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Master's Thesis

Academic Year 2021

Vibrain: A Haptic Entrainment Based Wearable Relaxation Device

Keio University

Graduate School of Media Design

Rahul Mehta

A Master's Thesis
submitted to Keio University Graduate School of Media Design
in partial fulfillment of the requirements for the degree of
Master of Media Design

Rahul Mehta

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Abstract of Master's Thesis of Academic Year 2021

Vibrain: A Haptic Entrainment Based Wearable Relaxation Device

Category: Science / Engineering

Summary

Stress is the feeling of being overwhelmed or unable to cope with mental or emotional pressure. Work-related stress is the response people may have when presented with work demands and pressures that are not matched to their knowledge and abilities and which challenge their ability to cope. This thesis presents Vibrain: a Haptic Entrainment based Wearable Relaxation Device. The goal of this study is to develop a wearable device that can relax the user and help them relieve stress. Vibrain's working is based on the concept of Brainwave Entrainment where a rhythmic stimuli causes the brainwaves to synchronize to the frequency of the stimuli. The evaluative study performed in this research is an Electroencephalography (EEG) study. In user study EEG data is compared between Vibrain and an EMS neck massager in a Within and Between Subject study.

Keywords:

brainwave entrainment, EEG, rhythmic haptics, stress, alpha waves

Keio University Graduate School of Media Design

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Thanks to all my electronics that I dearly love and barely clean. Sorry guys. Thanks to Valorant for keeping (and destroying) my sanity throughout this thesis writing process.

Lastly, thanks to myself for working hard and fighting my constant need to procrastinate. Good job, Me.

Chapter 1
Introduction

1.1. Workplace Stress

Stress is a common part of our life in the 21st century. Whether it is school or workplace, everyone experiences some level of stress. The World Health Organization (WHO) defines stress as body's response to one's inability to cope with the pressure or challenges of a work place[1]. It can manifest as anxiety, frustration, depression and so on.

Biologically speaking, there are a multitude of consequences of stress but this study focuses on the psychological aspect of stress. One of the psychological consequence of stress is the loss of focus. Psychological stress influence's one's desire to work and performance at work and can greatly affect the productivity. Continued release of stress hormones also have detrimental effects on health.

The focus of this study is on designing a non invasive device for relaxation using the concept of brainwave entrainment.

Although there are a few products commercially available that intend to help the consumers to relax and release stress, these device often rely on meditation and/or closing eyes to achieve that effect. However, in an office/school setting and with deadlines, users often don't have the time to sit and relax in one place as their mind is still filled with worries of the work not getting completed on time.

Therefore, this study also aims to make the device in a way that acts passively while the user can focus on their work.

1 `who.int/news-room/q-a-detail/ccupational-health-stress-at-the-workplace`

1.2. Research Motivation

Stress is a serious condition that could lead to several health problems. As a student pursuing higher studies, stress is very much a part of my daily life. Almost all students and working professionals experience stress to varying degrees and it affects their mental and physical health.

As a master's student, I am constantly working against deadlines and competing against my peers. I am lucky enough to be mentally resilient but a lot of people break under pressure. Elevated stress levels can impede performance on tasks that require divided attention, working memory, retrieval of information from memory, and decision making. [1]

Meditation is a great tool to deal with stress as it calms down the brain and relaxes the body but it is not an option when people are running on deadlines. This causes people to rely on medication or other substances to deal with stress.

I wanted to design a wearable device that can work in the background and help me relax myself while I continue to focus on my work. While browsing videos on YouTube on "study music", I came across "Binaural Beats" videos (fig 1.1). This led my way into the field of brainwaves and brainwave entrainment. This study explores the effect of rhythmic vibrations on the brainwaves, also known as haptic entrainment, and it's effectiveness on stress relief.

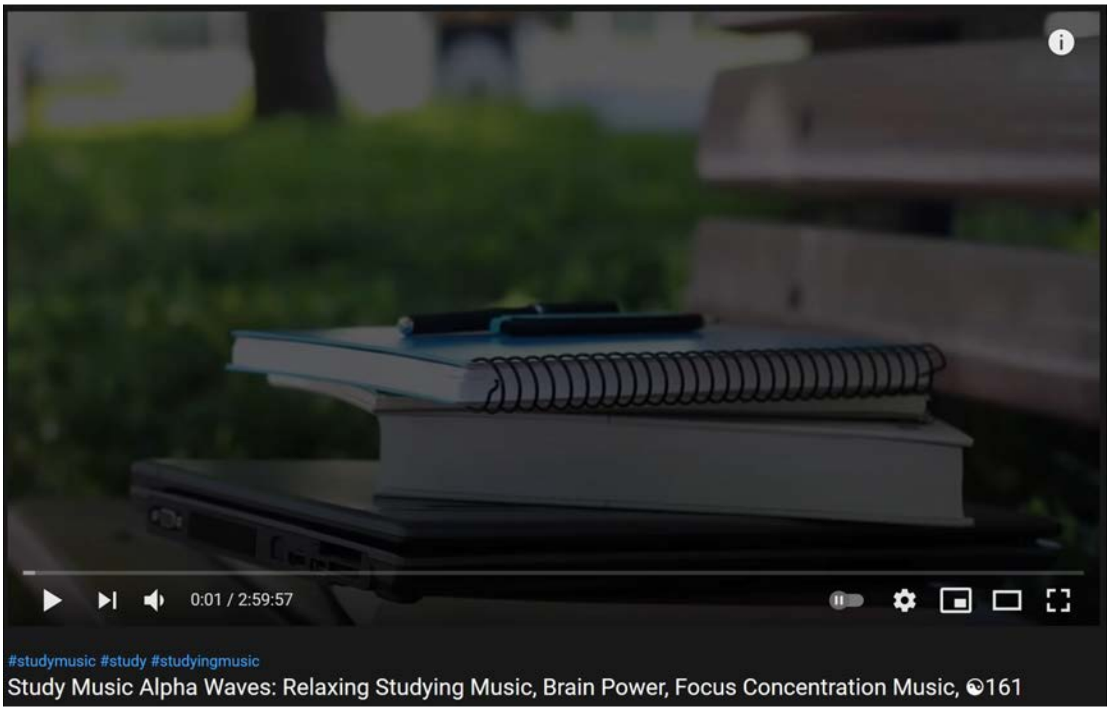


Figure 1.1 Binaural Beats on YouTube[2]

1.3. Research Goals

In this study, I apply the concept of haptic entrainment to synchronize the brainwaves to an external rhythmic haptic stimuli. When an individual is under psychological stress, the dominant brainwaves in the brain are high beta waves (HBW) (21-30 Hz) [2]. HBW are associated with anxiety, overthinking and overstimulation. [3] A stressful state of mind causes a loss in productivity. [4]

Alpha waves, on the other hand, are often associated with relaxation, eased state of mind and focus [5].

Following are the goals of this study,

- Build a wearable device that can be used while performing office/school

2 `youtube.com/watch?v=WPni755-Krg&ab_channel=YellowBrickCinema-RelaxingMusic`

work to help the individual to relax and manage stress.

- Perform an EEG study to evaluate the effects of the wearable device.

1.4. Thesis Outline

- **Chapter 1** introduces stress in workplace and how it negatively affects people. It also discusses about the general direction of this study.
- **Chapter 2** discusses about literature related to EEG, brainwave entrainment, stress and stress relief wearables.
- **Chapter 3** describes the concept behind Vibrain. It goes over the design process and the core mechanism of the device.
- **Chapter 4** validates (or invalidates) the hypothesis using the EEG data obtained from the user test.
- **Chapter 5** summarizes the study and discusses about the limitations and future possibilities of the study.

Chapter 2

Literature Review

2.1. Inside the Human Brain

This chapter discusses literature from various fields including brainwaves, stress, electroencephalography (EEG) and brainwave entrainment. Related works are used to lay the groundwork for this study.

2.1.1 Neural Oscillations

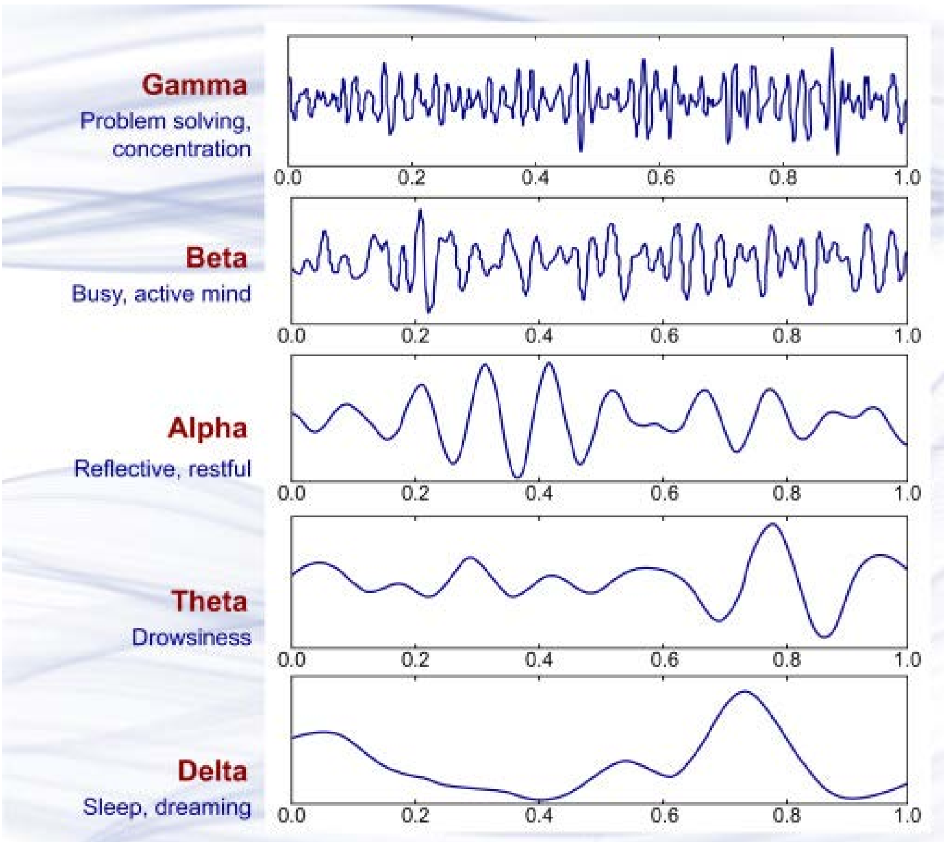
Neural Oscillations are electrical impulses, measuring just a few millionths of volts, in the brain caused due to communication between the neurons. These impulses are also known as brainwaves. [6] Different brainwaves exist in different regions of the brain and these pattern are unique to each individual.

There are five different types of brainwaves (fig 2.1) that exist in the human brain and they are classified on the basis of frequencies.

- Delta Waves (0.5 - 4 Hz) are low frequency waves that exist during deep sleep in a normal healthy adult brains and infants brains that are still developing. In some cases, they are also present in adults who are awake but their brains have experienced some kind of damage due to inflammation, a tumour, or a vascular blockage.
- Theta Waves (4 - 8 Hz) in normal healthy adults appear transiently during sleep. Studies have also found that theta waves, different from the ones during sleep, occur during Transcendental Meditation. [7]
- Alpha Waves (8 - 12 Hz) in healthy adults commonly occur in the occipital region of the brain. They exist when the individual is resting with eyes closed and vanish when the individual concentrates on a specific task.

- Beta Waves (12 - 35 Hz) are common when an individual is concentrating or experience stress and/or psychological tension. Beta waves usually replace alpha waves when an individual opens their eyes and are also present in the occipital and frontocentral regions of the brain.

- Gamma Waves (Above 35 Hz) are associated with heightened perception or peak mental state and are the fastest waves detectable by EEG.



(Source: Technological Basics of EEG Recording and Operation of Apparatus [6])

Figure 2.1 Classification of Brainwaves

The focus of this study is on psychological stress and relaxation which is why only the alpha and the beta waves will be explored in chapter 4.

2.1.2 Measuring Brain Activity

Over the years, numerous technologies have been developed to explore what goes inside the complex organ, the human brain. Some of these technologies are invasive and some are non invasive and each has its own advantages and disadvantages as compared to others. This section explores these technologies.

Electroencephalography (EEG)

Electroencephalography (EEG) (fig 2.2) is a non invasive neuro-imaging technique. It is a graphic representation of the difference in voltage between two different cerebral locations plotted over time. The scalp EEG signal generated by cerebral neurons is modified by electrical conductive properties of the tissues between the electrical source and the recording electrode on the scalp, conductive properties of the electrode itself, as well as the orientation of the cortical generator to the recording electrode [8]. This study employs the use of EEG for measuring the brain activity because of it's ease of use and non-invasive nature.

