day and even the regulation of emotions [12].

Rapid Eye Movement (REM) sleep is the last stage of the sleep cycle occurring after about 90 minutes of sleeping. As the name suggests, REM sleep is characterised by distinct eye movement which can be observed with EEG and electrooculography (EOG) equipment. Dreaming occurs in this stage which is often referred to as paradoxical sleep as the brain is often just as active as an awake brain and the body is all but paralysed [21].

The characteristics of each sleep stage are important to note as they are what this project relied upon, the EEG device used in this project produces a current meditation and attention value based on the individual brain waves state discussed above. The meditation and attention values produced can then be processed and are used to determine the users current sleep state.

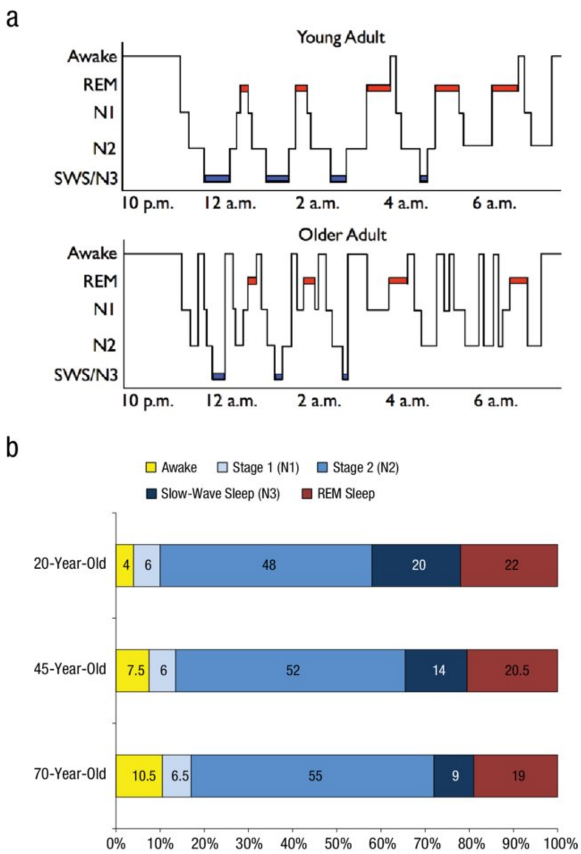

Figure 1. Sleep stages thought ordinary nights sleep [22]

Aside from diagnosing sleep disorders another reason for analysing sleep is to find out what makes for a 'good sleep' or in the case of this project a good nap. Existing research tells us that napping can improve reaction time, reduce the effects of sleep deprivation and can even improve our mood [23]. If carried out effectively this can be of huge benefit to those who suffer from sleep disorders and consequently are often sleep deprived during the daytime. In fact, a well-timed nap can increase vigour and alertness to a greater extent and for a longer period of time than caffeine [24] (a stimulant). However, the combination of stimulants such as caffeine or modafinil being administered just before a nap and then napping for 25 minutes (the amount of time caffeine and modafinil takes to have an affect) is an ideal pairing [25] [26].

Sleep deprivation is a serious condition and can cause major disruption to normal bodily functions. Besides the obvious short-term effects such as drowsiness or poor reaction time, those affected can also experience memory loss in the short term and even a decrease in cognitive performance [27]. The long-term effects of sleep deprivation are even worse: higher blood pressure, weight gain, increased risk of heart attack or stroke and a significant drop in testosterone levels are some of the most common effects [28]. This is particularly concerning since one UK study found 30% of participants to be sleep deprived [29]. This is a concerning result and could be a huge hidden cost to our quality of life. Napping can help to reduce these effects and can therefore be an effective treatment for those suffering with the consequences of sleep deprivation, if carried out correctly. This is where the project will be most beneficial.

2.2 Related Work

This section will discuss the existing technology that is closely related to the project. It will look at the benefits and drawbacks of these technologies and analyse how this project draws from them.

Wrist actigraphy is a method of recording sleep data predominantly through the subject's movement during their sleep. A device is worn on the wrist which contains a piezoelectric sensor which are used to measure variables such as acceleration, strain, changes in pressure and temperature changes [30]. This data can be used to track a subject's sleep pattern and is often used to diagnose sleep disorders in a subject's sleep-wake cycles [30]. A study by the AAMS found that wrist actigraphy data was a useful research tool as it helps to diagnose specific sleep disorders such as insomnia or sleep apnoea [31] but its medical use remained uncertain [32]. Although the wrist actigraphy does offer some insight to a subject's sleep pattern, it does not however look at specific sleep stages. Instead, it paints a much broader picture of a subject's daily movements. This project relies on observing the subject's current mind state which the wrist actigraphy is simply not advanced enough to do and should not be considered as a possible alternative.

Like wrist actigraphy, mobile apps exist that allow a user to track their sleep. These apps rely solely on microphone data collected during a period of sleep. The use of a microphone may seem odd but is in fact an effective way of measuring a person sleep disturbance. An influx of sound picked up by the microphone during a sleep period can be a strong indication of a poor-quality sleep. As previously discussed, more bodily movement is expected in some sleep stages than other sleep stages. In REM we expect none. Despite having major flaws, this is a possible way of tracking a subject's current sleep stage. Some people move more in their sleep than others, while some often do not move at all. This means microphone tracking does not yield the detailed information needed to accurately predict a subject's current sleep stage, unlike EEG readings, as microphone readings can vary wildly from person to person. One study of an application called iSleep found that microphone recordings during sleep were particularly sensitive to noise and required the distance of the microphone to the user to be considered before sleeping as well as requiring a high microphone sample rate to record the best quality data [33]. This risk of collecting poor quality data combined with the lack of insight microphone readings provides meant it was not a viable solution for this project.

A polysomnography study (or sleep study) may be carried out on a patient if a doctor believes they are suffering from sleep disorders. A polysomnography collects a comprehensive set of data related to sleep. The data collected is normally EEG data, oxygen level in the blood, heart rate and bodily movement [34]. Some polysomnography studies also collect Electrooculography (EOG) data which records a subject's eye movement. Whilst this is excellent for diagnosing some sleep disorders, EOG is somewhat overkill for this project as it requires much more hardware and is generally out of the scope of this project. In addition, the project focuses on napping (where REM sleep is not reached) meaning EOG data is not necessary to collect as EOG specialises in collecting REM sleep data. As well as EOG data, blood oxygen level is recorded to diagnose sleep apnoea [35], a condition similar snoring where the subjects air ways become temporarily blocked causing gasping and a change in blood pressure. This project is not concerned with sleep apnoea, so blood oxygen level is not necessary to collect. Although EEG data alone is not comprehensive enough for diagnosing sleep disorders (the goal of polysomnography), it is comprehensive enough for tracking when a user falls asleep. For this reason, EEG data is the only necessary data collection tool for this project.

