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Using EEG in neurofeedback training to decrease visual motion sensitivity and motion-sickness

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Abstract

Patients who suffer from motion-sickness, visual vertigo and other conditions relating to visual hypersensitivity will often feel dizzy when exposed to rapid visual motion or cluttered fields-of-view. Previous studies indicate that attentiveness to these stimuli influence the intensity of discomfort for these individuals, which suggests that mentally ignoring visual stimuli might help make them more tolerable.

This thesis project had two goals. The primary goal was the development of a visual biofeedback system for use with a commercial electroencephalographic headset and a personal computer. The secondary goal was to evaluate its usefulness for treating motion-sickness and other related illnesses through regular training sessions.

A neurofeedback program was constructed using MATLAB and a Muse 2 Brain Sensing Headband (Muse). The program projected a spinning maze-like pattern on a monitor where increase in velocity was proportional to increase in theta wave activity (3.5-6.5 Hz) detected by the Muse. Five test subjects (three men and two women) were given a copy of the program and a Muse, and then instructed to practice reducing their EEG activity (e.g. by calming themselves), which would be reflected in the program as a slower spin velocity of the maze. These practice sessions took place daily for seven days. Neurofeedback proficiency and body sway data was collected before and after. Mean spectral power data from the training regimen shows a 23.7% drop in theta wave activity from first session to last ($p = 0.005$). Using Pearson's correlation, no significant results were obtained while comparing training improvements and proficiency test improvements ($r = -0.22$, $p = 0.72$) or reduction in body sway ($r = 0.78$, $p = 0.12$).

Keywords

EEG; vertigo; motion sickness; neurofeedback training; rehabilitation

Sammanfattning

Patienter som lider av åksjuka, visuell yrsel och andra tillstånd relaterade till visuell överkänslighet känner sig ofta yra när de exponeras för visuell rörelse eller röriga visuella miljöer. Tidigare studier har indikerat att uppmärksamhet på dessa faktorer påverkar symptomens intensitet och obehag för dessa patienter, vilket indikerar att förmåga till att ignorera visuella faktorer kan vara en del i rehabiliteringsprocessen.
Den här avhandlingen har två mål. Det primära målet var att utveckla ett system för visuell biofeedback nyttjandes kommersiell EE-utrustning och en persondator. Det andra målet var att utvärdera effekten av interventionen i syfte att lindra åksjuka och liknande symptom genom regelbundna träningspass.
Ett program för neurofeedback utvecklas med hjälp av MATLAB och Muse. Programmet projicerade ett roterande labyrintmönster på en monitor där hastigheten ändras proportionerligt med bärarens hjärnaktivitet i form av thetavågor (3.5-6.5Hz) som registrerades av Muse. Fem forskningspersoner (tre män och tre kvinnor) gavs en kopia var av programmet och en Muse, och blev instruerade att träna på att sänka den rotatoriska hastigheten, genom att sänka sin EEG-aktivitet, under 7 dagars hemträning. Skickligheten och kroppssvajet utvärderades före och efter träningen. Mean spectral power från träningen avslöjade att theta-aktiviteten sjönk med 23.7% från första till sista träningspasset. Ingen korrelation sågs mellan förbättringen och skicklighetsutvärderingen ($r = -0.22$, $p = 0.72$) eller förbättring i kroppssvaj ($r = 0.78$, $p = 0.12$).

Nyckelord

EE-utrustning; visuell yrsel; åksjuka; neurofeedback träning; rehabilitering

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Stockholm, June 2021
Ódinn K. Rúnarsson

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List of acronyms and abbreviations

ANOVA Repeated Measures Anova

C-ETD Chronos Eye Tracking Device

COP center-of-pressure

EEG electroencephalogram

EPOC Emotiv EPOC EEG headset

ERP event-related brain potential

FRN feedback-related negativity

IS 10-20 International 10-20 System

KI Karolinska Institutet

LSL lab streaming layer

MAD MATLAB App Designer

MBC Marianne Bernadotte Centrum

MSSQ-Short Motion Sickness Susceptibility Questionnaire - Short version

Muse Muse 2 Brain Sensing Headband

NFB Neurofeedbacklab

OKR optokinetic reflex

PCA Pearson's Correlation Analysis

SNR signal-to-noise ratio

VMH visual motion hypersensitivity

VNS visual neurofeedback system

VNT visual neurofeedback training

VOR vestibulo-ocular reflex

WBB Wii Balance Board

Chapter 1

Introduction

Vertigo and *motion-sickness* arise when our senses, visual, vestibular and somatosensory, provide conflicting information, creating a sensation of dizziness [1]. Some form of motion sickness can be induced in practically everyone, and about one in three individuals are highly susceptible to it [2]. A chronic example of this is visual motion hypersensitivity (VMH), also known as *supermarket syndrome* due to it often being triggered by the visually cluttered environments of supermarkets [3]. Individuals suffering from VMH experience severe vertigo with nausea which can lead to an increased fall risk and general discomfort [3].

Patients who suffer from motion-sickness are often treated with anti-histamines since they are available prescription-free, are relatively quick to take effect and have few side-effects [4][5]. The efficacy of anti-histamines for motion-sickness prevention is uncertain, however. Wibble et al. hypothesized that their antiemetic effects can be traced to their effects on patient alertness levels, rather than directly targeting the vestibular system [4]. If true, then patients could reduce their sensitivity to visual stimuli by modulating their alertness, which could potentially be achieved through regular practice.