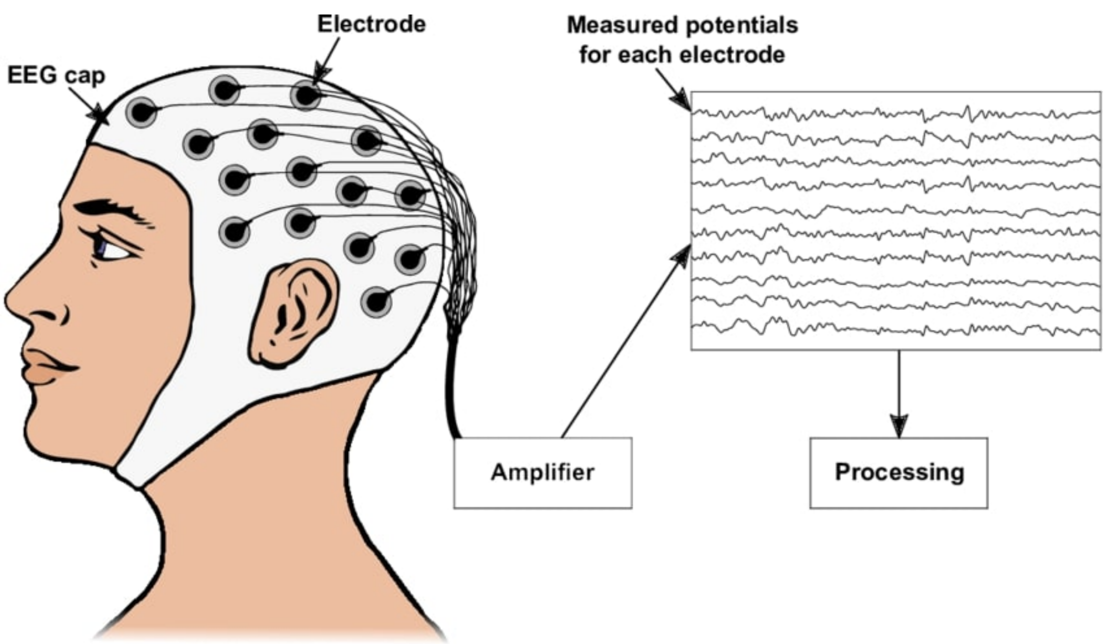


Figure 2.2 Electroencephalography and Electroencephalogram [9]

Electrocorticography (ECoG)

Electrocorticography is similar to EEG in the sense that it record electrical activity but in ECoG, the electrodes are placed directly onto the exposed surface of the brain. Due to this, the attenuation of the signal due to the scalp and skull are not present in the ECoG output, the electrocorticogram. ECoG is employed mainly to confirm and outline the actual site and extent of the epileptogenic process prior to resection. It is also used to determine if the epileptogenic tissue has been removed after the resection [10].

Magnetoencephalography (MEG)

Magnetoencephalography (MEG) uses an array of sensors positioned over the scalp and these sensors measure the magnetic field produced by the change in electrical activity in the brain. It is therefore, a direct measurement of brain activity [11]. MEG was originally used in the 1960s but it's full potential was realised in the 1990s where researchers used high density detector grids that cover the whole head.

functional Magnetic Resonance Imaging (fMRI)

Functional Magnetic Resonance Imaging (fMRI) measure brain activity by detecting the changes in the blood flow in the cortical region. It uses the blood oxygenation level dependent (BOLD) contrast. BOLD fMRI detects local increases in relative blood oxygen levels that are supposedly a direct consequence of neural activity [12]. fMRI has a much precise spatial resolution as compared to EEG and MEG.

functional Near Infrared Spectroscopy (fNIRS)

Near Infrared Spectroscopy was originally designed for tissue oxygenation. Functional Near Infrared Spectroscopy (fNIRS), similar to fMRI, monitors the blood oxygenation by the optical differences in oxygenated and deoxygenated haemoglobin [13, 14]. fNIRS is immune to motion artifacts and subject positioning.

Why EEG?

The above mentioned technologies are just a few of all existent brain activity measurement technology. Even though some of these technologies provide precise and accurate picture of what goes inside the brain as compared to EEG. EEG is still very much reliable and much easier to use as compared to the other technologies.

Current technological advances have made it possible to have EEG in a wearable form which makes it potable and easy to use even for non-professionals. Numerous EEG wearables are commercially available for those curious to know about what goes inside their brains.

2.1.3 Psycho-physiology and Brainwaves

As mentioned in the previous section, brainwaves are different frequencies of electrical activity in the brain. There are five major brainwaves delta, theta, alpha beta and gamma waves. Brainwaves are unique to each individual. Various regions of the brain do not emit the same brain wave frequency simultaneously but two or more than two brainwaves can exist in a particular region of the brain at one point of time.

Researchers, over the years have found that brainwaves change greatly depending on the physiological state of the person. These frequency change as the person ages. By detecting excess or lack of a particular brainwave, it is possible to detect an underlying neural disease.

Visual analysis of the EEG in Alzheimer's patients has demonstrated a slowing of the dominant posterior rhythm, an increase in theta and delta rhythms and a reduction in beta and alpha activities [15].

Meditation and EEG is a very commonly researched topic in the field of Neurology. Most of the studies conclude that there is an increase in theta power during mindfulness meditation [16, 17].

The following section discusses literature about alpha-beta rhythms and the relation of brainwaves to stress.

2.2. Entrainment

Entrainment is a phenomenon where two or more oscillating entities oscillating at different period synchronize to each other and assume a common period. Dutch physicist, Christiaan Huygens, the inventor of the pendulum clock, introduced the concept after he noticed, in 1666, that the pendulums of two clocks mounted on a common board had synchronized.

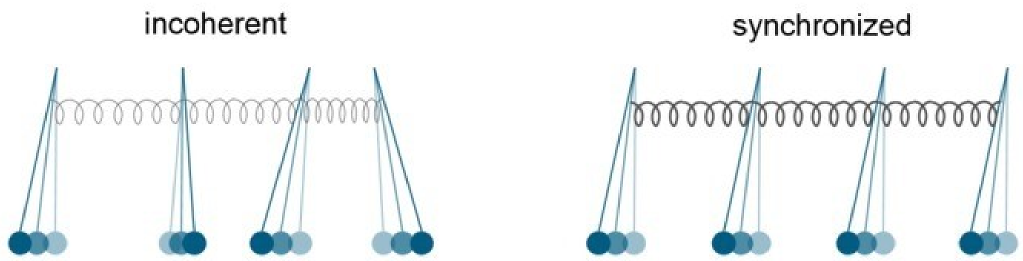


Figure 2.3 Incoherent pendulums achieving synchronization due to entrainment

We experience entrainment a lot of times in a day without even realising it. Tapping feet to the beat of the music or two people walking together and their footsteps synchronizing with each other are both examples of entrainment.

Neural rhythms, i.e. brainwaves, also synchronize to external stimuli and this phenomenon is called Brainwave Entrainment.

2.2.1 Brainwave Entrainment Methodologies

Brainwave entrainment is the brain's electrical response to external rhythmic stimuli like sound, light or vibrations. These changes in the brainwave can be measured through neuro-imaging techniques such as EEG and are known as Evoked Potentials.

Brainwave entrainment has a lot of hypothesized benefits such as [18]

- increase in focus or concentration
- increase in creativity and problem solving

- improved sleep quality
- relaxation and stress relief

The most common studies for brainwave entrainment are performed by using sound. Binaural Beat is the resultant of two pure tone sinusoidal waves. It is usually played through headphones where frequency of one tone is 10Hz more than the other side and the brain perceives the sound as a 10 Hz sinusoidal wave. T. Zhuang et. al. [18] found in their studies that listening to brainwave music resulted an increase in alpha power in participants.

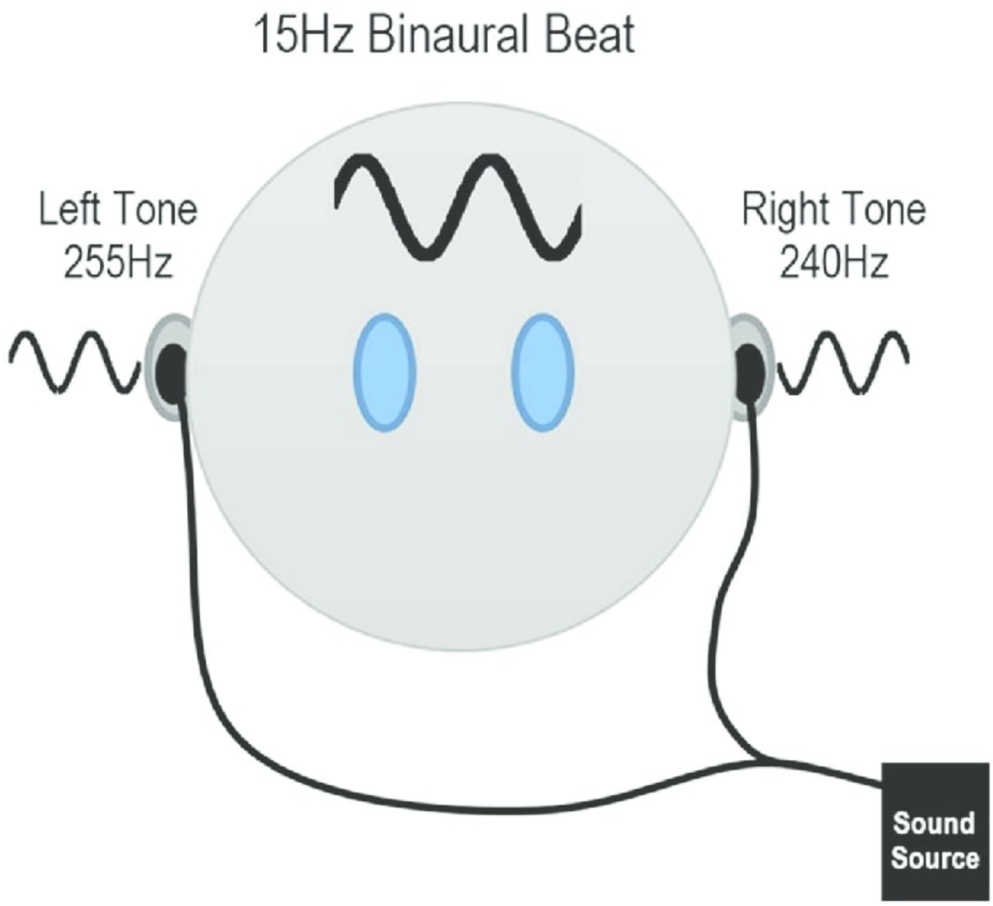


Figure 2.4 Binaural beats are a resultant wave of two pure tone sinusoids [19]

Another common type of BWE methodology is audio-visual entrainment (AVE) where flashing lights and pulsing tones are used to entrain the brain into a desired state. AVE has been used to treat kids with Attention Deficit Hyperactivity Disorder (ADHD). Children with ADHD have higher concentration of theta (4 - 7 Hz) and lower activity of beta (12 - 35 hz) then other normal children. In a study conducted in 1999 [20], elementary school children were subject to AVE for seven weeks which resulted in children being calmer and could focus better as compared to before. However, flashing lights might cause seizures in some people [21, 22].

In recent years, direct stimulation of neuronal elements by using transcranial stimuli has become popular in treating depression and other mental diseases. Two common stimuli are magnetic (Transcranial Magnetic Stimulation (TMS)) and current (Transcranial Alternating Current Stimulation (tACS)). Stimulation by tACS and rTMS (r stands for repetitive) has caused plastic effects i.e. the effect lasted long after the stimuli was applied and have shown antidepressant effects in case of rTMS [23–25].

Finally, brainwave entrainment has also been performed by using rhythmic vibration and it's called haptic entrainment. This study is based on haptic entrainment. In 1941, Dempsey and Morison [26] found that similar to light and sounds, tactile stimulus also lead to cortical response and could induce brainwave entrainment. Since then, researchers have performed studies using haptic/tactile stimuli to induce various brainwave states. S. Zhang et. al. [27] found in their research that rhythmic haptic stimuli of 15Hz was able to improve short term attention in the subjects by evaluating with Test of Variable Attention (T.O.V.A) analysis.

2.2.2 Brainwave Entrainment and Stress

Brainwave entrainment (BWE) has been used to change the state of the brain in numerous studies. Studies on people with mental disorders such as ADHD and mental diseases such as Alzheimer's Disease have seen significant results with different methodologies of BWE.