Brain computer interfaces (BCI) use EEG data collected from users' brains to execute computer inputs, for example thinking 'harder' will move the mouse up or send a specific key stroke. This technology was only in the realm of Sci-Fi not so long ago but has advanced in recent years and even broken into the hobbyist market with relatively cheap kits available from online suppliers such as OpenBCI which facilitate collection of high-quality EEG data without having to pay for medical grade equipment [36]. However, these hobbyist kits can still cost thousands of pounds. There is an active hobbyist community surrounding BCI devices which discovered that an old toy produced in 2012 called the 'MindFlex' (which was originally designed to play a game based on how hard the user was thinking) had some key internal components such as a NeuroSky chip [37] which could be modified or 'hacked' to read EEG data directly to an Arduino micro controller. In fact, this discovery led to research papers being published on the hack and its various possible uses [38]. While these communities and their findings focus on BCI projects they were still of great use to this project as the general data collection method is very similar regardless of the fact that the aims of BCI projects differ to this project.

It should be noted that there does exist a patent for a design similar to this project published in the United States. The patent describes a head-rest style device which a user places their head on to record EEG data. The device aims to wake the user up once they have reached a specific sleep stage [39]. This is not the same as this project as this project allows the user to sleep for a specific duration of time regardless of the sleep stage achieved and the US bases the output not only on EEG data but also ECG data making the system more accurate. In addition, this project allows the user to move during their sleep as the EEG device will be worn on the head using a headset, unlike the US patent which requires the user to rest in a specific way on the device. Figure 2 below shows the existing patent design.

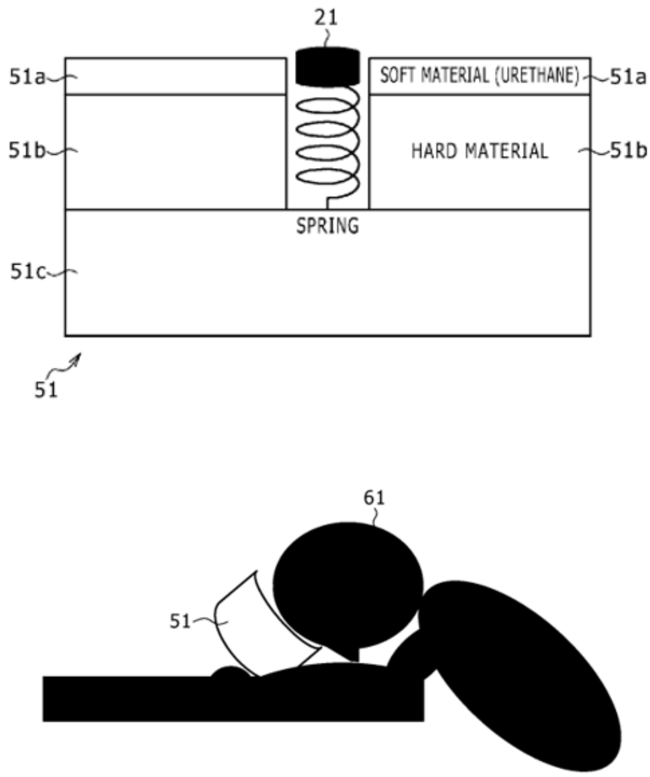

Figure 2. Patent on related idea [39]

2.2.1 Related Processing Techniques

Many processing techniques exist for analysing sleep data collected. A considerable part of this project is the processing of the EEG data collected and analysing when the user has entered a certain level of relaxation to begin the sleep timer/alarm.

Some studies have been carried out on automatically detecting a sleep stage based on EEG data such as one conducted on neonates which used advanced computation, mathematical and statistical tools to categorise the EEG data collected from neonatal sleep [40]. However, those papers assume medical grade EEG equipment is being used as well as advanced processing techniques to extract useful data such as filtering out noise. In addition, unlike the papers discussed, this project was mainly concerned with identifying the onset of sleep rather than the specific sleep stages the user is currently in, therefore those techniques were not followed but were still useful to draw general ideas from.

Chapter 3

Methodology

This chapter discusses how the project was carried out as well as the key tools and technology that were used to facilitate the research and findings produced by the project.

3.1 Tools

3.1.1 Hardware

Choosing suitable hardware for the project was a hugely important task because the quality and suitability of the hardware chosen for any project is a key limiting factor to how effective the final systems can be. Therefore, a significant amount of time was dedicated to researching what hardware would be best suited for this project. While researching for acceptable hardware it was important to consider one of the key aims of the project – 'design a physical system that uses inexpensive hardware modules to read relevant data related to sleep from the human body.'. This aim meant not only was the accuracy and reliability of the hardware an important criterion to consider but also the price as it was another key factor to examine.

- **MindFlex**

  One of the most challenging aspects of this project was discovering a method of collecting electroencephalogram (EEG) data. Usually, the collection of EEG data requires medical grade equipment which can cost tens of thousands of pounds for even a used system. This was clearly not feasible for this project and therefore a far different approach was necessary. The MindFlex, previously mentioned in section 2.2 of this document, offers a far more affordable method of collecting EEG data.

  The MindFlex was chosen to take on this task as it featured an inexpensive and dependable chip which can be rewired or "hacked" to siphon off the EEG data from the inbuilt NeuroSky chip produced by ThinkGear AM [37]. The idea behind the hacking of the MindFlex has been around for several years and is commonly used by hobbyists and researchers in brain computer interface projects . The MindFlex only has one data channel, meaning one electrode sensor, and is therefore not appropriate for use when very sensitive readings are necessary, for example during medical procedures such as a polysomnography study (sleep study). However, one channel is still suitable for this project as the project only requires a general overview of the status of the brain as opposed to needing highly accurate readings from different brain locations. In addition, the MindFlex demonstrates that the system can be created using inexpensive and mass-produced hardware.

- **Eleegoo Uno**

  A suitable microcontroller was necessary to parse the data collected from the MindFlex's NeuroSky chip and send this data onto the main computer for processing. The microcontroller chosen for this project was the Eleegoo Uno, this microcontroller is extremely similar to an Arduino Uno and offers all the same functionality and hardware options. These microcontrollers are designed for prototyping due to their versatility and reliability, for example the Eleegoo Uno board has dozens of input pins allowing communications with several other PCB modules. Whilst this may be considered overkill for this project, it was the only board available at the time and allows for future proofing if any more modules were needed later. The cost of this board was around £3.00 however a more optimised and compact board such as the ATMega328 can be purchased for as low as £2.00, meaning the project was still able to stick to its aim of producing an inexpensive solution.

- **Additional Hardware**

  A few additional tools were needed for integrating the MindFlex and the Eleegoo Uno to send data to the main Java program. These tools were the following.

  Copper Wire (x2) For connecting the NeuroSky chip inside the MindFlex to the Eleegoo Uno.
  Soldering Iron For soldering connections on copper wires.
  USB Type A For testing serial transmission from the Eleegoo Uno to the Java processing software.

3.1.2 Software

The table below details the key languages and libraries the project has made use of, please note this is not an exhaustive list of all software used.