This thesis details an attempt to develop a non-pharmaceutical treatment regimen for motion sickness and other related illnesses. It takes the form of a *biofeedback* system, or more specifically a *neurofeedback* system, the construction and validation of which was the primary goal of this thesis project. A secondary goal of this project was to determine its effectiveness in the treatment of motion-sickness and other related illnesses.

1.1 Introduction to method

A biofeedback system detects physiological signals, e.g. from heartbeats or muscle contractions, and presents them to the subject being measured in real-time [6]. These presentations most often come in the form of a monitor displaying data from the measurements. Since alertness is a mental attribute, brain activity was chosen as a target for feedback in this project. This can be achieved using *electroencephalography*, a non-invasive method for monitoring electrical activity thorough the scalp [7]. Electroencephalographic data is collected using a device known as an Electroencephalogram (EEG). An EEG will typically consist of multiple electrodes, a minimum of two and a maximum of several hundred, that have been placed in predefined locations and then connected to hardware capable of recording the signals detected by those electrodes [7][8]. See appendix A.2.1 for more information about EEGs.

When EEGs are used for biofeedback purposes the resulting system can be referred to as a *neurofeedback* system [9]. During neurofeedback treatment regimens, patients will use the data presented to them to influence their thinking, emotions, behavior etc. in a desired way, in the hope that the changes will persist after the conclusion of the sessions [6][9].

1.2 Context

This project is a continuation of two studies done at the Marianne Bernadotte Centrum (MBC) of the Karolinska Institutet (KI) (see [3] and [4]), which is where this thesis project takes place. Those studies made extensive use of eye-tracking, as eye-movement analysis is the most commonly used clinical approach to evaluating vertigo, with particular reference to the Vestibulo-ocular reflex (VOR), which sees the eye move in the opposite direction of a head movement so as to maintain clear visual acuity [10], and the Optokinetic reflex (OKR), clamping the eye to a moving visual target to avoid motion blur. Both gaze-stabilizing reflexes involve *ocular torsion* and *vertical skewing*. In order to capture these responses, the researchers used an eye tracker, namely a Chronos Eye Tracking Device (C-ETD). Data from a balance board, namely a WBB, was also included in those studies to monitor body sway while test subject were exposed to visual stimulus. The proposed EEG-platform would consequently constitute a novel line of research at MBC.

1.3 Problem statement

Using EEGs for biofeedback training is not a new concept [6][9]. The problems with using EEGs to treat dizziness and motion-sickness are the devices themselves and the resources required to provide regular training sessions to patients. Clinical EEGs are often expensive, require specialists to setup and to prepare the patient by replacing and applying conductive gels on electrodes, placing them on precisely defined locations and then monitoring the incoming data [7]. A short session might therefore take upwards of an hour, where most of that time is spent on preparation. This makes regular neurofeedback sessions unfeasible to both patients and hospitals/institutions hosting them. However, considering that dizziness and motion-sickness diagnosis and treatment are a significant financial strain on the global health care system every year [11][12][13], there is certainly a demand for more cost-effective methods of treatment, enough to justify exploring more practical methods of neurofeedback training.

For a few years there has been a growing industry of commercial EEG headsets [14][15][16], designed to be cheap and low-profile for use by hobbyists and researchers alike. Before this project started, MBC invested in a Muse for use in future studies, including this one. It is uncertain whether a relatively simple device such as the Muse can be used for clinical research, but it does show promise (see appendixes A.2.1 and A.3). Whether the Muse suffices for a neurofeedback treatment regimen will have to be established.

1.4 Purpose

Considering the apparent connection between attention to visual stimulus and the severity of resulting motion sickness [3], patients having the means to condition themselves to ignore such stimulus might prove to be beneficial. This project will set out a potential way of achieving that. The aim of this project is to design and validate an EEG neurofeedback training regimen using a commercial EEG headset, specifically the Muse, paired with a visual stimulation system intended for use with patients suffering from VMH and motion-sickness. Such a system, geared towards clinical utility, will allow patients to not only train themselves to control their level of alertness to visual motion, but to do so from the comforts of their own homes with equipment that is relatively cheap and not overly cumbersome.

1.4.1 Goals

This thesis project was divided into two goals, labeled as **primary** and **secondary**.

1. **Primary goal** Develop a visual neurofeedback system (VNS), that when finished uses no more than a Muse headset and a personal computer (See figure 1.1).

   (a) Determine how to extract, process and utilize data from the headset in real-time and be certain that it is a sufficiently accurate representation of neural activity rather than noise.

   (b) Construct a visual biofeedback program that can be deployed to a subject's personal computer in as simple a way as possible. This will include setting up a system for labeling and later retrieval of data.

2. **Secondary goal** Evaluate the effectiveness of visual neurofeedback training (VNT) in reducing the severity of VMH and motion-sickness. This will involve establishing a controlled testing protocol for evaluating the effects of the VNT regimen on visually induced postural sway.