Alpha brainwaves naturally exist in the brain when a person is falling asleep or waking up or simply when they close their eyes [28] and they start to attenuate as the person starts focusing on something [29].

According to recent literature, alpha rhythms in the cortical region are associated with cognitive tendencies such as decreased symptoms of depression, increased hemispheric coherence in the frontal lobe, and increased creativity [30].

A lot of videos are freely available on YouTube that claim that listening to "brainwave music" could help with stress relief. One such category of auditory stimuli is called Isochronic Tones (fig 2.5). Isochronic tones are tones that come on and off at regular intervals often played with a carrier frequency. In a research conducted in 2020, researchers tested the effectiveness of isochronic tones for stress relief in a gender-specific study conducted among female participants. Researchers found that BWE using isochronic tones helped with stress relief and increased concentration in participants [31].

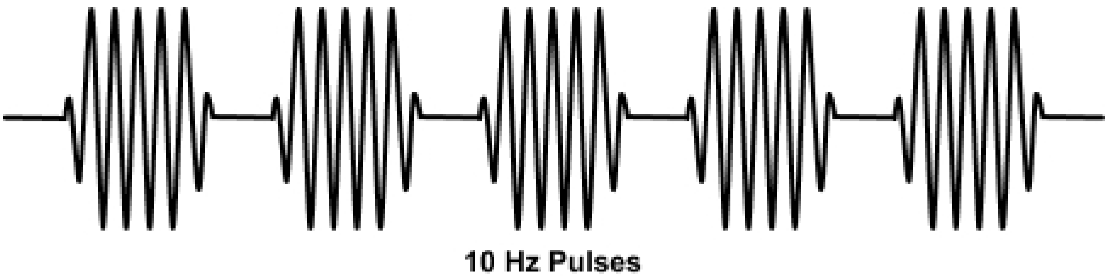


Figure 2.5 Isochronic tones are pulses of sounds usually paired with a carrier frequency

Apart from alpha waves, studies have also been done on inducing theta waves which can help with meditation. F.R. On et. al. [32] found that listening to binaural beats in the theta range caused and increase of theta rhythms in 76% of the participants and made them feel more relaxed.

There is enough evidence on the effectiveness of brainwave entrainment on not just stress relief but also on increased focus and improved memory. This study will further explore the effectiveness of haptic entrainment on stress relief.

2.3. Stress Relief Wearable Devices

This section introduces some existing commercially available products that claim to help with stress relief and the current situation of wearable relaxation devices.

A recent fad in the industry is mindfulness meditation and self-regulation. Devices based on EEG and other technologies are being developed to help consumers with meditation by allowing them to see what goes inside their brains.

Neurofeedback, also known as neurotherapy, is a type of biofeedback that provides real-time information about brainwaves and brain activity. It is possible to recondition and train the brain into certain brainwave states [33] and hence the field of neurofeedback was discovered.

With the recent developments in wireless EEG technology, neurofeedback-based wearable devices (fig 2.6) such as Interaxon's Muse headbands, Emotiv's line of EEG Brainwear®, Neurosky and so on are becoming popular in the market especially amongst researchers and meditation practitioners. These devices are also seeing a lot of use in Brain-Computer Interfaces (BCI).

(a) Muse 2 Headband[1]

(b) Emotiv EPOC[2]

Figure 2.6 Commercially available wearable EEG devices

Neurofeedback devices are often paired with brainwave entrainment to enhance

1 amazon.co.jp/-/en/improve-concentration-perfect-meditation-parallel/dp/B07L92XLSS

2 researchgate.net/figure/Emotiv-Epoc-BCI-headset_fig3_305847009

the experience while being able to see the induced changes. C. Sas et. al. [34] developed a wearable neurofeedback system (MeditAid) by using binaural beats and Emotiv's EPOC headband to help with mindfulness meditation.

While EEG based biofeedback might be of interest to researchers and other enthusiasts, there are other products in the market that, on the basis of research, claim to help with stress relief. One such product is Apollo Neuro (fig 2.7), by Apollo Neuroscience. Apollo Neuro is based on Heart Rate Variability biofeedback and it creates gentle vibrations on wrists or ankles (depending on where it is worn) which helps to decrease the fight-or-flight response that comes with the stress.[3]

Figure 2.7 Apollo Neuro's wearable relaxation device[4]

3 apolloneuro.com/blogs/news/100-of-children-with-adhd-and-anxiety-experience-symptom-improvement-with-apollo-in-pilot-study

4 apolloneuro.com/products/apollo-neuro

Chapter 3
Vibrain: A Haptic Entrainment Based Wearable Device

3.1. Why Do We Need Relaxation Devices?

This section discuss the need of relaxation devices in the current era and the direction of this research.

3.1.1 Research Direction

As mentioned in the preceding chapters, this research is about dealing with stress in the workplace by using technology, particularly a wearable device.

Stress can have very adverse effects on the physical and mental health of people. Effects of stress on the regulation of immune and inflammatory processes have the potential to influence depression; infectious, autoimmune, and coronary artery disease; and at least some (eg, virally mediated) cancers [35].

In the United States of America, excessive workplace stress cause a staggering 120,000 fatalities [36]. According to the American Institute of Health, this results in $190 billion in healthcare costs yearly. Over 83% of North Americans suffer from workplace stress and businesses lose $ 300 billion yearly as a result of that.

In a study conducted in 2019 among front-line health workers in Japan, more than 40% of nurses and more than 30% of radiological technologists and pharmacists experienced mental burnout due to the workload during the COVID-19 pandemic [37].

These studies are only a few examples and have a very small sample relative to the number of people that feel stressed due their work or school and thus it is necessary to come with measure to prevent or ameliorate the issue.

3.2. Ideation

This section introduces the inspiration and the ideation process behind Vibrain.

3.2.1 Background

Brainwave Entrainment has seen a lot of applications in the field of Neurotherapy or Neurofeedback training. Trials using photic entrainment (using flashing lights) have been done as far back as the 1900s by using a fan in front of a light source and the researchers found that it had a calming effect on the subjects.

In recent years, online video streaming platforms such as Youtube have popularized "Binaural Beats", which is a form of audio entrainment. These videos have claimed that they induce a certain brainwave state that can help people enhance their focus, relax them or help them fall asleep. In an uncontrolled study conducted in 2007, a group of researchers found that delta binaural beats (0-4 Hz) reduced anxiety in the group of subject [38].

This study is a result of inspiration from other experiments conducted and explores the effect of rhythmic vibrations on brainwaves.

Why Haptic Entrainment?

As mentioned previously, extensive research in the field of audio-visual entrainment (AVE) and transcranial current stimulation has been done. However, haptics or vibration based entrainment studies are sparse and the effects haven't been completely explored yet.

The goal of this study is to design a wearable device that uses tactile stimuli to entrain the brain into an alpha state and thereby physiological inducing relaxation. Audio stimuli like binaural beats and isochronic tones can be distracting during work and it is unfeasible and uncomfortable to wear earphones or headphones for an extended period of time and photic stimuli (flashing lights) might cause epileptic strokes strokes in people [21, 22].

Haptic entrainment, on the other hand, is purely mechanical stimulation in which a certain area of the body is subjected to rhythmic vibrations. No possible drawbacks of using vibrations to induce brainwaves have been discovered yet.

The following sections will introduce the concept and the functionality of Vibrain.

3.3. Concept

Inspired by and amalgamating everything mentioned until this point, the idea of Vibrain: a haptic entrainment based wearable relaxation device was born. The concept is to relax the user passively by taking advantage of the natural tendency of the brain to synchronize to the external haptic stimuli.

Most wearable device are in the shape of a watch, worn on a wrist but as Vibrain has a strong haptic stimuli, that is not possible as it might get in the way of the user while the user is working on something. To make the stimuli as symmetric as possible, the device needs to be either 1.) have a vibrating part on each half of the body or 2.) be mounted anywhere in the middle of the body. For the sake of convenience, it was decide that the device is going to be a single piece with two vibrating motors.

With the above considerations in mind, the only positions that satisfies the need is on the back or the chest. The following figure depicts the concept design of the wearable device (fig 3.1).

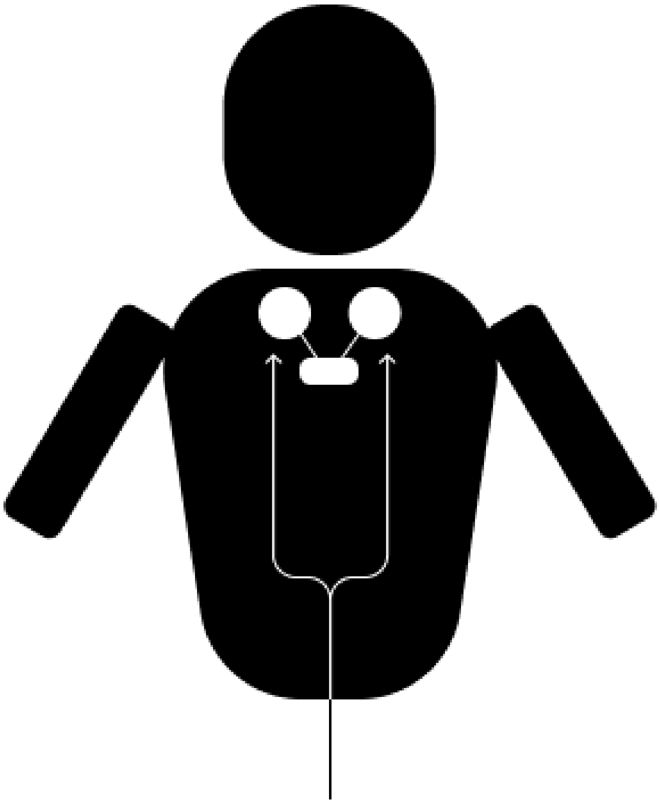


Figure 3.1 Concept design

The intended target users for Vibrain are white collar workers and students who spend a lot of time sitting in front of computers and are always fighting against deadlines. The idea is to use haptic entrainment to induce alpha brainwaves on the users' brain in order to cause physiological relaxation. The device can be used in any situation, ideally during 5-10 minute breaks between work and also while working.

The next section describes the functional design and the core working mechanism of the device and the introduces the prototypes

3.4. Functional Design

This section lists the functionalities of the prototype, the technology used and the core mechanism.

3.4.1 Core Mechanism

The core mechanism of the Vibrain prototype is, as mentioned in the preceding sections, rhythmic vibrations. These rhythmic vibration were created using tactile actuators.

There are three major categories of tactile actuators (fig 3.2):

- Eccentric Rotating Mass motors (ERM)
- Linear Resonant Actuators (LRA)
- Piezo

	ERM	LRA	PIEZO
Response time	~50ms	~30ms	~0.5ms
Accelaration	~1g	~1 - 2g	~3 - 5g
Audible Noise	Very Noisy	Moderate Noise	Silent
Power Consumption	High	Low	Low
Cost	$	$$	$$$

Figure 3.2 Comparison of the three categories of actuators

The main functionality of these actuators is to create vibrations but the mechanical process behind the vibrations differ. These actuators come in various shapes, size and specifications. Depending on the application, one type of motor have advantages over the other categories. Vibrain prototype uses LRAs to create vibrations. LRAs produce much less mechanical noise and last longer as compared to ERMs and create stronger vibrations as compared to piezo actuators. LRAs consist of a coil and a suspended magnetic mass that moves in a particular axis (X,Y or Z) when electricity is passed through the coil. Due to this feature it is very easy to control the vibration intensity of LRAs.

Binaural beats are resultant frequencies of two puretone sinusoidal sound waves and isochronic tones are pulsing frequencies with a carrier frequency but the biggest drawback of LRAs is that the amplitude of vibrations fall exponentially if the motor is not driven at its resonant frequency.

To overcome this shortcoming of LRAs, the actuators were driven at resonant frequency in order to get maximum amplitude and intensity of vibrations. In order to get the 10 Hz stimuli (for alpha brainwave entrainment), the concept of vibration occurrence was used. Vibration occurrence is the number of ”effects” per second, minute, day etc. A common example of vibration occurrence is BPM or beats per minute, commonly used in music.

Vibrain prototype consists of two LRAs driven at resonant frequency with 10 effects (or beats) per second.

The next section describes the two prototypes and the wearable device design for Vibrain.

3.4.2 Prototype Design

This section describes the prototype iterations in detail.

The First Prototype

The first prototype (fig 3.3) consisted of two Acouve labs VP2 actuators driven by a patch created in Pure Data software through a Fostex AP05 audio amplifier. The intensity of the vibration was maximized just until there was minimal mechanical noise (due to the magnet hitting the casing of the actuators). The stimuli felt like a metronomic beat with 10 beats per second being the ”frequency”.