Software	Use	Reasoning
Java	Java was used to develop the processing software that will take in raw data from the Arduino and predicts whether the user is currently asleep, as well as plotting the data on a graph.	Previous Java experience is a large reason for this choice. Java is also particularly good at handling multiple tasks such as receiving data from the Arduino, processing it and displaying the output in a GUI.
Arduino Code and IDE	The Arduino IDE runs on multiple languages such as C, C++, Java and more. This will be used to upload all scripts to the microcontroller.	This is the only reasonable choice for Arduino, it is more than suitable and offers all the features my project needs.
jSerialComm	This library facilitates serial communication from the Arduino to the main computer where the Java processing software created can pick up on the data transmitted along the USB.	The jSerialComm library was crucial for collecting the raw data and allowed for an input stream to be created meaning every time new serial data was received by the Scanner object it could immediately be sent for processing.
Arduino Brain Library	The Arduino Brain Library is installed on the Eleegoo Uno so that the microcontroller can interpret the data received from the NeuroSky chip inside the MindFlex.	The Brain Library takes care of simple but crucial tasks such as formatting the data into a CSV style string as well as diagnosing errors using error codes that are also sent out as strings.
xChart	The Brain Library takes care of simple but crucial tasks such as formatting the data into a CSV style string as well as diagnosing errors using error codes that are also sent out as strings.	This was chosen as it was easy to work with and allowed for multiple line series to be plotted at one time and updated every time new data was received. In addition, xChart is light weight and requires no additional dependencies and so worked better on the less powerful computer used in the testing stage.
Swing	Swing was used to create the GUI.	The main reasoning behind this was that it seemed to work a lot better with xChart than its alternatives meaning it could easily and seamlessly be embedded into the GUI alongside the controls. This was achieved using a JFrame object that the line chart was assigned to, this JFrame object could then be automatically refreshed when new data was being processed.

3.2 Implementation

This project has successfully developed a proof-of-concept system that uses electroencephalogram (EEG) brain data to determine when a subject has fallen asleep and allow an alarm to be set from that moment. This system was implemented in two stages: hardware development and software development. The hardware functions as a sensor and relay, meaning it collects the brain wave data and then sends it to the software. The software acts as the brains of the operation – processing the raw data to determine when the user has fallen asleep.

Both the hardware development and software development processes are discussed in detail in chapter 5 and chapter 6 of this document.

3.2.1 Design Diagrams

The below diagram is a high-level flow diagram of the system that has been created. In addition to this a UML design diagram can bee seen in figure 7 on page 19.

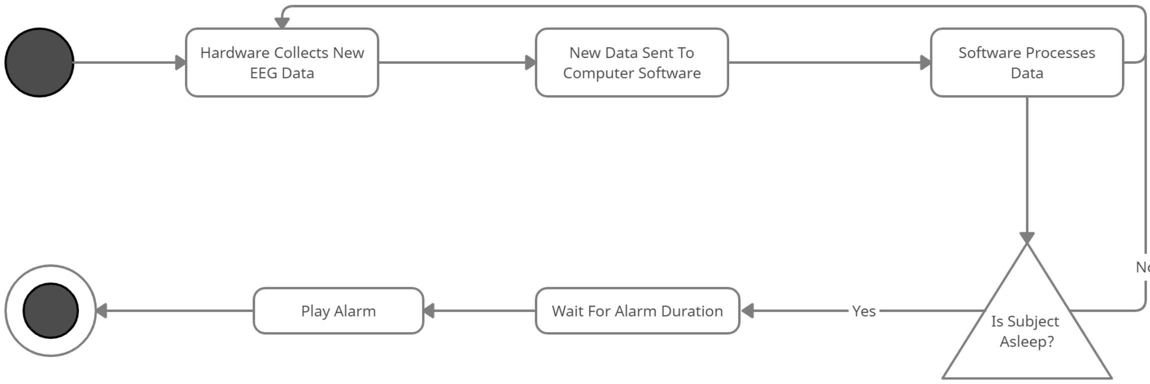

Figure 3. High-Level Project Flow Diagram

3.2.2 Development Methodology and Research Methodology

The research methodology chosen for this project was the build methodology. This methodology focuses on producing a physical and/or digital system with a novel aspect, this aligns closely with what the project aims to produce and was therefore seen as the ideal methodology to follow.

Similarly, the prototyping methodology was chosen for the hardware and software development lifecycles. The prototyping methodology focuses on creating minimum viable products by incrementally improving upon the current design, it also allows for much greater development flexibility and rapid changes to be made. These sorts of changes were seen as likely due to the nature of creating a novel product and therefore a prototyping approach was most suitable. After building a new prototype an evaluation process takes place to identify areas for improvement which can then be taken back to the design and build stage. This iterative process means a final process is much more likely to meet its goal and reduces the overall risk of the project falling short on its aims.

Chapter 4

Project Planning and Management

4.1 Planning

A Gannt chat was produced in the preliminary stages of the project which was used to track progress of the project. Tracking progress and regularly reflecting and updating the chart ensured the project would be delivered on time as expected.

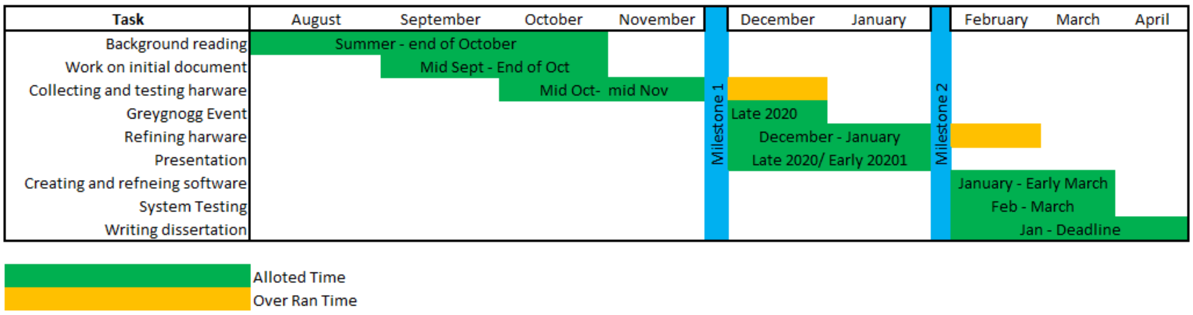

Figure 4. Gannt Chart of Completed Work

As you can see in figure 4, collecting and testing hardware and refining hardware stages of the project over-ran. This was due to a few issues I had with the hardware early on such as incorrect parts arriving meaning new ones had to be ordered. This only slowed down this initial hardware stage and the lost time was quickly made up.

4.2 Management

In terms of managing the project various tracking and management software was used to reduce the likelihood of running out of time and producing an incomplete system, this software also helped to minimise risk and the impact of other factors such as hardware or software failure or unexpected challenges the project might face for example due to Covid-19.

- **GitHub**

  GitHub was used throughout the development of the project to track software changes over time. This meant the project could easily roll back to an earlier stage if needed.

- **Google Docs**

A Google Doc page was setup so that quick notes and to-do-lists could be created easily and accessed on any device and shared with if needed.

- **Backups**

  A comprehensive backup structure was employed to ensure the work done was not at risk of being lost. This not only applies for software which used GitHub as a primary means of backup but also for documentation and progress tracking. Backups were stored on multiple devices as well as on cloud services such as Google Drive.