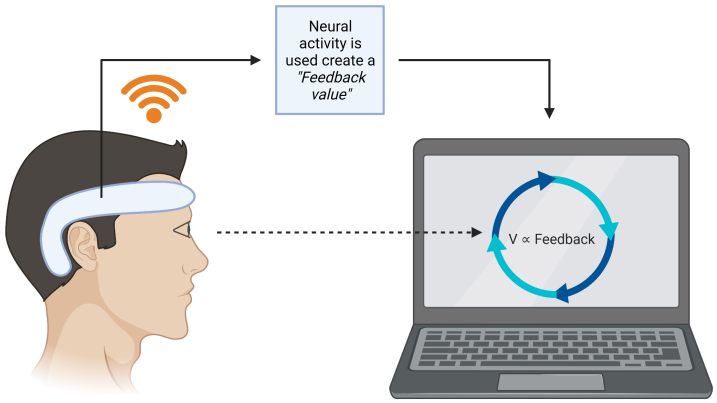

Figure 1.1: A diagram representing the intended final setup. The user wears the wireless Muse headset which communicates with a program that creates a *feedback value* from neural activity. The velocity v of the spinning program on the screen is proportional to the feedback value. Created with BioRender.com

Chapter 2

Methods

2.1 Resources

As mentioned in section 1.3, the EEG headset chosen for this project was the Muse 2 Brain Sensing Headband (Muse). A comparison of validation studies for different devices showed the Muse as a promising candidate for this study [14][16][17] (See appendix A.3 for more information). Figure A.7 shows a photograph of the device in use.
A Wii Balance Board (WBB) was used to collect body-sway data in a controlled testing environment, which will be discussed further in section 2.7.
Programming, data collection and processing was done using the MATLAB programming language, because of familiarity and available online resources, namely Psychtoolbox-3 and Neurofeedbacklab (NFB). Psychtoolbox enables greater synchronization between MATLAB and computer hardware while also providing additional graphical functions [18]. NFB is a MATLAB package created by Arnaud Delorme, a professor of Neuroscience at Paul Sabatier University in Toulouse [19]. NFB is intended as a resource to be built upon and has limited functionality as a neurofeedback program by itself [19]. It does, however, enable MATLAB to communicate, process and display data from a variety of commercial EEG headsets in real-time, using a framework known as a Lab streaming layer (LSL) [20]. LSL was intended as a system for time-synchronization and collection of data from a network of research experiments and is widely used by researchers in different fields [20].
Almost all programming and testing leading up to the training regimen was done on a Microsoft Windows 10 Notebook equipped with an i7-8565U processor which, while fairly powerful, was expected to give a good indication of how the program would perform on most modern laptops.

2.2 Evaluation of EEG device

In order to evaluate whether the Muse would suffice for this project, repeated experiments using programs included in NFB were performed. These initial experiments were intended to establish whether or not the program showed consistent and predictable behaviour when communicating with the Muse, as the final system would depend on the same code and methods of processing. As was mentioned in section 2.1, NFB is intended as a resource to be expanded upon, but there are a few examples included to demonstrate how it can be used. One of those involves a colored square that changes color depending on data sent from an EEG headset, in this case the Muse. The data is converted into *spectral power* of the targeted frequency range (in this case the *theta brainwave*, more on that in sections 2.5 and 2.6). The example program uses the intensity of neural activity to change the color, with higher activity progressively changing the color of the square to a light blue color, while lower activity leads to a darker color until it eventually becomes black. Figure 2.1 shows an example of this.
The project could not move forward until it was established that this program would behave in the desired manner during testing, as the final product was supposed to function in a similar manner. See section 3.1 for the results.

Figure 2.1: Three snapshots taken during a single session. "High activity" was induced through rapid motion within the subject's field of view. The square got progressively darker after subject closed his eyes and relaxed. In terms of spectral power, the "high activity" square represents about 140 $[\mu V^2/Hz]$ while the "low activity" square represents about 90 $[\mu V^2/Hz]$, targeted at theta brainwaves.

2.3 Motion Sickness Susceptibility Questionnaire - Short version

The MSSQ-Short is a revised version of an earlier questionnaire, called MSSQ, intended to provide insight into a patient's motion sickness susceptibility [21]. It is split into two parts with identical questions, one covering current susceptibility to motion sickness in various situations over the last 10 years, while the other is how they remember those same situations during childhood (before age 12). Table 2.1 shows the setup of the questionnaire in English. It should be noted that the MSSQ-Short the subjects in this study filled in was in Swedish.

The questionnaire scores participants on a scale from 0 to 54, where the maximum is very unlikely [21]. The *"Not Applicable"* columns are their own separate variable, with *"Never"*, *"Rarely"*, *"Sometimes"* and *"Frequently"* giving *0*, *1*, *2* and *3* points, respectively [21]. Each part of the questionnaire is graded separately, according to the following equation:

$$MS = \frac{(\text{Total sickness score}) * 9}{9 - (\text{number of types not experienced})}$$

The total of the child and adult questionnaire gives the final score.