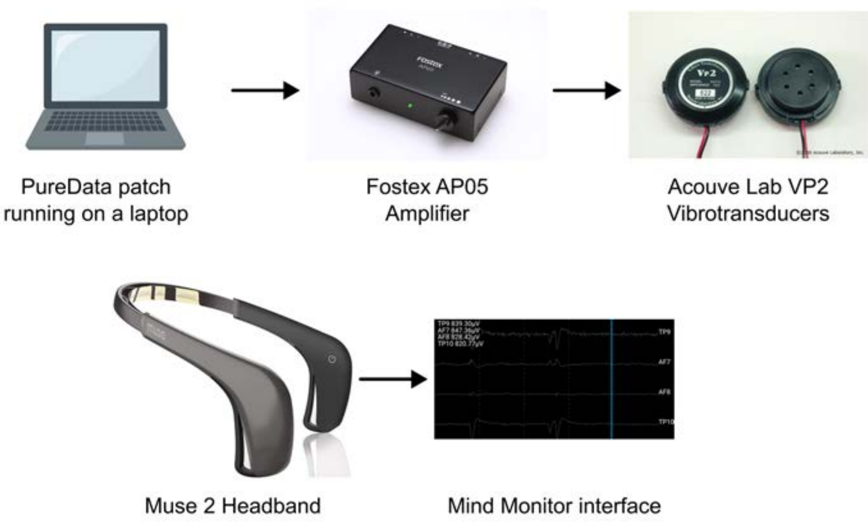


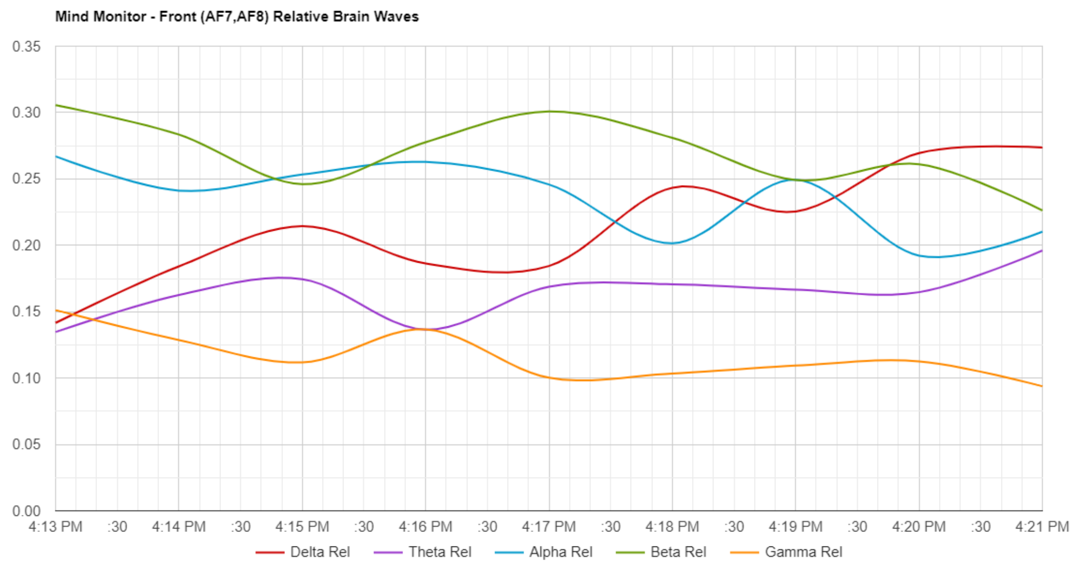
Figure 3.3 The first prototype and the neurofeedback loop[1]

Preliminary Testing

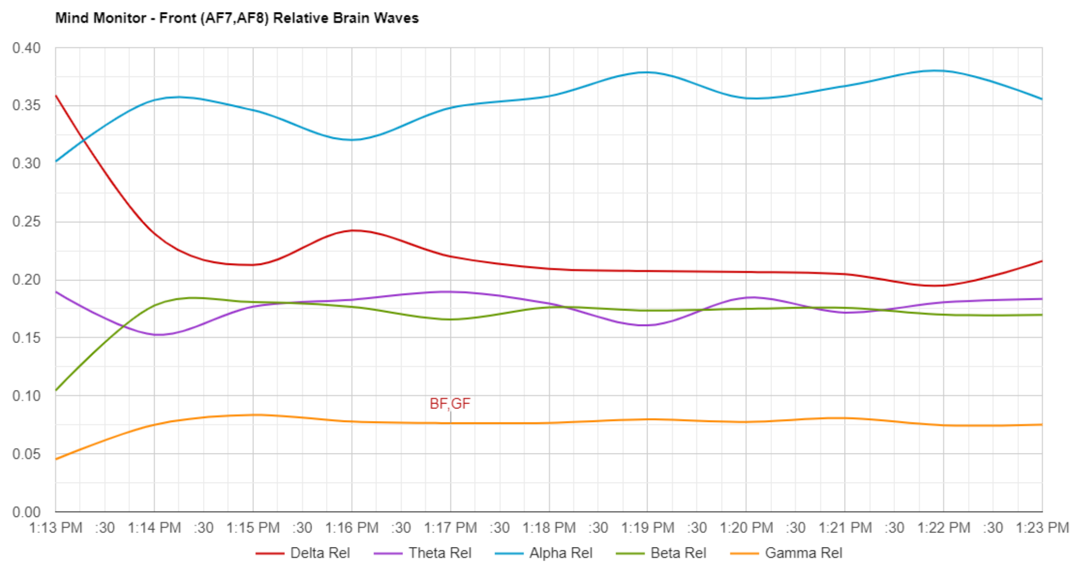
The stimuli was paired with a neurofeedback loop using Interaxon's Muse 2 headband and the EEG data was streamed to the Mind Monitor app. This neurofeedback loop was tested on myself to see whether there is any evidence of brainwave entrainment and plotted the graphs using Mind Monitor's online graphing function. Comparison was made between the following for state by using the relative power plot: 1.) no stimuli (fig 3.4a), 2.) meditation (fig 3.4b), 3.) wrist stimuli (fig 3.4c) and 4.) neck stimuli (fig 3.4d).

Results

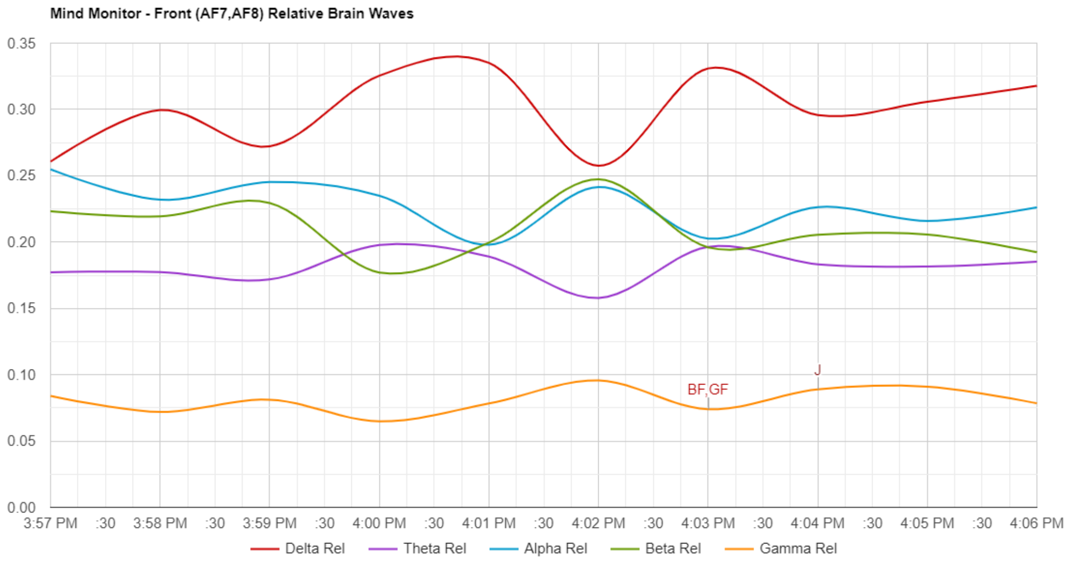
In the following plots alpha waves are depicted by blue colour and beta waves are depicted by green colour. From the plots, it is clear that the stimulus applied to the neck has a much greater effect on the relative power of alpha waves as compared to when the stimulus is applied to the wrists.



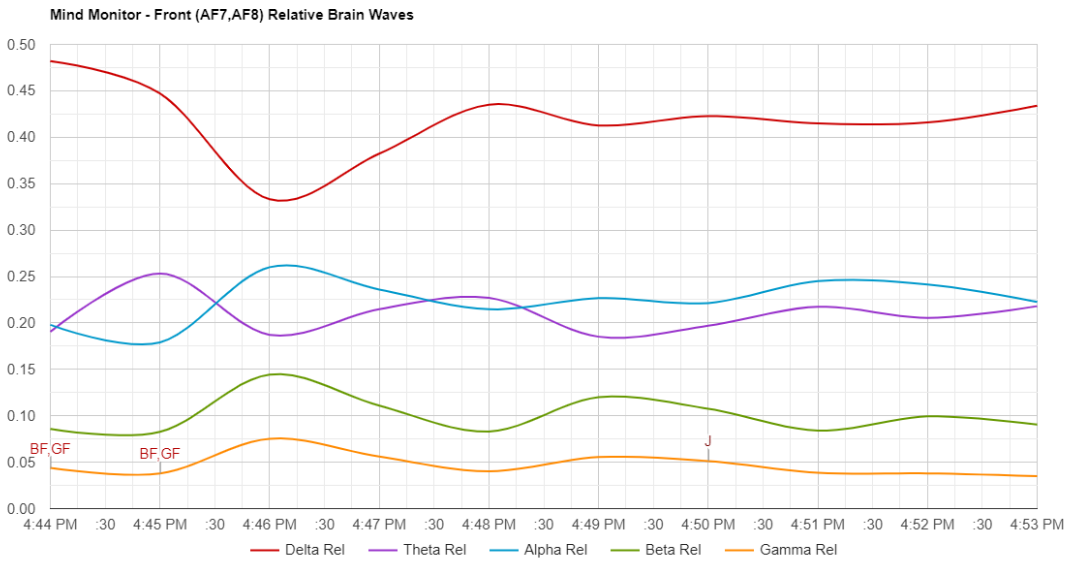
(a) Relative band power with no stimuli



(b) Relative band power during meditation



(c) Relative band power with stimuli applied to dorsal wrist



(d) Relative band power with stimuli applied to neck

Figure 3.4 Comparison of Relative Band Power graphs created using Muse Monitor[3]

Discussion

The actuators were placed on the trapezius muscles (fig 3.5) directly in contact with the skin. The reason for placing the actuators on the upper back was so that the actuators do not get in the way of the users' work as it would've, had the actuators been placed on the arm or the wrist. This might also help in releasing muscular tension and help with relaxation [39].