Chapter 5

Hardware Development

5.1 The MindFlex Hack

At the heart of this project lies the method of collecting EEG data, this was carried out using a MindFlex.

Finding a MindFlex for sale was initially considered to be a difficult process as production on had stopped and the product had been discontinued, however after searching around online it became clear Facebook Marketplace was the best bet as it advertised a few MindFlexs for sale from all over the UK. This discovery meant that process ended up being much less of an ordeal than was thought and within a week a MindFlex arrived for a mere £5.00 (excluding shipping). This was particularly good news as the MindFlex was thought to be one of the largest financial costs to the project and this purchase had proved how affordable a production quality version of this project would be. This meant the project was able to adhere to its key aims, one of which was 'producing an inexpensive solution to the problem in hand'.

In terms of physical changes, the hack required two copper wires to be soldered, the first wire was soldered onto the TX pin on the NeuroSky chip. The TX pin on any plastic circuit board (PCB) represents the transmission pin, meaning that the collected data flows though. In this case the EEG data would flow from the TX pin along the copper wire into the microcontroller to then be sent to the computer. The second wire is simply a ground connection from the main PCB to the microcontroller, this ground connection is the same as the one used by the ear clips on the MindFlex which are used to ground the person wearing the headset.

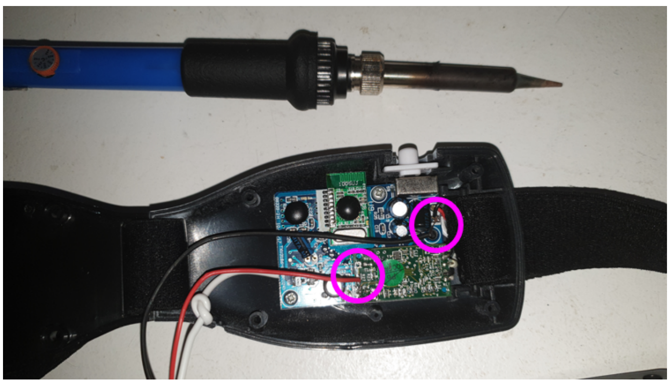

Figure 5. Soldering MindFlex to Eleegoo Uno

5.2 Micro-controllers

The Eleegoo Uno was used to connect to the NeuroSky chip inside the MindFlex. This means the two wires (data and grounding) that were soldered on in the MindFlex hack from the internals of the MindFlex lead directly into the GND and RX pins on the Eleegoo Uno. This microcontroller acts as a temporary hub for the collected data, the microcontroller has the Arduino Brain Library software installed so that it can parse the NeuroSky EEG data and send the interpreted data to the main computer.

The also project makes use of the NeuroSky chip which is built in to the MindFlex (see figure 5). The NeuroSky chip is produced by ThinkGear AM [41]] and is used in millions of other devices all over the globe, the chip is mainly used in professional level medical equipment to process raw EEG data. The original purpose of the chip in the MindFlex was to determine the subject's current concentration level, this is achieved using the single electrode on the headset which allows the chip to internally calculate an 'Attention' and 'Meditation' value. The calculation method for these values is not public and so the NeuroSky chip is essentially a black box that results can be collected from. Although there is have no insight into how the attention and meditation values are calculated they are still extremely useful, it is also apparent that the values are reliable due to how commonly this chip is used in much higher-grade medical equipment.

Figure 6. Assembled Device

5.3 Hardware Considerations

Originally the project planned to make use of a few other hardware modules such as a small speakeras well as an ECG electrode to supply heart rate readings to compliment the EEG data. However, it quickly became apparent that this was not possible due to the NeuroSky chip using half-duplex transmission [42]. This meant data could be received from the Eleego Uno, but data could not be sent back, making additional hardware modules not possible. However, this did not turn out to be a large issue as software can easily be used to play an alarm sound and an ECG was unnecessary due to how comprehensive the EEG data was.

Chapter 6

Software Development

6.1 Arduino Code

The Arduino code used for the project was taken from the freely available project ‘Brain’ by Kitschpatrol [43]. The project prerequisites require the MindFlex to have the TX and ground pins rewired so they can be fed into the Arduino/Eleegoo ports (see section ** for more details). The code provided by the Brain project is written in C++. This code then needed to be opened inside the Arduino IDE and imported.

Next the example script provided titled ‘BrainSerialTest’ was uploaded to the Arduino, the script uses the Brain library installed and instructs the Arduino how to deal with the inflowing data from the NeuroSky chip. The main purpose of this script was to print the EEG data received to the serial port so it could be received by the Java software, this was set up so that every time new data was received the data would be printed. As well as the EEG data it was necessary to send error codes that may occur so faults could be diagnosed and dealt with effectively, therefore these error codes were also sent down the serial port.

6.2 Data Processing

6.2.1 Data Processing in Java

This section covers how the raw data collected from the NeuroSksy chip is processed and used in calculations in order to determine if the subject is asleep, this process can be described as the algorithm which provides functionality in the system.

The first stage of this process formats the data to ensure the data is ready for processing. This first stage essentially turns the raw data collected into formatted data objects which are then used to determine if the user is asleep. Readings are taken and transmitted to the computer from the Eleegoo microcontroller about once every second, each transmission contains two lines of CSV-style data that are transmitted as Strings. The first line represents the brain wave values the NeuroSky chip has produced. An example line can be seen below (the first few characters are a timestamp).

15:44:41.273 -> 200,0,0,2403506,268580,165134,499332,148156,149799,81382,209521

There are 11 values in total: [Signal Strength, Attention, Meditation, Delta, Theta, Low Alpha, High Alpha, Low Beta, High Beta, Low Gamma, High Gamma]

Every second line produced by the NeuroSky chip is reserved for error reports. These lines are also transmitted as they allow the processing software to filter out data that may be corrupt or incorrect. This is done by simply checking for an error and if one is seen the next line of data is discarded. The error lines come in multiple different forms though a generic example, which can be seen below (the first few characters are a timestamp).

15:44:57.196 -> ERROR: Packet too long

The following process is a summary of how each new line of data received is processed and used to ultimately determine if the subject is currently asleep. Specific details on the classes involved and their key code can be seen in the next subsection of this document as well as in the source code itself. Please note this process only describes the back-end data processing done in Java, it does not describe how this data is represented in the GUI or how the Eleegoo microcontroller processes data.

1. The error line is used to filter out data that could be of poor quality and should be discarded.

2. A new RawReading object is created and the string of data called ‘currentLine’ is added as the only parameter. The RawReading class is used to split the currentLine string and return an array of String values (rather than a single CSV-style string).

3. A new SerialData object is created and takes the current line count ‘y’ (which will be used as the time axis) as well as 11 individual string values from the newly created RawReading object, produced in the ‘splitRawCsv’ method.
This SerialData object handles the auxiliary data functions such as returning the normalised values (as doubles) or returning an array of the values (as integers).

4. This newly created SerialData object is then added to the eegData ArrayList (that was initialised on startup to take SerialData objects).