Table 2.1: MSSQ-Short, identical for childhood and adulthood but both must be filled in in order to calculate the score

	How often did you feel sick/nauseated?				
	Not Applicable	**Never**	**Rarely**	**Sometimes**	**Frequently**
Car					
Buses/Coaches					
Trains					
Aircrafts					
Small Boats					
Ships					
Swings in playgrounds					
Roundabouts in playgrounds					
Funfair Rides					

2.4 Body sway with WBB

The Wii Balance Board (WBB), originally designed for use with the Nintendo Wii Entertainment System, was used to evaluate postural control in this project. Figure 2.3 shows a custom program for recording body sway, created in-house at MBC. The green dot in the figure represents center-of-pressure (COP) and was calculated by the program using scales positioned beneath the board in each corner [22]. Data from each sensor was recorded in a .csv file which contains measurements of weight displacement in two dimensions, horizontal by vertical. This allowed for calculating postural displacement [22]. The data from each .csv file was then used to create a scatter plot of each subject's COP. A 95% confidence ellipse was then plotted and the area taken as representing body sway [22].

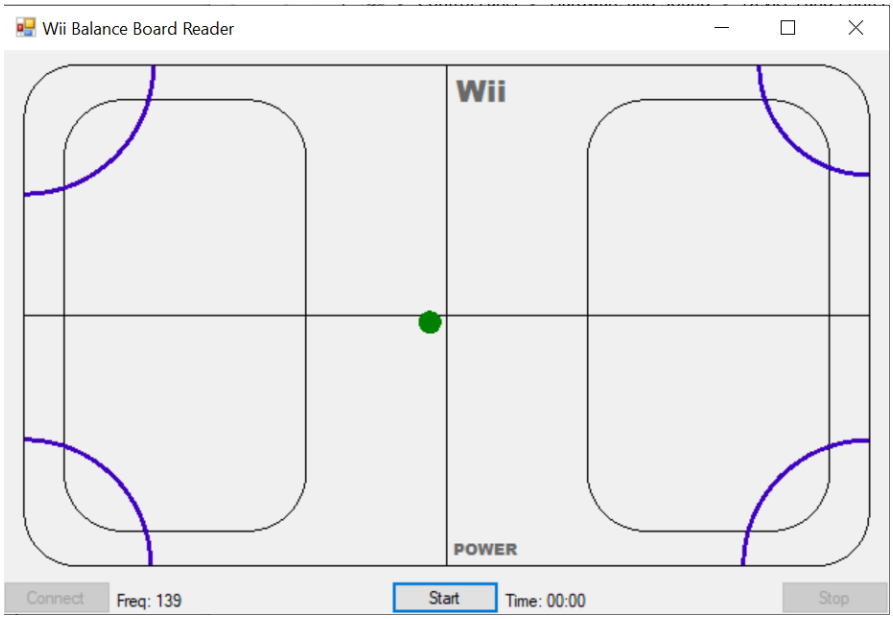

Figure 2.2: Demonstration of the Wii Balance Board reader. The software records center of gravity using a coordinate system which can be processed to reveal body sway.

2.5 EEG data of interest

Detectable EEG signals generated from brain activity are not homogeneous and vary in both amplitude and frequency [7][23]. These neural oscillations are often called brain-waves [23] and fall under five categories depending on frequency range. They are often broadly associated with certain states of mind, these being [23]:

- **Delta** (0.5-4 Hz), associated with sleep.
- **Theta** (4-8 Hz), relaxation, inward focus and sleep.
- **Alpha** (8-12 Hz), relaxation and passive attention.
- **Beta** (12-35 Hz), anxiety and external attention.
- **Gamma** (35+ Hz), concentration.

Considering that some of them, like beta and theta for example, seem to correlate with nearly opposite states of mind it seems prudent for this project to focus on a narrow frequency band when attempting neurofeedback. The associations with states of mind are a simplification, however, as their prevalence in different situations can vary between regions of the brain [24][25] [26]. Theta waves for example, while being associated with relaxation and sleep, have been detected in strong bursts from the hippocampus of rats during periods of high alertness and attention [26]. These bursts have also been reported in rats experiencing motion sickness [24], also from the hippocampus. A hypothesis about the connection between motion sickness and alertness is what inspired this project, so theta waves will be used as a primary focus going forward. There are studies correlating similar bursts of theta wave activity from the occipital and the frontal lobe in humans during motion-sickness inducing scenarios [25][27]. There are no indications that the Muse can accurately detect brain waves from either the hippocampus or the occipital lobe, but the electrode placement suffices for frontal lobe activity detection [14].

2.6 Software

2.6.1 Neurofeedbacklab

As was mentioned in section 2.1, NFB is a MATLAB framework for communicating with EEG headsets through LSLs. The files provided can be modified

to handle the processing of multiple types of EEG headsets although it was partially designed with an older version of the Muse in mind. In the example detailed in section 2.2, the code has several important features. Before the program can be attempted, the user must create a *baseline*. This baseline defines a *dynamic range* which determines what constitutes high- and low-activity. When running the actual program, spectral power is handled as input and is compared with the dynamic range, giving a *feedback* value as an output. This feedback value is between 0.0 and 1.0, with 0.0 representing the minimum value of the range and 1.0 the maximum value. If the spectral power is lower or greater, the feedback value does not surpass 0.0 or 1.0. Another thing of note is that the code limits large increments, so the feedback value cannot change by more than 0.05 at a time, resulting in smoother transitions (e.g. of colors in the blue square program) in case of significant changes in neural activity.
One of the most important factors is the chosen frequency range in the code. While recording the headset collects a large amount of data, but as was discussed in section 2.5, using a wide frequency range for neurofeedback might result in different brain-waves conflicting with each other. The programmer of NFB decided to focus on frequencies between 3.5 Hz and 6.5 Hz for his examples, which means that the program will mostly focus on theta waves [23]. Theta wave recording is an established method of motion-sickness and alertness monitoring [24][25][26], so the VNS will keep those settings as is.