3 `mind-monitor.com/Chart.php`

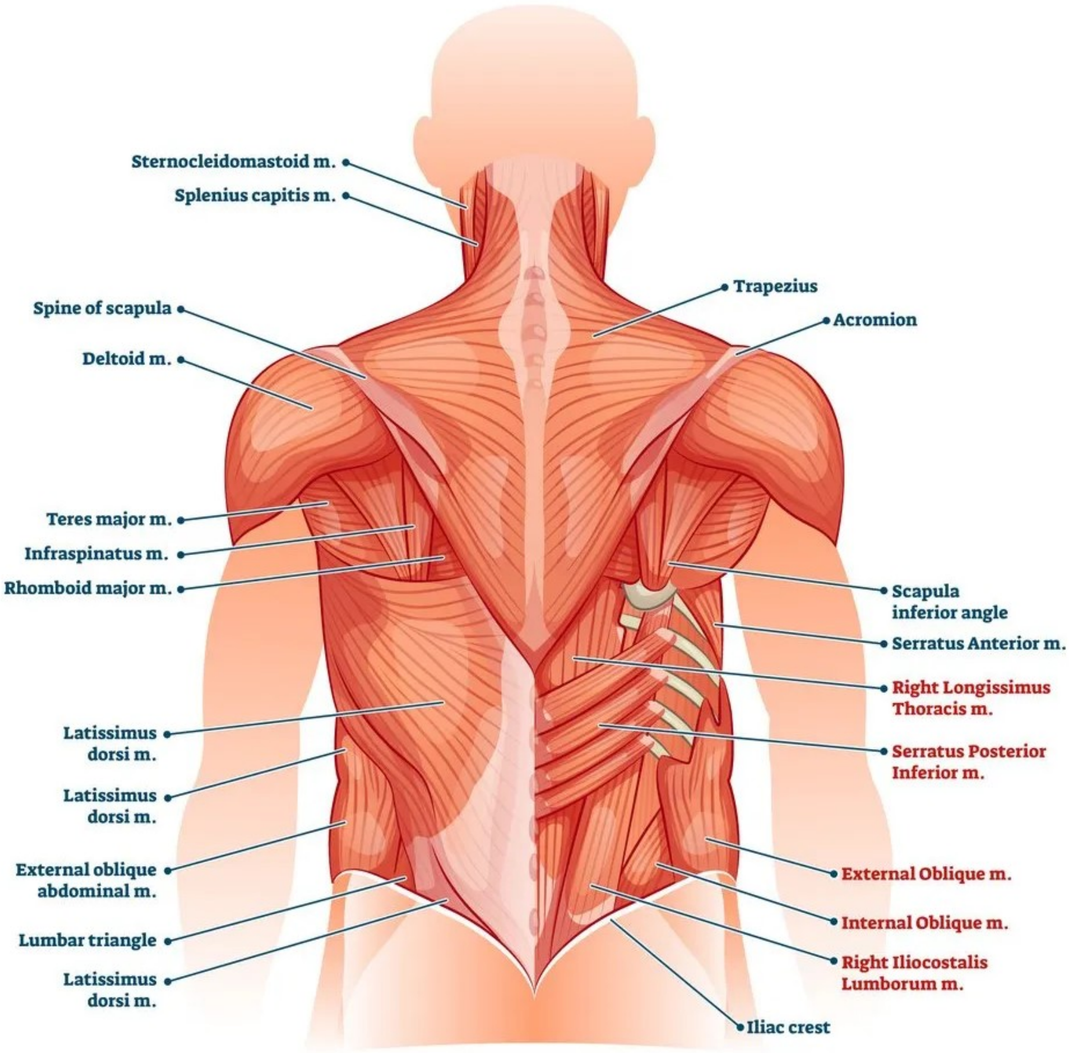


Figure 3.5 Muscles in the upper and the lower back[4]

This iteration performed well in the sense there was minimal distraction from the mechanical noise but the actuators kept getting displaced and the device wasn't wireless and wearable due to it being connected to a laptop. Also, ergonomically, it was very difficult for users with eye glasses to wear both the eye glasses and the Muse headband at the same time.

4 joionline.net/trending/content/lower-back-anatomy-and-low-back-pain

The Second Prototype

The second prototype initially consisted of a circuit driven by an Arduino uno module. The actuators were driven using Adafruit's DRV2605L haptic driver (fig 3.6) and the signal were amplified with a PAM8304 amplifier module. This iteration was rejected as the inbuilt waveforms of the haptic driver were not sinusoidal in nature and caused a lot of mechanical noise which was distracting.

Figure 3.6 Adafruit DRV2605L Haptic Driver[5]

To improve this iteration, the actuators were replaced by motors from a PS5 controller[6]. The audio signal created by the Pure Data was recorded on to the computer and processed through Audacity (fig 3.7). The .wav file from Audacity was converted to hex code and was loaded on to the ESP32 module using the XT_DAC_Audio library and the ESP32's DAC output allowed the signal to be directly sent to the PAM8304 amplifier module. The dampening at the end of the sound wave caused a softer vibration effect and hence resulted in negligible noise from the motors.

4 http://www.acouve.co.jp/product/pd_vp2.html,https://www.fostex.jp/products/ap05/,mind-monitor.com/Technical_Manual.php,choosemuse.com/muse-2

5 adafruit.com/product/2305

6 playstation.com/en-us/accessories/dualsense-wireless-controller/

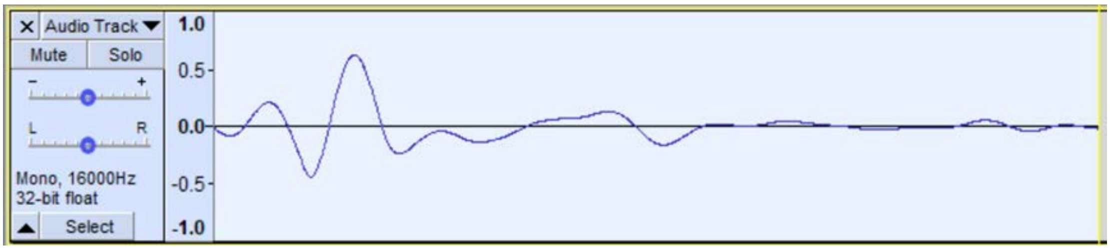


Figure 3.7 Waveform of the audio signal in Audacity

Similar to the first prototype, the stimuli was a repetitive beat like a metronome with 10 beats per second being the effective frequency of the stimuli.

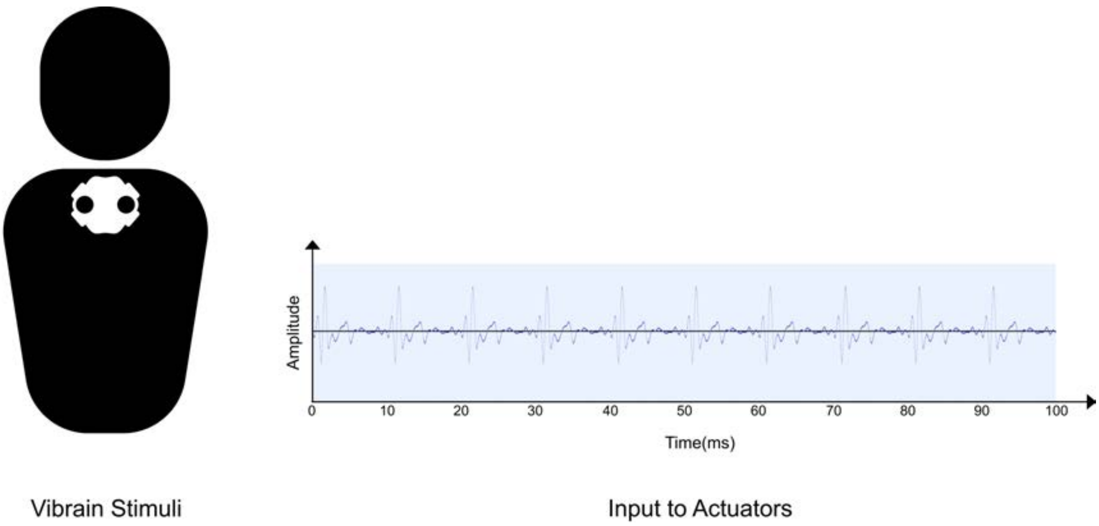
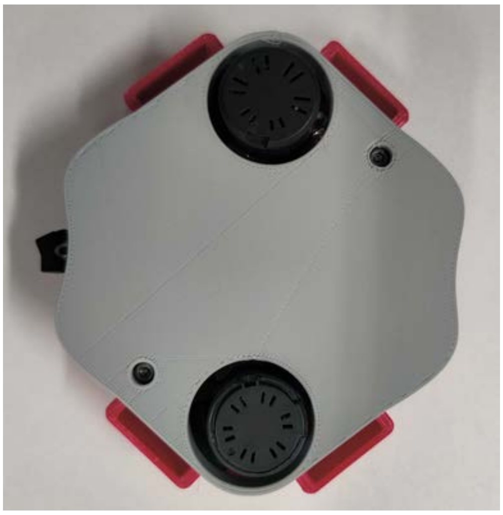


Figure 3.8 Graphic representation of the stimuli

The whole circuit was powered using a 3.7V LiPo battery and installed into a two piece 3D printed casing(fig 3.9). In order to minimize the noise from the casing itself, neodymium magnets were used on the insides of the lid and the case and gaps were filled using foam to clamp down the circuit and the motors in order to avoid sound from moving pieces. The casing was mounted on to the user's back by using posture corrector straps (fig 3.10). This was the final iteration of the second prototype .



(a) Vibrain front view

(b) Vibrain side view

Figure 3.9 Vibrain final prototype

(a) A user wearing Vibrain

(b) A user using Vibrain during work

Figure 3.10 Final prototype in an actual scenario

Chapter 4
Evaluation

This section describes the tests performed using the prototype and the results from the EEG study.

4.1. EEG Within and Between Subject Study

To evaluate the effects of the rhythmic haptic stimuli of the final prototype from chapter 3, an EEG study was conducted among 10 right handed participants (8 females and 2 males, age 24-28).

4.1.1 How Did Vibrain Fare Against a Commercial EMS Massager?

While performing the guerilla testing (user test with random users in the university premise) to test for the optimum vibration intensity output from the prototype, a lot of users said that the experience feels like a massage. So I decided to test Vibrain against a commercial electrical muscle stimulation (EMS) massager (fig 4.1) in an EEG study.

Figure 4.1 Commercial EMS massager[1]

The participants were divided into two group, 1) the Vibrain group and 2) the massager group. Both the groups were subjected to, approximately, 3.5 minutes (depending on the participant's reaction time) of stressor stimulus using PsyToolkit's stroop task [40, 41] (fig 4.2) before each stimuli in order to set a baseline for the EEG analysis.

1 amazon.co.jp/-/en/Cordless-Relaxation-Charging-Lightweight-Birthday/dp/B08VJGJ3FW/ref=sr_1_5?dchild=1&keywords=%E9%A6%96+%E3%83%9E%E3%83%83%E3%8%B5%E3%83%BC%E3%82%B8&qid=1627279426&sr=8-5

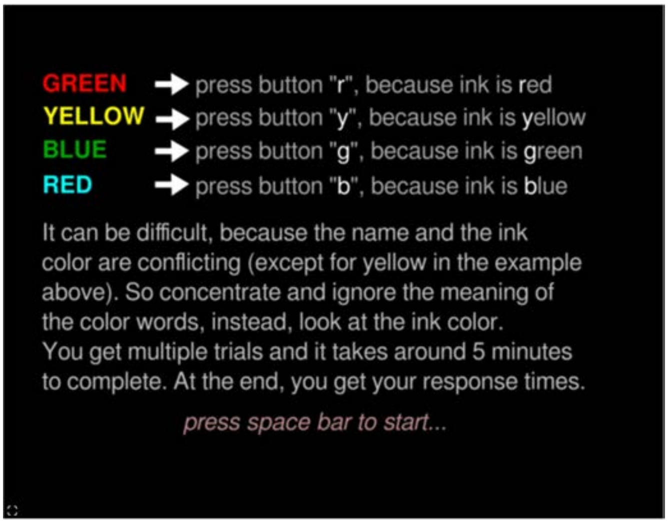
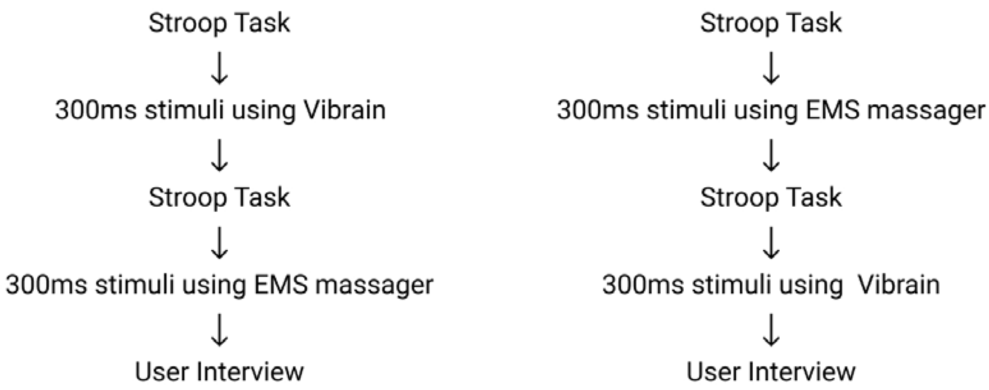


Figure 4.2 Psytoolkit's stroop task

Experiment Setup

Depending on the group, the experiment flow (fig 4.3) consisted of the participants being subjected to a 300ms stimuli, either Vibrain or EMS stimuli, first, followed by stroop task and the alternate stimuli. This was followed up by a user interview regarding the experience.