5. A rolling average value is then calculated for all 11 data channels for the previous 100 samples. The reason for this is discussed in the calibration testing section of this document (see section 7.1).

6. This data now represents the past 100 sample average for each brain wave channel so we can now do a simple check to see if the current mediation value is above 0.75 and the low alpha value above

0.05. This checks that the subject has, on average, been feeling relaxed above a certain threshold value for the past 100 seconds. If this value returns a True result, then we know the user is asleep and the alarm countdown can be set from this moment.

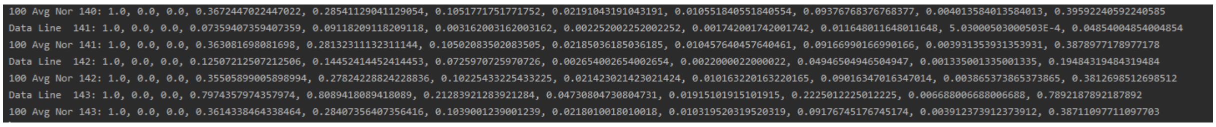

Figure 7. Data and Rolling Average Calculated

6.2.2 Java Processing Classes and Methods

This section aims to provide a brief overview of purpose of the four java classes created and their key methods, for full documentation please refer to the source code.

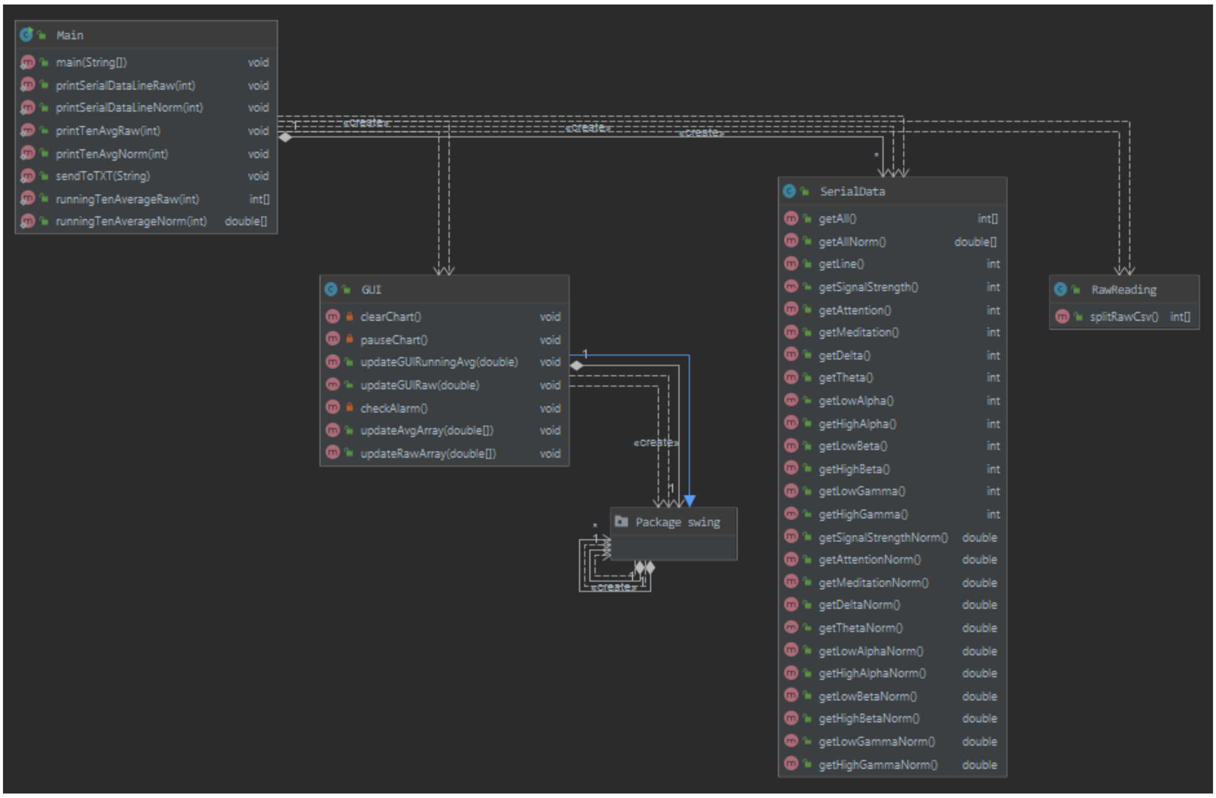

Figure 8. Java Software UML Diagram

- **Main.java**

  The main method starts off by listening for available serial ports and creates a Scanner object out of the first open communication port it finds. This scanner object is then used to listen for new data in the data stream.

  The main method also starts the GUI class as well as creates the other class objects which facilitates the data processing. In addition, the Main class provides helpful test functions such as printing live data to terminal, saving test data to a text file as well and catching exceptions if any are thrown.

- **RawReading.java**

  The RawReading object is one of the first class objects to be created (besides the GUI), this objects only purpose is to take in the String object from the scanner, which originated from the Eleegoo Uno, and split this CSV-style string into 11 individual values which can be called upon later. Therefore, this class only has one method 'splitRawCsv' and takes a single String in its constructor called 'rawCsv'.

- **SerialData.java**

  The SerialData class is where most of the data formatting take place. This class takes multiple integer parameters which have been created from the splitting of the String in the RawReading method. These values can then be processed, this is done using many methods which return the normalised values of the integers passed (the raw readings from the MindFlex). These values can be remotely accessed individually or as a group in an Array object.

- **GUI.java**

  The GUI class takes care of the user interface and charts. To achieve this it holds arrays of rolling averages of the data collected so far which are then updated and plotted onto the line chart. This class also takes care of listening for user inputs such as the pressing of buttons. It also takes care of deciding when the alarm should be set using its 'checkAlarm' method. This method checks that the past 100-sample average reading for the meditation value is above 0.75 and the 100-sample average for the alpha value is above 0.05 and if so, the wait to sound the alarm begins.

6.3 Interfaces

6.3.1 Graphs

To visualise the data a line chart was seen as the best option as they are particularly good at visualising changes in the data over time. An external library for Java called xChart was used to implement the line chart. One important feature of the chart is its high refresh rate, which is necessary to keep up with live data, this was achieved by using a method call to re-plot the chart when new data is received (about every second), which would add a new point on the chart and increment the X axis (time). The chart is also designed in a clear and concise manner to help with quick diagnostics, this is achieved through clearly showing all the channels using distinct colours, as well as automatically updating the max value on the Y axis to the max value of the set of data collected so far, this helps to remove white space from the visualisation.

6.3.2 GUI

This project focuses on demonstrating the possibility of such a product being produced and made available to those who need it as a useful tool. Therefore, it should be noted that the project was not focusing on producing an aesthetically pleasing user interface as it is not intended to be used by anyone else outside the project. There were a few requirements of the user interface, these requirements helped in development to make using the system easier and to help with accessing the effectiveness of the system quicker and more intuitive.