2.6.2 The Neurofeedback Program

The neurofeedback program was constructed using MATLAB, the MATLAB App Designer (MAD) to be specific. MAD is a built-in feature of MATLAB which allows the programmer to create a deployable software which does not require its user to have MATLAB installed.
The program utilized several different toolboxes in order to function. Besides NFB, it depended heavily on Psychtoolbox-3 for its graphical functions. The program had to both collect data and run visual functions at exactly same time so features from MATLAB's own *Parallel Computing Toolbox* were implemented. This allowed the program to allocate resources to different CPU cores which did, however, prevent the program from running on lower-end computers.
Figures 2.3 and 2.4 show examples of MAD, the user interface and the maze-like pattern generated in the final program. The maze-pattern was randomly generated during each run.

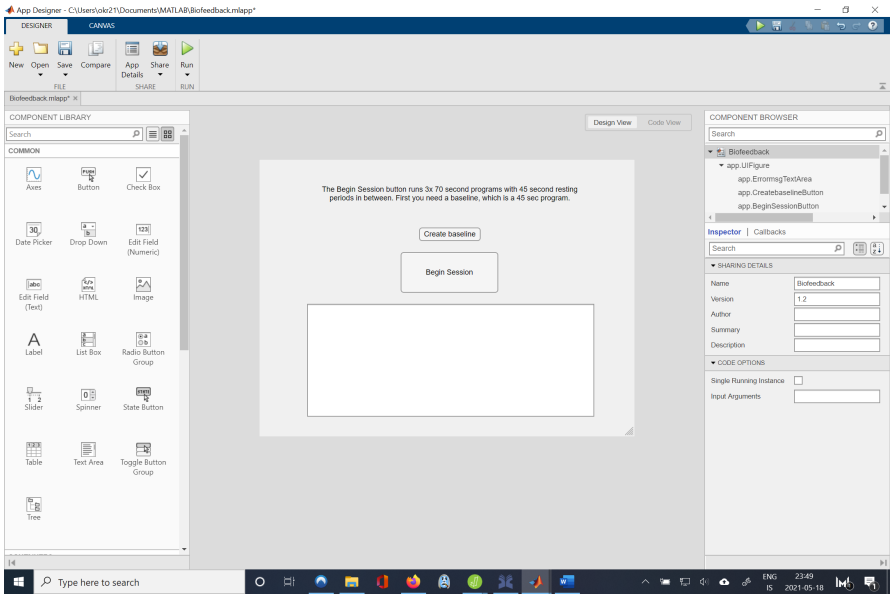

Figure 2.3: Demonstration of the MATLAB app designer, with the completed UI of the neurofeedback app

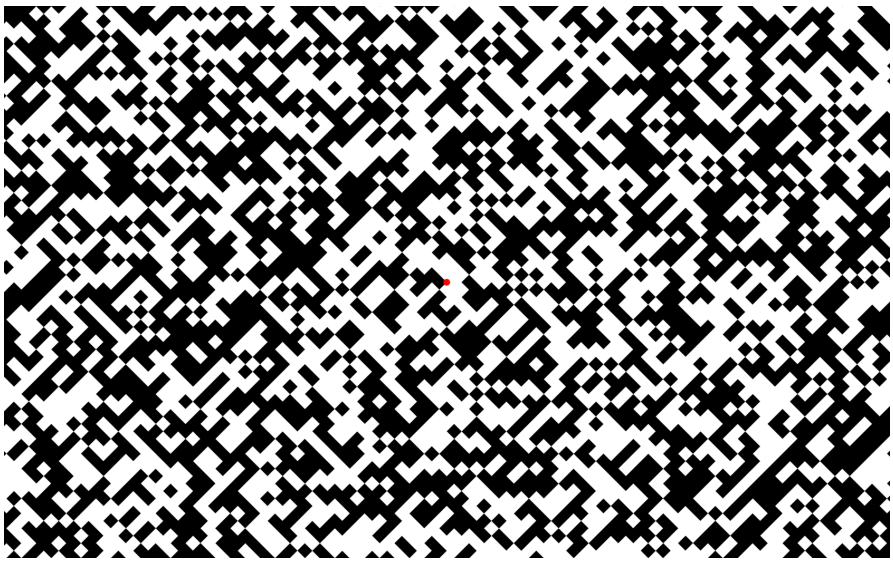

Figure 2.4: One example of the maze-like patterns every user saw after beginning a neurofeedback session. 5 seconds of no spin were followed by 60 seconds of spin, followed by another 5 seconds of no spin. Users were instructed to focus on the red dot.