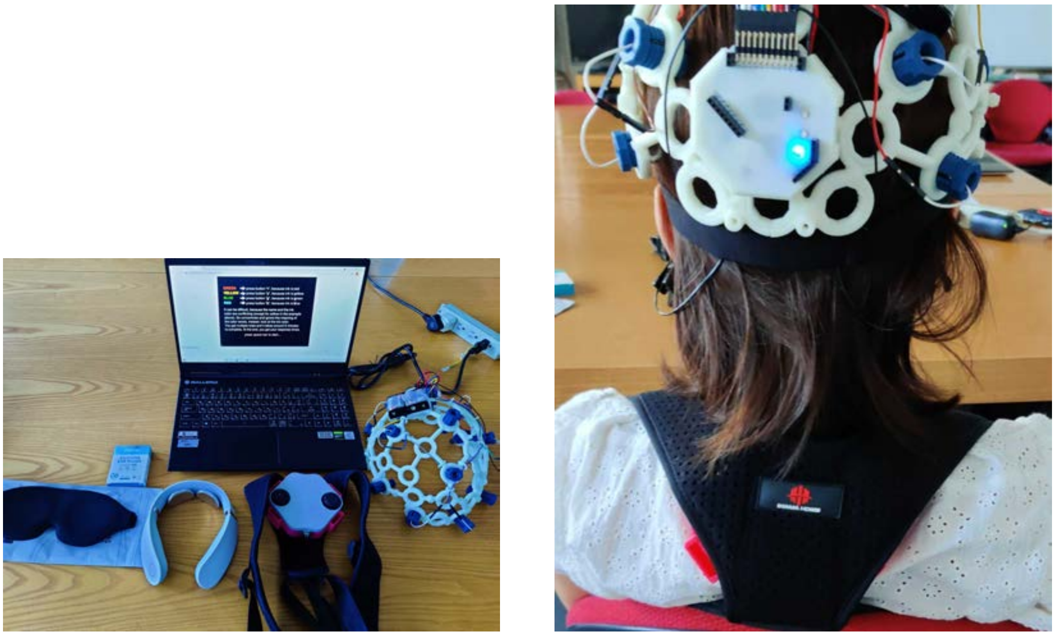


(a) Experiment flow for Vibrain group (b) Experiment flow for EMS group

Figure 4.3 Experiment flow

During the stimulus, the participants (fig 4.4b) were asked to sit in a comfortable position and to avoid movement and they were blind folded with an eye mask in order to prevent EOG (eye movements) and EMG (muscle movements) artifacts in the EEG signal. Fig 4.4a shows the experiment setup.

The prototype was placed on the trapezius muscle for the Vibrain group and the neck massager was placed on the neck. The neck was moistened with a wet wipe to ensure proper conduction from the EMS electrodes of the massager.

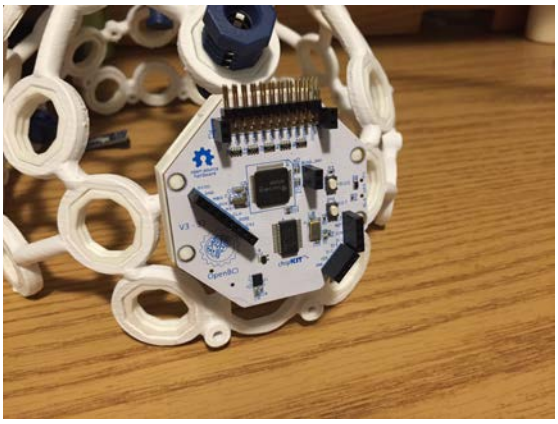


(a) Experiment setup (b) Participant from the Vibrain group

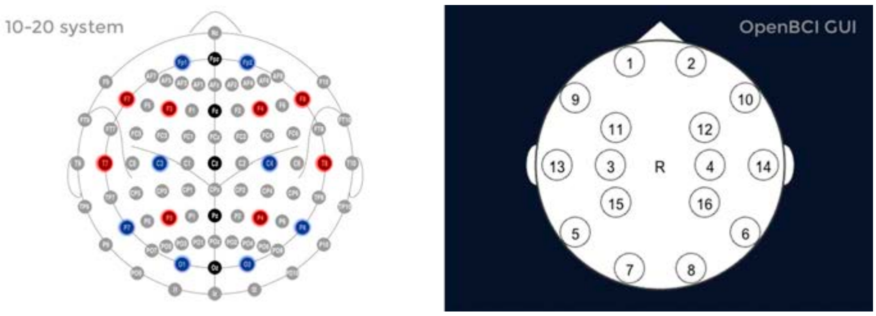
Figure 4.4 Experiment setup and Vibrain group trial 1

Apparatus

The EEG signal was recorded through an OpenBCI Ultracortex Mark IV headset with an OpenBCI 8 channel Cyton Board (fig 4.5a). The electrodes were dry electrodes placed at FP1, FP2 (frontal lobe), C3, C4 (central lobe), P7, P8 (parietal lobe), O1 and O2 (occipital lobe) positions according to the international 10-20 system [42] of EEG electrode placement (fig 4.5b). Reference nodes (A1 and A2)) were attached to the right and the left earlobes. The data was streamed to the OpenBCI GUI during the experiment and later processed and analysed with MATLAB's EEGLAB toolbox.



(a) OpenBCI Ultracortex Mark IV and 8-channel Cyton Board



(b) International 10-20 System EEG electrode placement

Figure 4.5 EEG headset setup[2]

Results

A total of twenty (n=20) datasets were obtained from the user study (two datasets per participant). The datasets were imported into MATLAB by using a script[3] and the datasets were transposed and processed with EEGLAB. In EEGLAB, the data was subjected to a bandpass filter to remove signals below 0.5 Hz and above 50 Hz and notch filter to remove line noise (50 Hz). The data was cleaned

2 docs.openbci.com/docs/04AddOns/01-Headwear/MarkIV

3 irenevigueguix.wordpress.com/2016/04/22/loading-openbci-datasets-in-eeglab/

both manually and by using CleanRaw data function and Automatic Subspace Reconstruction (ASR) built-in functions of EEGLAB. After data pre-processing nine data sets were rejected due to gibberish data (pertaining to electrical noise). The number of datasets analysed after pre-processing was n_r=11.

Power (dB) of frequency bands were extracted from O1 channel for each participant for both, the Vibrain and the massager trial (alpha rhythms are dominant in the occipital region [43]) and relative alpha power (table 4.1) was measured by using total power (sum of power of all frequency bands) as the denominator. RAP during Vibrain and during massager trials were compared for each participants (from all the viable datasets). Bold text in the table depicts the greater of the two values.

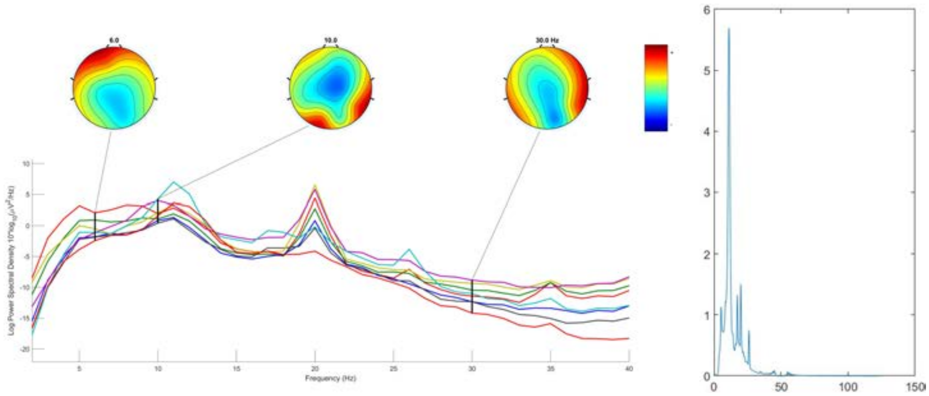
	Relative Alpha Power (Vibrain)	Relative Alpha Power (EMS)
Participant 1	-	-
Participant 2	-	-
Participant 3	**32.59%**	30.86%
Participant 4	**31.31%**	27.64%
Participant 5	33.28%	**35.48%**
Participant 6	-	-
Participant 7	**29.73%**	28.37%
Participant 8	-	22.28%
Participant 9	-	-
Participant 10	**57.73%**	49.17%

Table 4.1 Comparison of relative alpha power values from Vibrain and the massager trials

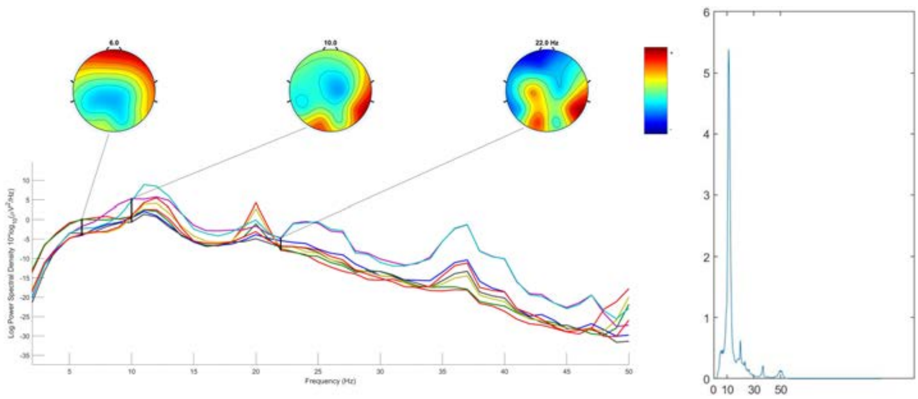
Alpha Activity at 10 Hz

To visualise the alpha activity at 10 Hz, headplots and log Power Spectral Density were plotted for each participant, for each trial. MATLAB's pwelch() function was applied to plot Welch Periodogram (fig 4.6, 4.7, 4.8, 4.9, 4.10). Welch Periodogram is the plot of Power Spectral Density (uV^2/Hz) against Frequency (Hz).

From the Power Spectral Density graph, it can be said for the Vibrain trials, there is a clear peak at 10 Hz i.e., there is alpha activity in the posterior region, occipital lobe of the brain depicted by the red colour on the headplots. Hence, alpha brainwaves might be induced due to entrainment.