The main use of the GUI is to display the line chart which represents the subjects state of mind over time, this is discussed in detail in the previous sub-section seen above. The GUI also features a slider which allows the subject to pick a nap length between 5-40 minutes. A maximum of 40 minutes was chosen as anything over 40 minutes means the user has likely entered a later sleep stage such as REM sleep. These later stages of sleep can cause somewhat unpredictable fluctuations in the user's mind state and could cause an untimely alarm to be set off. In addition to this the vast majority of people would likely nap for far less than 40 minutes, these two reasons combined meant that a 40-minute upper bound was seen as a sensible choice. The GUI also features two minor buttons: one that clears the chart to make it more readable after a long period of time, and another to cancel the current alarm set.

Please see figures 10 and 11 on page 24 for GUI.

6.4 Software Complications

One of the earliest issues encountered was caused by the Brain library installed on the Eleegoo microcontroller. The problem surrounded the error lines produced by the Brain library; these lines are transmitted after every line of data to announce any issues that may have occurred. The issue was caused when the error lines would for no apparent reason repeatedly print "ERROR: Packet Too Long" indefinitely. After some digging on online forums it became apparent that the issue was a buffer overflow issue with the Brain library C++ code installed on the Eleegoo Uno. The bug is thought to be caused by sending too much data down the output stream at one time. This bug had far reaching consequences and in some caused the data outputted to be corrupted and therefore unusable. It was crucial for this to be fixed as soon as possible, some solutions required changing the baud rate which was not ideal as it would lower the processing speed of the microcontroller and consequentially lead to less data being made available.

This issue was however predictable which made avoiding it easy. The buffer overflow would consistently begin within the first 10 lines of data being received and then would endlessly overflow until the program was terminated. This means a simple check could be carried out to ensure the error did not occur and if it did the code was just restarted. It should be noted that this issue will likely not exist for long as the creator of the Brain library has acknowledged the issue and is working on a fix.

Chapter 7

Testing and Results

7.1 Calibration Testing

After assembling the hardware and software, the next step was to test that the data being collected was of high quality, this means ensuring the data is not skewed in any way and was as accurate as possible. Accuracy consists of variance and bias, an example of this would be one of the channels showing huge variances in the readings, represented on the line graph as a sharp drop up or down. Another example are biases in the readings, meaning the collected data does not represent reality and is consistently above or below what is expected.

The first challenge to tackle was the variance, this was the main challenge in the calibration stage due to the hardware limitations of the MindFlex. The headset uses a single FP1 'dry electrode', this is a far cry from the medical grade electrodes which often use silver chloride gel to yield far less raw noise in the data collected. However, even though the producers of NeuroSky chip inside the MindFlex claim they have an effective method of filtering noise, the initial graphs plotted still showed significant variance for each individual channel (attention, meditation, delta etc.).

Two techniques were used to try and reduce the persisting variances in the data channels. The first was a simple filter added to the SerialData.java class, this filter was placed within the 'getters' of the class which were a simple if-else statement which would check to see if the data was out of bound, meaning if the current normalised reading produced was above 1.0 (values should strictly be between 0.0 and 1.0 in normalised data) the value would be discarded and 0.5 would be used. A value of 0.5 was chosen as it is a middle ground between high and low values. Normalised values above 1.0 are produced by anomalies the electrode picks up, likely from background interference, it is vital to discard these anomalies to reduce variance and increase overall accuracy of the data.

The second technique used to reduce variance was the use of a rolling average. It quickly became apparent that simply plotting raw data after it had been filtered for anomalies would still produce too high variances. To reduce this effect a 100-sample rolling average was used to take an average of the past 100 data samples. This drastically reduced the variance in the graphs and the line graphs were much smoother. This method does come with the compromise that the first 100 seconds of wearing the headset produces no data as there are not enough samples to calculate an average, however this was seen as an acceptable cost as it is highly unlikely that the subject will fall asleep within 100 seconds of putting on the headset. A comparison between live data and averaged data over a 200 second period can be seen below in figure 9.

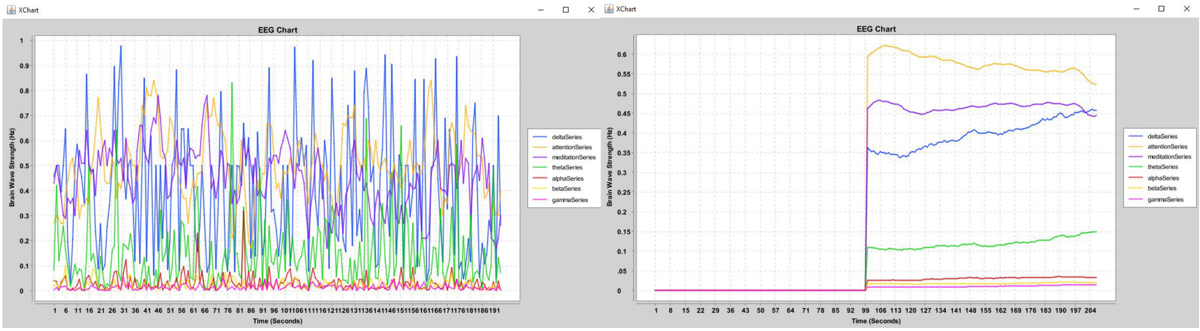

Figure 9. 200 Seconds Graph of Live Data Vs 100 Sample Rolling Average

The most affected method found to reduce bias in the system was correct use of the headset. This meant ensuring the electrode was placed cleanly against the skin and above the subjects left eyebrow for the clearest readings. Another considerable obstacle was the interference the electrode experienced from other nearby electronic devices, this was only mitigated through using the device in a room with thick walls and minimal electronics nearby. This however is a problem that all EEG machines experience as power lines operate around 50-60Hz which is the same frequency as gamma waves which can be picked up on by the electrodes.

7.2 Functionality Testing

Due to the nature of this project unit testing was not suitable, therefore the black box testing approach was seen to be more appropriate as it will specifically test the requirements of the software. To achieve this, ten test subjects were recruited using the snowball recruitment method. These test subjects would then each attempt to take a nap for and see how effective the system was at identifying when they had fallen asleep and therefore when the alarm time was set. The test subjects were also instructed to complete short questionnaire which had been prepared. The questionnaire allowed for control questions to be asked such as ‘how often do you nap’ to help further explain the test results. The questionnaire meant the subject were able to reflect on their their experiences and help the project gain more insight into the device form an end user’s perspective. The questionnaire and results can be seen in Appendix A.

To carry out this process a few preparations were necessary. For example, the test needed to be set up in each room the individual subject felt most comfortable falling asleep in. The user also had to consent to the project making use of their questionnaire data.

Out of the 10 test subjects, 4 were unable to fall asleep and out of the 6 that did fall asleep 4 alarms were successfully set around the time of the subject falling asleep. The test subjects who were unable to fall asleep also indicated it often took them a while to fall asleep in the questionnaire they filled out. Figure 10 is a prime example of the system working as intended on test subject number 2.