2.7 Controlled testing and reference data collection

Table 2.2: Basic information on the five subjects that participated in this study

Subject	Age	Sex
1	32	F
2	30	M
3	25	M
4	49	M
5	21	F

Five healthy subjects were recruited for the initial round of testing. Before being equipped with a Muse and the neurofeedback program on their personal computers, the subjects went through a proficiency test. It involved trying out the program while standing on a WBB and staring at a large projector screen. They were first shown a demonstration of the spinning pattern on a smaller monitor (see figure 2.4), as seeing it for the first time on a large screen in a dark room can be disorienting. The subjects were positioned one at a time on a WBB while wearing a Muse in front of a projector screen. They were informed that after the researchers turned off the lights and left the room, the screen would turn dark. A red dot would appear in the middle and they should focus their attention on it until the screen reset. After that, the spinning maze pattern they saw earlier would appear and after a five second delay it would start spinning. They were told that the velocity of the spin would influence the velocity of the spin, with calmness leading to lower velocity. They were instructed to attempt to slow down the velocity of spin as much and for as long as possible while staring at the red dot in the middle, but in order to not influence individual approach to that task, no further details were given on how exactly to achieve that. They were also instructed to breathe normally and keep facial movements and blinking to a minimum. This would also apply to the at-home training regimen. The test was repeated after the subjects finished their training regimen, which is detailed in the next section.

2.8 Training regimen

Between the controlled testing sessions the subjects were provided with a Muse headset and the neurofeedback program was installed on their personal computers. The subjects were instructed to practice once per day for a week and then return for their second controlled testing session. The training regimen had the following format:

1. Baseline establishment for 45 seconds, where the subjects stare at a red dot in the middle of a black screen.

2. Five seconds of a (randomly generated) static maze pattern, after which it suddenly begins spinning for 60 seconds where the velocity depends on their neural activity. The pattern then stops abruptly and stays in its final position on the screen for five seconds before disappearing.

3. The subject is then instructed to relax, stretch and stand up. This is intended to prepare them to focus again on the program, as it will restart 45 seconds after step 2.

4. Once the rest period is over, the program repeats steps 2. This happens until the subject has finished three sessions.

Data from their performance was saved after each session. No data was collected during the rest period although subjects were instructed not to remove their headsets during that time. As during the proficiency test, they were instructed to limit facial movements and to breathe normally during every session.

2.9 Statistical methods

All data was prepared and processed using a combination of Microsoft Excel, MATLAB and Origin. Statistical analysis was performed using JASP, an open-source statistics program maintained by the University of Amsterdam [28].
Each subject's training data was analysed using the Repeated Measures Anova (ANOVA) method [29], where the mean of each day's theta wave spectral power was the focus.
Results from proficiency testing before and after the training regimen were analysed using paired sample t-testing.
Pearson's Correlation Analysis (PCA) was used to compare overall training

improvement with both recorded spectral power and body sway changes between proficiency tests. It was also used to compare MSSQ-Short scores with values obtained during testing.

Chapter 3

Results and Analysis

3.1 Evaluation results

During evaluation sessions with two subjects (male, age 27 and 30) the blue square experiment, described in section 2.2 and shown in figure 2.1, behaved predictably and in a consistent manner. Exact values varied depending on the baseline in use, but typically the maximum blue value correlated with a spectral power of about 140 $\mu V^2/Hz$ at the defined theta band (3.5-6.5 Hz) while the minimum correlated with a spectral power of about 90 $\mu V^2/Hz$. The Muse was deemed sufficient and the project moved forward.

3.2 MSSQ Results

Table 3.1 shows the results from the MSSQ-Short questionnaire.

Table 3.1: MSSQ Results for each subject

Subject:	1	2	3	4	5
Score:	20.6	14.0	10.0	13.5	49.5

3.3 Training progress

All at-home training data from the subjects was collected and the mean spectral power recorded per session was calculated. The results were then averaged between subjects, the results can be seen in table 3.2.

Table 3.2: Mean spectral power results of all subjects by day.

Day	**Mean** $[V^2/Hz]$	**SD**	**N**
1	129.66	26.46	5
2	109.89	22.34	5
3	106.46	18.28	5
4	104.12	10.91	5
5	103.61	15.56	5
6	99.77	8.10	5
7	98.96	10.23	5