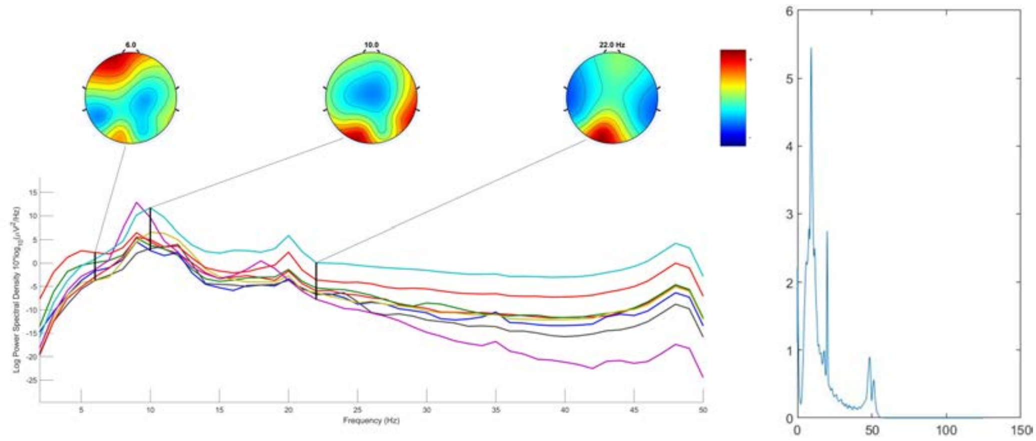


(a) Headplot and Welch periodogram for participant 3 during Vibrain trial

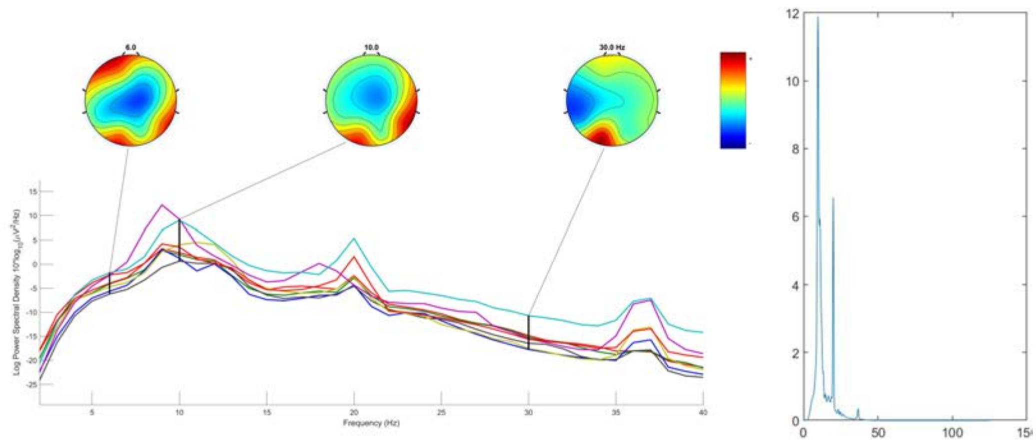


(b) Headplot and Welch periodogram for participant 3 during the massager trial

Figure 4.6 Comparison for participant 3

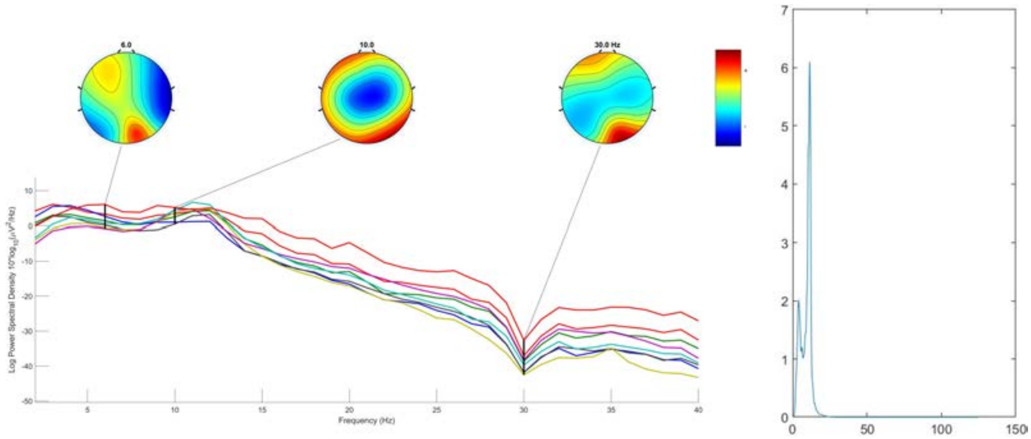


(a) Headplot and Welch periodogram for participant 4 during Vibrain trial

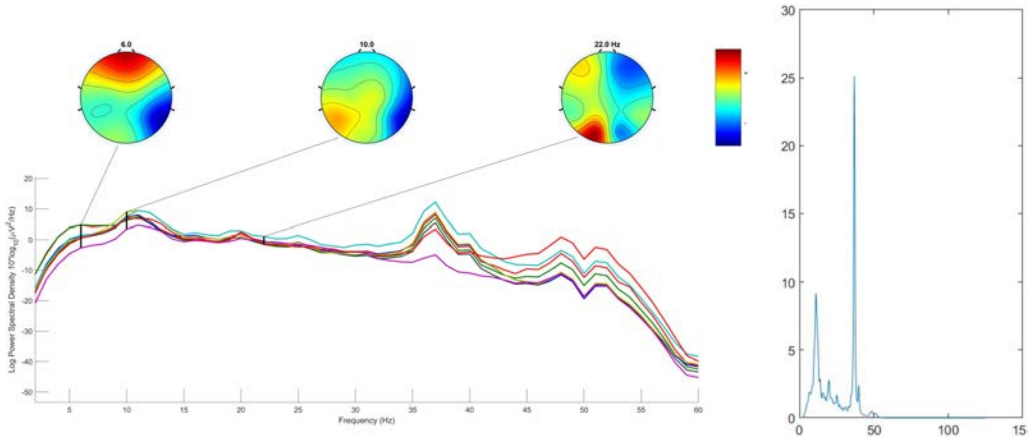


(b) Headplot and Welch periodogram for participant 4 during the massager trial

Figure 4.7 Comparison for participant 4

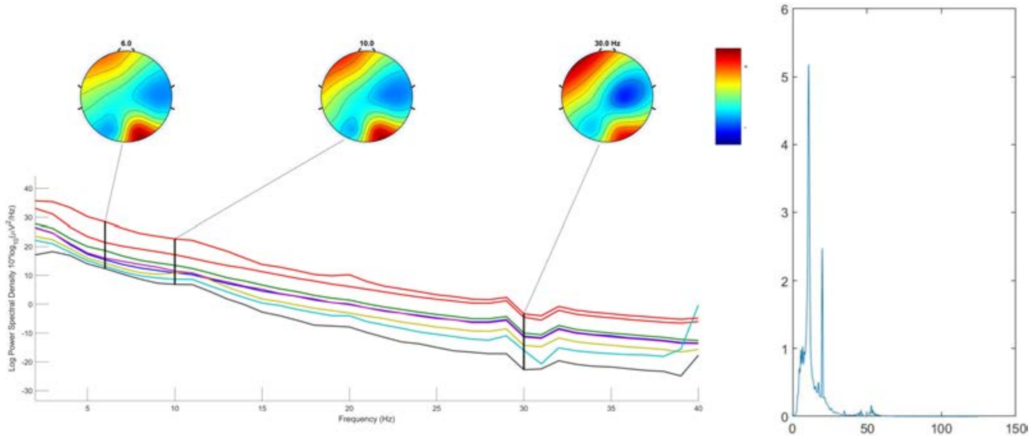


(a) Headplot and Welch periodogram for participant 5 during Vibrain trial

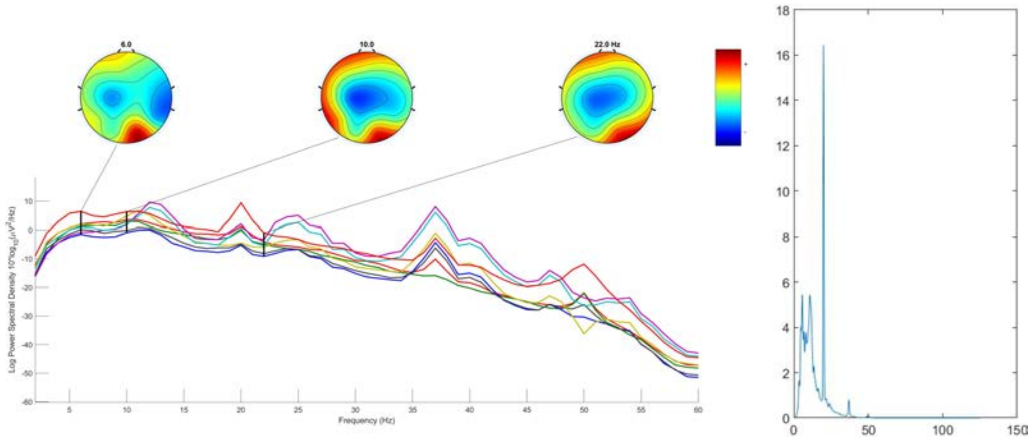


(b) Headplot and Welch periodogram for participant 5 during the massager trial

Figure 4.8 Comparison for participant 5

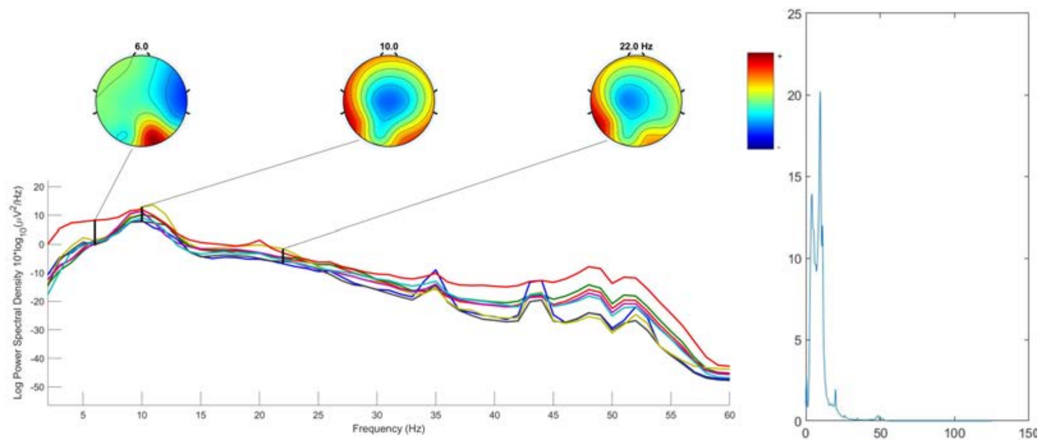


(a) Headplot and Welch periodogram for participant 7 during Vibrain trial

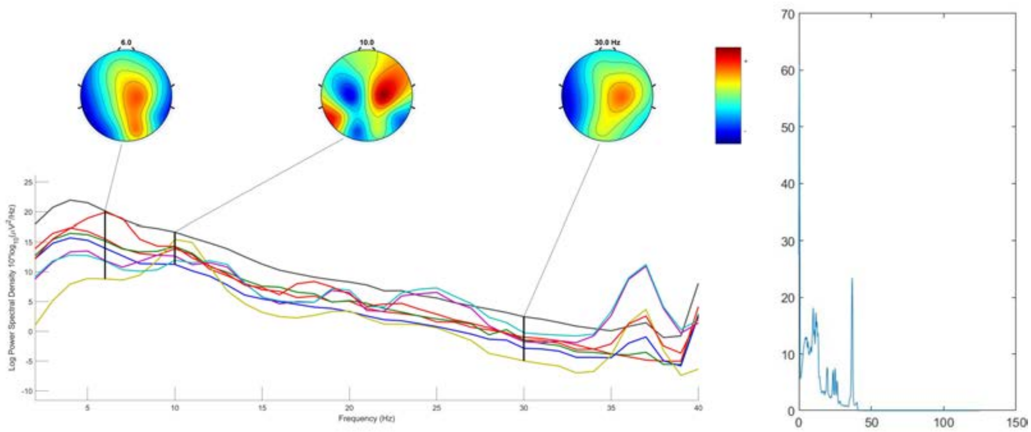


(b) Headplot and Welch periodogram for participant 7 during the massager trial

Figure 4.9 Comparison for participant 7



(a) Headplot and Welch periodogram for participant 10 during Vibrain trial



(b) Headplot and Welch periodogram for participant 10 during the massager trial

Figure 4.10 Comparison for participant 10

The user study was followed up by a user interview asking the users questions about the experience. The interview questions were:

- What were your first impressions about the device?
- Do you usually use any relaxation devices?
- How did the experience feel?
- Did you feel any discomfort?

- What were you thinking about during the 5-minute stimuli?

4.2. Discussion

The above EEG data analysis give some insight into the possibilities of brainwave entrainment using haptic entrainment and wearable relaxation devices.

Both the massager and the prototype performed almost equally well looking at the Relative Alpha Power (RAP) values. The massager did not have any rhythm and it's functioning was greatly dependent on the moisture on the users neck (as electricity conduction was reduced on dry skin) . It can be said from the RAP values that the prototype might have induced alpha brainwaves on to the participants in the Vibrain trials, resulting in the slightly higher RAP. However, more data and analysis is required to get concrete evidence of brainwave entrainment from the stimuli created by the prototype.

The OpenBCI headset is an easy way to record EEG data but the data had a lot of noise and a lot of the data was lost during pre-processing. Therefore, further studies need to be performed with better apparatus to precisely measure the effectiveness of rhythmic haptic stimuli.

However, interesting conclusion can be drawn from the interview conducted with all 10 of the participants. One participant from the massager group stated that the "zaps from the massager did not feel good" even though the RAP was very high. It can be said that RAP might be a good measure of brainwave entrainment but more parameters might be required for "relaxation"

This study serves as a preliminary investigation in measuring the effects of a haptic entrainment and the importance of wearable relaxation devices to tackle stress in workplace and schools.

Chapter 5
Conclusion

In a world where stress is an epidemic and almost everyone experiences stress, it is important to have measures to cope with stress and this study introduces one such way.

Vibrain is haptic entrainment based wearable relaxation device. It works on the concept of brainwave entrainment where the dominant brainwave in the brain synchronizes to an external rhythmic stimuli. It is possible to synchronize the brain to a certain brainwave state in order to reap the benefits of the physiological state associated with that particular brainwave state. In this study, the focus was on alpha waves and these brain rhythms are associated with a relaxed but alert physiological state.

The effects of the stimuli from Vibrain were tested on a group of participants and an EEG study was performed to evaluate the results from the study and preliminary evidence of brainwave entrainment due to the haptic stimuli was found by measure the relative alpha power across the EEG channels.

Vibrain was also compared to commercial massager and interviews were conducted among the participants to assess it's effectiveness. Although, the intended purpose for Vibrain is not for massaging, the experience was similar and the prototype did well against a commercial device, according to the results from the interview.

5.1. Limitations

Measuring the effectiveness of wearable prototype requires a large sample size and better apparatus to have more concrete evidence and results which were not present in this study.