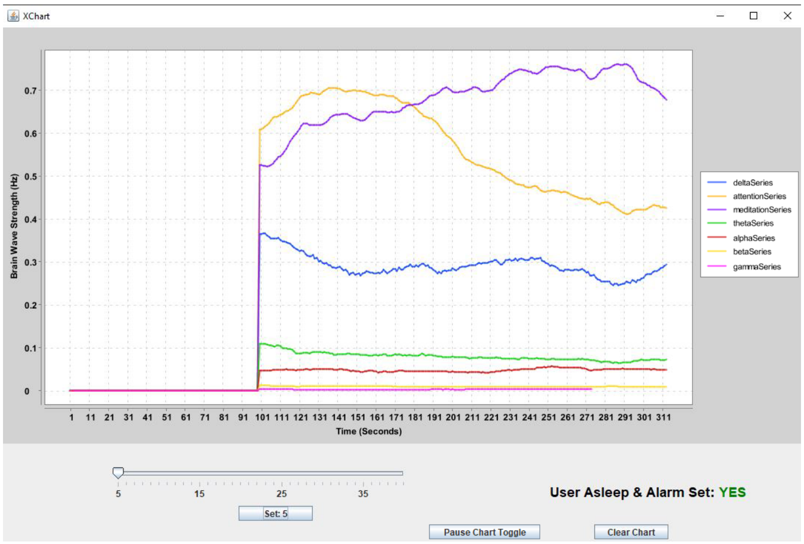

Figure 10. Test Subject #2 Data

The test subject was able to fall asleep quite quickly and around at the 150 second mark the attention value fell sharply while the meditation value continued to rise. This is the first indication the subject is beginning to drift off to sleep. Then around the 230 second mark the alpha readings began to rise ever so slightly, this indicates the subject's mind state is no longer thinking about anything in particular which is typical of the early sleep stages. At around the 240 second mark both the meditation value was greater than 0.75 and the alpha value was above 0.05 meaning the alarm was set at that moment. This is a good demonstration of the system working perfectly the system working perfectly.

Although the values do somewhat fluctuate after this point the trend stays the same. It is also quite common for people to move around in the early sleep stages as they subconsciously move around as they try to find a comfortable position. These factors can contribute to some of the fluctuations, this is also the reason the subject is not constantly checked for being asleep, but is instead checked until they have fallen asleep and then no more.

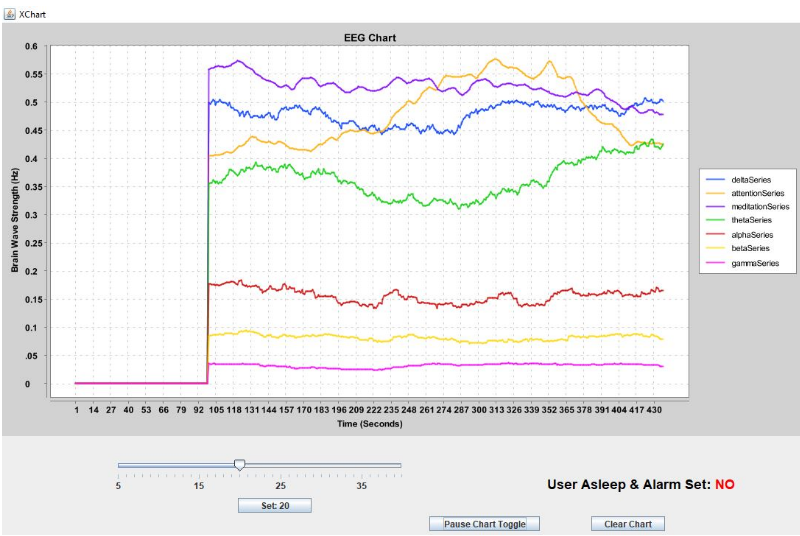

Figure 11. Test Subject Failed to be Recognised as Asleep

Figure 11 shows one of the two subjects who were able to get to sleep but the system was unable to recognise this as their meditation value never rose above 0.75.

Chapter 8

Evaluating Results

8.1 Results and Effectiveness

8.1.1 User Testing Evaluation

Looking back at the user testing stage we can estimate an effectiveness and accuracy rating of 67% based on the six subjects who were able to fall asleep. For a proof-of-concept system this is more than acceptable, this minimum viable product proves the real-world capabilities of such a system and that it is a viable product.

By looking at the outputted graphs from the user testing it was clear to see that the system worked as intended, the meditation and alpha waves increased as the user fell asleep, and this was recognised by the system which would consequentially begin the alarm timer.

When reviewing these results, it is important to consider the limited test size caused by Covid-19. The pandemic meant the project's user testing was only able to safely use of a limited number of test subjects and so the sample size is not considered large enough to draw definitive conclusions from. Though the small sample size still indicated the system does work as is intended on end users.

It is also important to consider the two subjects who fell asleep but the system was not able to recognise it. One of these two subjects stated on their questionnaire that they often struggled to fall asleep, meaning the unusual nature of the testing environment might have cause an abnormal sleeping pattern. Although there are several other possible technical reasons for these two failures. The most likely being nearby electrical interference.

During the project calibration testing stage, it was observed that some nearby electrical devices can interfere with the device and cause noise in the data. For example, it was observed that a nearby laptop on charge caused issues with the meditation value produced. The testing was conducted in the test subject's bedroom it which meant there were possibly other unknown devices nearby which could cause some interference and produce poor data leading to the system failing. There are also other more obvious causes of these failures, such as the test subject wearing the headset imperfectly meaning the electorate may not have been in the ideal position, or even factors such as how thick the user's hair was or how moist their forehead was could impact on the data. The brain wave patterns are also unique for each person which could also be a contributing factor [44].

8.1.2 Comparing to Related Methods/ Products

It is difficult to compare this device to other products and methods as very few of them serve a similar purpose. However, we can compare the options a subject has when in a specific situation. For example, if a lorry driver is required to take a 30-minute nap to continue driving, they have limited options to choose from. Arguably their current best option is to make use of an alarm and sleep tracking app to help them learn about the quality of their sleep. However, this does not really solve their problem of needing a 30-minute nap as the alarm does not know how much sleep they will actually end up getting and the sleep tracking app only helps themlearn to sleep better in the future.

While these tools are useful, they do not solve the problem at hand, on the other hand the device this project has created does solve the problem. The driver will be able to get the specified amount of rest and continue driving on safely. This is applicable to other situations as well, people who know their perfect nap length can now achieve it consistently.

8.1.3 Limitations

The development of this device has helped to highlight a few pitfalls in the current version. However, it is more than likely that a future version of the device would be able to improve and overcome these limitations.

One of the most obvious issues with the device is that it is unable to adapt to different environmental settings. This means a person who may emit different strength brain waves may not have as much success using the device. One possible solution to this issue would be the use of an unsupervised machine learning approach to predict when the subject has fallen asleep based on the previous data points rather than a hard threshold value as is used in this project. Though this is big task to carry out and so was not seen to be feasible in the scope of this project.

Noisy data caused by electrical interference has also been a limiting factor of this device. The anomalies in the data can cause the system to be processing bias data which could lead to failure. This could be mitigated by developing a filtering algorithm.