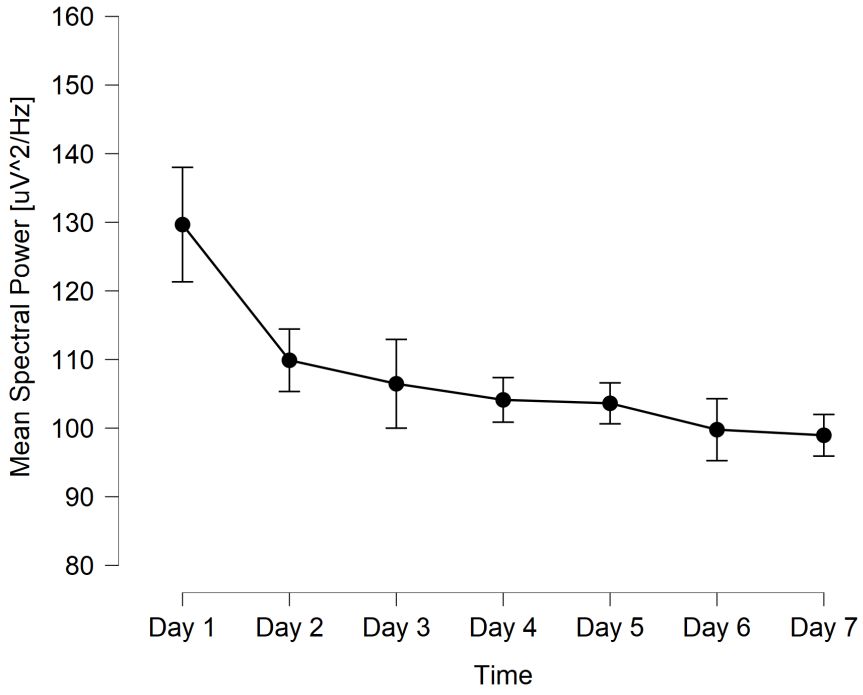

Figure 3.1: Plot of the mean daily spectral power of all the subjects during the training regimen, at frequencies 3.5-6.5 Hz (theta waves). The error bars represent standard error.

3.4 Proficiency tests

3.4.1 Feedback results

The *feedback score* is what the neurofeedback program uses to set the velocity of the spinning maze. Therefore, it can be used to tell the number of rotations the maze completed during each run. Table 3.3 shows the average score for each subject, separated into results from the *pre-training regimen* test and the *post-training regimen* test. Since each 70 second program includes a total of 10 seconds of stillness, a *spin-score* is also provided to show the average of only the values that directly influenced the spin velocity. There was no function counting number of cycles included in the program and commands that incremented the spinning animation depended on CPU cycles, not a consistent timer. The following equation was arrived at through repeated experimentation:

$$\text{Number of rotations} = k * (F_{spin} * 2.5 + 0.3)$$

$(F_{spin} * 2.5 + 0.3)$ represents how the program calculates the angle for each spin increment, where F_{spin} is the average of all feedback values recorded while the program is spinning. Note that while running the program always uses the most recent feedback value, not an average. k is a constant arrived at through repeated experimentation by counting the number of cycles per unit of time while the feedback values are known, and multiplying the results by spin time (60 seconds). The average result was $k = 9.875$, with a standard deviation of 0.479 after 4 trials.

Table 3.3: Feedback score comparison

	Pre-training			**Post-training**		
Subject	**Spin score**	**Total score**	**Approx. # of rotations**	**Spin score**	**Total score**	**Approx. # of rotations**
1	0.48	0.51	14.8	0.63	0.64	18.5
2	0.49	0.49	15.1	0.39	0.40	12.6
3	0.68	0.68	19.8	0.70	0.68	20.2
4	0.61	0.62	18.0	0.76	0.76	21.8
5	0.63	0.62	18.6	0.55	0.59	16.7

3.4.2 Body sway and spectral power results

The spectral power from the proficiency tests, as well as the body sway calculated from WBB data, is displayed in table 3.4.

Table 3.4: Body sway area and spectral power (3.5-6.5 Hz) by subject comparison between proficiency tests

	Pre-training			Post-training		
Subject	**Sway area**	**Mean power**	**MP STD**	**Sway area**	**Mean power**	**MP STD**
1	0.99	127.61	9.33	0.97	99.78	9.36
2	1.16	98.46	9.72	1.49	96.80	7.72
3	1.32	91.11	6.57	0.12	96.09	8.33
4	1.08	115.03	8.92	1.02	97.74	8.78
5	3.02	128.12	8.04	1.75	117.62	6.71

Paired sample t-testing showed no significant results between scores from before training and after training.
PCA showed no significant correlation between training improvement and changes in body sway ($r = 0.78$, $p = 0.12$), training improvement and mean power change ($r = -0.22$, $p = 0.72$) nor power change and changes in body sway ($r = -0.39$, $p = 0.52$).
MSSQ-Short scores correlated significantly with body sway area from before training ($r = 0.93$, $p = 0.02$) but not after training ($r = 0.68$, $p = 0.21$). No other significant correlation was found between MSSQ-Short scores and values measured during the proficiency tests.

Chapter 4

Discussion and conclusion

4.1 Discussion of results

4.1.1 Primary goal

The primary goal of this thesis project was the development of a visual neurofeedback system (VNS) using a Muse 2 Brain Sensing Headband (Muse) and a personal computer. The correlation analysis between MSSQ-Short scores and body sway indicate that the program succeeds in inducing a motion sickness response ($r = 0.93$, $p = 0.02$ when subjects were first exposed to the program). These results, in addition to those presented in section 3.1 for the blue square experiment, show that at least a rudimentary neurofeedback functionality has been established, while the significant improvements displayed over the course of the training regimen show its potential for more advanced work. The primary goal is therefore deemed a success.

4.1.2 Secondary goal

The secondary goal was to evaluate the VNS's usefulness for VMH and motion-sickness treatments. Starting with the training regimen, table 3.2 and figure 3.1 show a substantial improvement during the first two days of training, after which subjects tended to continue their improvements in smaller increments day-by-day. While most of the improvements happened early in the training regimen, the results did not plateau during those seven days. Therefore, longer training regimens should be implemented in future studies in order to gain further insight into how a treatment plan based on this system should be designed and implemented.