The results from the interview made it clear that the wearable design needs more improvement as there were some users who found some discomfort when the flat surface of the device hit the bone. The device was also more noisy than originally intended which hinders the purpose of relaxation.

5.2. Future Work

The future iteration of the wearable device can have a more ergonomic and modern look in order to make it appealing enough for daily use. Improvement in design is necessary to get rid of the mechanical noise created by the device hitting the back of the user.

The device can also be modified to have adjustable intensities and vibration patterns which allows the possible of entrainment in other brainwave states. A neurofeedback loop using Muse or Emotiv can also be added to make the product appealing to meditation practitioners and other enthusiasts.

References

[1] Vicki R LeBlanc. The effects of acute stress on performance: implications for health professions education. *Academic Medicine*, 84(10):S25–S33, 2009.

[2] Ssang-Hee Seo and Jung-Tae Lee. Stress and eeg. *Convergence and hybrid information technologies*, 27, 2010.

[3] Andreas K Engel and Pascal Fries. Beta-band oscillations—signalling the status quo? *Current opinion in neurobiology*, 20(2):156–165, 2010.

[4] George Halkos and Dimitrios Bousinakis. The effect of stress and satisfaction on productivity. *International Journal of Productivity and Performance Management*, 2010.

[5] Herbert Benson, John F Beary, and Mark P Carol. The relaxation response. *Psychiatry*, 37(1):37–46, 1974.

[6] Priyanka A. Abhang, Bharti W. Gawali, and Suresh C. Mehrotra. Chapter 2 - technological basics of eeg recording and operation of apparatus. In Priyanka A. Abhang, Bharti W. Gawali, and Suresh C. Mehrotra, editors, *Introduction to EEG- and Speech-Based Emotion Recognition*, pages 19–50. Academic Press, 2016. URL: `https://www.sciencedirect.com/science/article/pii/B9780128044902000026`, `doi:https://doi.org/10.1016/B978-0-12-804490-2.00002-6`.

[7] J.P Banquet. Spectral analysis of the eeg in meditation. *Electroencephalography and Clinical Neurophysiology*, 35(2):143–151, 1973. URL: `https://www.sciencedirect.com/science/article/pii/0013469473901703`, `doi:https://doi.org/10.1016/0013-4694(73)90170-3`.

[8] Piotr Olejniczak. Neurophysiologic basis of eeg. *Journal of clinical neurophysiology*, 23(3):186–189, 2006.

[9] Sebastian Nagel. *Towards a home-use BCI: fast asynchronous control and robust non-control state detection.* PhD thesis, 12 2019. doi:10.15496/publikation-37739.

[10] DL Keene, S Whiting, and ECG Ventureyra. Electrocorticography. *Epileptic Disorders*, 2(1):57–64, 2000.

[11] Peter Hansen, Morten Kringelbach, and Riitta Salmelin. *MEG: An introduction to methods.* Oxford university press, 2010.

[12] Paul M Matthews and Peter Jezzard. Functional magnetic resonance imaging. *Journal of Neurology, Neurosurgery & Psychiatry*, 75(1):6–12, 2004.

[13] Michael E Hoffer and Carey D Balaban. *Neurosensory disorders in mild traumatic brain injury.* Academic Press, 2018.

[14] YOKO Hoshi and MAMORU Tamura. Dynamic multichannel near-infrared optical imaging of human brain activity. *Journal of Applied Physiology*, 75(4):1842–1846, 1993.

[15] Roberta Lizio, Fabrizio Vecchio, Giovanni B Frisoni, Raffaele Ferri, Guido Rodriguez, and Claudio Babiloni. Electroencephalographic rhythms in alzheimer ' s disease. *International Journal of Alzheimer ' s Disease*, 2011, 2011.

[16] Jim Lagopoulos, Jian Xu, Inge Rasmussen, Alexandra Vik, Gin S Malhi, Carl F Eliassen, Ingrid E Arntsen, Jardar G Sæther, Stig Hollup, Are Holen, et al. Increased theta and alpha eeg activity during nondirective meditation. *The Journal of Alternative and Complementary Medicine*, 15(11):1187–1192, 2009.

[17] Asieh Ahani, Helane Wahbeh, Hooman Nezamfar, Meghan Miller, Deniz Erdogmus, and Barry Oken. Quantitative change of eeg and respiration signals during mindfulness meditation. *Journal of neuroengineering and rehabilitation*, 11(1):1–11, 2014.

[18] Tianbao Zhuang, Hong Zhao, and Zheng Tang. A study of brainwave entrainment based on eeg brain dynamics. *Computer and information science*, 2(2):80–86, 2009.

[19] Christine Beauchene, Nicole Abaid, Rosalyn Moran, Rachel Diana, and Alexander Leonessa. The effect of binaural beats on visuospatial working memory and cortical connectivity. *PLOS ONE*, 11:e0166630, 11 2016. doi:10.1371/journal.pone.0166630.

[20] Michael Joyce and Dave Siever. Audio-visual entrainment program as a treatment for behavior disorders in a school setting. *Journal of Neurotherapy*, 4(2):9–25, 2000.

[21] Robert S Fisher, Graham Harding, Giuseppe Erba, Gregory L Barkley, and Arnold Wilkins. Photic-and pattern-induced seizures: a review for the epilepsy foundation of america working group. *Epilepsia*, 46(9):1426–1441, 2005.

[22] Robert Baldwin. Kinetic art: On producing illusions by photic-stimulation of alpha brain waves with flashing lights. *Leonardo*, 5(2):147–149, 1972.

[23] Alexandra Vossen, Joachim Gross, and Gregor Thut. Alpha power increase after transcranial alternating current stimulation at alpha frequency (α-tacs) reflects plastic changes rather than entrainment. *Brain stimulation*, 8(3):499–508, 2015.

[24] Andrew Francis Leuchter, Ian A Cook, Yi Jin, and Bill Phillips. The relationship between brain oscillatory activity and therapeutic effectiveness of transcranial magnetic stimulation in the treatment of major depressive disorder. *Frontiers in human neuroscience*, 7:37, 2013.

[25] Randolph F Helfrich, Till R Schneider, Stefan Rach, Sina A Trautmann-Lengsfeld, Andreas K Engel, and Christoph S Herrmann. Entrainment of brain oscillations by transcranial alternating current stimulation. *Current biology*, 24(3):333–339, 2014.

[26] Edward W Dempsey and Robert S Morison. The interaction of certain spontaneous and induced cortical potentials. *American Journal of Physiology-Legacy Content*, 135(2):301–308, 1941.

[27] Shusheng Zhang, Dangxiao Wang, Naqash Afzal, Yuru Zhang, and Ruilin Wu. Rhythmic haptic stimuli improve short-term attention. *IEEE transactions on haptics*, 9(3):437–442, 2016.

[28] Marjorie Schuman. The psychophysiological model of meditation and altered states of consciousness: A critical review. *The psychobiology of consciousness*, pages 333–378, 1980.

[29] Jahangir Moini and Pirouz Piran. Chapter 6 - cerebral cortex. In Jahangir Moini and Pirouz Piran, editors, *Functional and Clinical Neuroanatomy*, pages 177–240. Academic Press, 2020. URL: `https://www.sciencedirect.com/science/article/pii/B9780128174241000069`, `doi:https://doi.org/10.1016/B978-0-12-817424-1.00006-9`.

[30] Morgan L Alexander, Sankaraleengam Alagapan, Courtney E Lugo, Juliann M Mellin, Caroline Lustenberger, David R Rubinow, and Flavio Fröhlich. Double-blind, randomized pilot clinical trial targeting alpha oscillations with transcranial alternating current stimulation (tacs) for the treatment of major depressive disorder (mdd). *Translational psychiatry*, 9(1):1–12, 2019.

[31] Jeannette Stark and Denise Dörfel. Fast and effective stress relief in women through brainwave-entrainment technology in pandemics. 2021.

[32] FR On, R Jailani, H Norhazman, and N Mohamad Zaini. Binaural beat effect on brainwaves based on eeg. In *2013 IEEE 9th International Colloquium on Signal Processing and its Applications*, pages 339–343. IEEE, 2013.

[33] D Corydon Hammond. What is neurofeedback: An update. *Journal of Neurotherapy*, 15(4):305–336, 2011.

[34] Corina Sas and Rohit Chopra. Meditaid: a wearable adaptive neurofeedback-based system for training mindfulness state. *Personal and Ubiquitous Computing*, 19(7):1169–1182, 2015.

[35] Sheldon Cohen, Denise Janicki-Deverts, and Gregory E. Miller. Psychological Stress and Disease. *JAMA*, 298(14):1685–1687, 10 2007. URL: `https://doi.org/10.1001/jama.298.14.1685`, `arXiv:https://jamanetwork.com/journals/jama/articlepdf/209083/jco70057\_1685\_1687.pdf`, `doi:10.1001/jama.298.14.1685`.

[36] Joel Goh, Jeffrey Pfeffer, and Stefanos A Zenios. The relationship between workplace stressors and mortality and health costs in the united states. *Management Science*, 62(2):608–628, 2016.

[37] Takahiro Matsuo, Daiki Kobayashi, Fumika Taki, Fumie Sakamoto, Yuki Uehara, Nobuyoshi Mori, and Tsuguya Fukui. Prevalence of health care worker burnout during the coronavirus disease 2019 (covid-19) pandemic in japan. *JAMA network open*, 3(8):e2017271–e2017271, 2020.

[38] Helane Wahbeh, Carlo Calabrese, and Heather Zwickey. Binaural beat technology in humans: a pilot study to assess psychologic and physiologic effects. *The Journal of Alternative and Complementary Medicine*, 13(1):25–32, 2007.

[39] Antoinette R Domingo, Melissa Diek, Kathleen M Goble, Katrina S Maluf, Daniel J Goble, and Harsimran S Baweja. Short-duration therapeutic massage reduces postural upper trapezius muscle activity. *Neuroreport*, 28(2):108–110, 2017.

[40] Gijsbert Stoet. Psytoolkit: A software package for programming psychological experiments using linux. *Behavior research methods*, 42(4):1096–1104, 2010.

[41] Gijsbert Stoet. Psytoolkit: A novel web-based method for running online questionnaires and reaction-time experiments. *Teaching of Psychology*, 44(1):24–31, 2017.

[42] Robert Oostenveld and Peter Praamstra. The five percent electrode system for high-resolution eeg and erp measurements. *Clinical neurophysiology*, 112(4):713–719, 2001.

[43] Jeffrey David Lewine and William W. Orrison. Chapter 8 - clinical electroencephalography and event-related potentials. In William W. Orrison, Jeffrey David Lewine, John A. Sanders, and Michael F. Hartshorne, editors, *Functional Brain Imaging*, pages 327–368. Mosby, 1995. URL: https://www.sciencedirect.com/science/article/pii/B9780815165095500126, doi:https://doi.org/10.1016/B978-0-8151-6509-5.50012-6.

Appendices

A. Plotting Welch Periodogram from an EEGLAB Dataset in MATLAB

Matlab commands for calculation absolute bandpower and plotting welch periodogram

```
x  = EEG.data(7, :);          % For channel 7 (O1)
Fs = EEG.srate;               % Sampling frequency
L  = EEG.pnts;                % Length of signal
NFFT = 2^nextpow2(L);         % Next power of 2 from length of x
% X    = fft(x,NFFT)/L;
% freqs   = Fs/2*linspace(0,1,NFFT/2+1);
% spectra = abs(X(1:NFFT/2+1));
NOVERLAP = 0;
WINDOW = 512;
[spectra,freqs] = pwelch(x,WINDOW,NOVERLAP,NFFT,250);
deltaIdx = find(freqs>=1 & freqs <=4);
deltaPower = mean(10.^(spectra(deltaIdx)/10));
thetaIdx   = find(freqs>=4 & freqs<=8);             % theta=4-8
thetaPower = mean(10.^(spectra(thetaIdx)/10));      % abs theta power
alphaIdx   = find(freqs>=8 & freqs<=12);            % alpha=8-12
alphaPower = mean(10.^(spectra(alphaIdx)/10));      % abs alpha power
betaIdx  = find(freqs>=13 & freqs<=30);             % beta=12-30
betaPower  = mean(10.^(spectra(betaIdx)/10));       % abs beta power
gammaIdx = find(freqs>=30 & freqs<=100);            % gamma=30-100
gammaPower = mean(10.^(spectra(gammaIdx)/10));      % abs gamma power
totalPower = deltaPower+thetaPower+alphaPower+betaPower+gammaPower;
alphaRel = alphaPower/totalPower;
subplot(1,2,2); plot(freqs,spectra)
```