8.2 Reviewing the Project Aims

In the introductory chapter of this document four key project aims were laid out, each detailing key criterion for the project to be a success. All of these aims have been met. Aim one was to design an inexpensive hardware system for the project. This had been achieved though the use of cheap and mass-produced parts as well as minimal hardware modules, the total hardware cost is approximately £10.00.

Aim number two was to create bespoke data processing software to calculate whether a subject is asleep, this had been achieved in the Java software that was created for the task. Aim number 3 was to provide functionality to the system, this was achieved using a graphical user interface that was created to allow controlled over the alarm settings. The final aim was to provide a solution to those who struggle with lack of sleep and provide a device which encourages positive napping. It is clear from the user testing that this device demonstrates a possible solution to this problem and can help those who struggle with a lack of sleep and harness the medicinal value of napping.

Chapter 9

Conclusion

9.1 Future Work

This project has demonstrated a possible solution to regular nappers and to people who suffer with sleep disorders who want greater control over their nap length. This was achieved using a minimum viable product prototyping approach which aims to demonstrate the possibility of such a product and its potential far-reaching applications as not only a useful tool to regular nappers but also as a medicinal product.

The device produced in this project is a proof-of-concept style device, many improvements could easily be made to make to device more accurate, more comfortable, and more reliable. Future work will consist of improving upon these 3 aspects. This means making use of smaller, more efficient hardware to make the device more compact and therefore more comfortable. Accuracy can be improved by implementing a machine learning approach to predicting the users sleep state. Finally, the reliability could be improved by creating a bespoke noise filtering algorithm, this will help to reduce the effect of nearby electronic devices meaning it could be used in almost any situation

9.2 Discussion

This project has been an exciting and testing journey. Developing a novel piece of hardware and accompanying software over many months was a huge challenge, yet it was also extremely rewarding getting to see the device come together over time and end up work perfectly as intended. The project has also been a great learning experience, reading dozens of medical papers on electroencephalograms, and the technology surrounding them, has provided a good foundation of knowledge surrounding the health technology industry.

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Appendix A

Questionnaire and Results

1. Test Subject Number 0

2. How often per week do you take naps? 0

- <1
- 1
- 2
- 3
- 4+

3. When was the last time you slept ? 0

- Last night/ this morning
- Napped this afternoon
- Other (please specify)

4. How often do you struggle to get to sleep? 0

- Very Often
- Somewhat Often
- Rarely
- Never

5. How long do you usually take to get to sleep? 0

- 0-5 mins
- 6-10 mins
- 11-15 mins
- >15 mins
- I'm not sure

6. Do you think a polished version of this device could help you or someone you know of ? 0

- Yes
- No

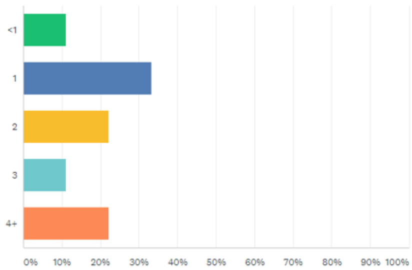
7. How often do you suffer from disturbed sleep e.g. nightmares, sleepwalking, sleep paralysis etc? 0

- Very Often
- Somewhat Often
- Rarely
- Never

Q2

How often per week do you take naps?

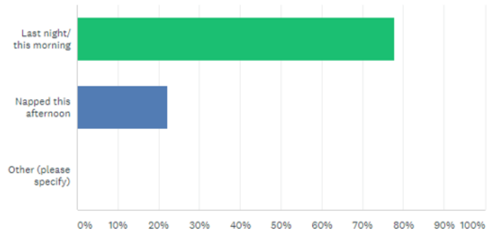
Answered: 9 Skipped: 1



Q3

When was the last time you slept ?

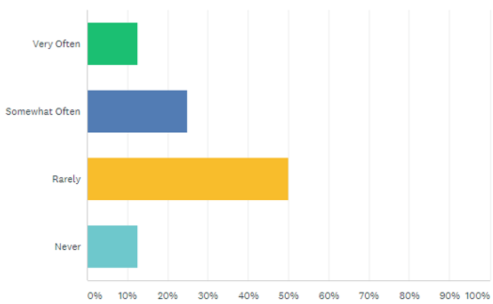
Answered: 9 Skipped: 1



Q4

How often do you struggle to get to sleep?

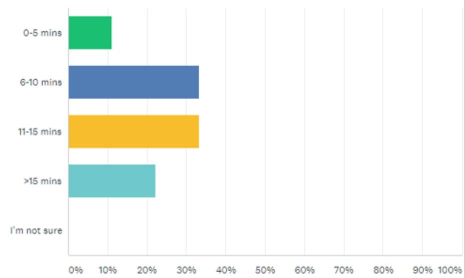
Answered: 8 Skipped: 2

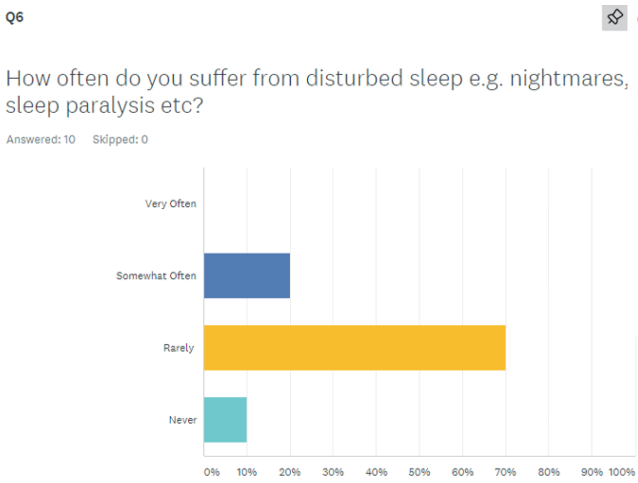


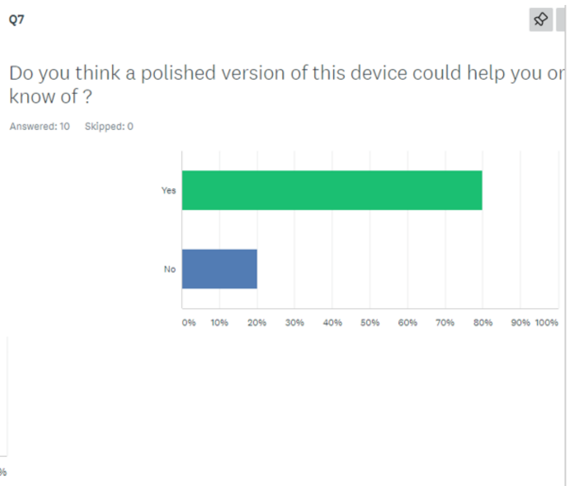
Q5

How long do you usually take to get to sleep?

Answered: 9 Skipped: 1




Q6
How often do you suffer from disturbed sleep e.g. nightmares, sleep paralysis etc?
Answered: 10 Skipped: 0
Very Often
Somewhat Often
Rarely
Never
0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%


Q7
Do you think a polished version of this device could help you or
know of ?
Answered: 10 Skipped: 0
Yes
No
0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%