The feedback score results in section 3.4.1 display no significant improvements between sessions, however each individual feedback value was calculated according to a dynamic feedback range and was limited by increments between 0 and 0.05 (see section 2.6.1). These values are therefore likely to be heavily skewed, especially if subjects experienced rapid changes in neural activity during the proficiency tests. Of greater importance are the spectral power values used to calculate the feedback values. Section 3.4.2 shows that there was no correlation between training improvements and mean power change during the proficiency tests. This was unexpected, since the training regimens and the proficiency tests were measuring the same thing with the difference being that the proficiency tests were performed in a controlled environment. The drop in training activity was consistent over time and between subjects, so it is unlikely that this discrepancy was caused by noise or random chance. Something might be fundamentally wrong with the setup of the proficiency tests or perhaps the problem had something to do with the subjects no longer performing the test in the comfort of their own home.

No significant correlation was found between changes in body sway and mean power change. Likewise, the correlation between training improvements and changes in body sway was not significant either. One notable case, however, was subject 5. She had the highest MSSQ-Short score by far (49.5 out of 54, indicating she frequently experiences motion sickness) and she showed the greatest improvement. Her body sway went from 3.02 down to 1.75 and her mean spectral power dropped from 128.12 $\mu V^2/Hz$ to 117.62 $\mu V^2/Hz$, which is still rather high considering that no one else had a mean power above 100 $\mu V^2/Hz$ in their second proficiency session. Nevertheless, the program may have reduced her sensitivity to motion sickness and there is nothing to suggest she would not have improved further given a longer training regimen. Also of note is subject 3. He had the lowest MSSQ-Short score (10 out of 54) and his sway area dropped from 1.32 to 0.12. For context, the second lowest sway area recorded was 0.97. The data was extensively reviewed to make sure that this drop in body sway was not caused by a software or measurement error, but everything suggests that it is valid. It is difficult to reach any sort of conclusion with a sample size this small, but subjects 3 and 5 indicate that future studies should have a wider variety of test subjects in terms of motion sickness susceptibility.

Finally, the correlation between MSSQ-Short scores and body sway. As was mentioned in section 4.1.1, there was a significant correlation between those values during the first proficiency session. However, that correlation disappears during the second session ($r = 0.68$, $p = 0.21$). This can be

interpreted in at least two ways; that the proficiency testing is flawed somehow, as was suggested earlier, or that the program did have an affect on the subjects' physiological behaviour but in an inconsistent manner. The relationship went from being significantly correlated ($r = 0.93$, $p = 0.02$) to no correlation ($r = 0.68$, $p = 0.21$). Future studies will have to see if these inconsistencies are also present in larger samples and if so, what causes them.

In summary, the results from this project show that visual neurofeedback are a potential treatment method for visual motion hypersensitivity (VMH), but a study with a larger and more varied sample size in terms of MSSQ-Short scores must be performed in order to confirm it. In addition, the proficiency testing process might have to be revised.

4.2 Conclusion

Over the course of this project a visual neurofeedback system (VNS) using a commercial EEG and a personal computer was successfully designed, constructed and validated for biofeedback research. Its usefulness as a treatment for individuals who suffer from motion-sickness, VMH and other related illnesses remains inconclusive, however. A greater sample size with both healthy and non-healthy individuals in terms of motion-sickness would provide a more conclusive answer.

4.3 Future studies

In addition to revising some of the testing and sample composition, this project could be expanded upon by utilizing similar eye-tracking devices as some of the studies that inspired this project. Exploring and comparing different brain-wave frequencies might also be prudent in order to evaluate whether or not the theta range (4-8 Hz, 3.5-6.5 Hz in this study) is ideal.

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Appendix A

State of the Art

A.1 Introduction

This appendix is intended to provide a greater insight into the scientific and technological principles behind biofeedback and EEGs, with a focus on the small commercial devices that make a study like this one possible.

A.2 Electroencephalography

The practice of recording bio-electric signals is over 200 years old, with the earliest experiments dating back to the 18th century and the first attempts to record electrical signals from a mammalian brain date back to at least 1870 [30][31]. One common modern method of recording electrical activity of brains is called *electroencephalography* which is carried out using devices appropriately called electroencephalograms (EEGs), which were first used in a clinical application in 1924, Germany [32].

A.2.1 Application and physiology

The brain contains a vast amount of nerve cells, called *neurons*, held together by a supporting tissue called *neuroglia* [33]. Neurons are quite distinct from other cells in the body due in part to their uniquely polarized structure. In addition to a cell body, called *soma*, neurons are also composed of *dendrites*, which receive nerve signals, and *axons*, which propagate signals (known as *action potentials)* to other neurons or surrounding tissue [7]. The synchronized electrical activity of a significant number of neurons creates what is known a *field potential*, an electrical signal that can be detected by an electrode placed

on the scalp in the case of neural activity originating in the brain [7]. An EEG is a test that detects signal between "active" electrodes on the scalp, where the neural activity takes place, and "indifferent" electrodes, which are located a certain distance away from the active ones [7]. By measuring the potential difference between a pair of such electrodes as a function of time, a graph representing the activity of the targeted brain regions can be formed [7]. A setup consisting of one active and one indifferent electrode would count as an EEG, but would provide limited data. EEG activity varies significantly depending on the location of electrodes and therefore a network of electrodes must be constructed to create an accurate graph of encephalic activity [7].

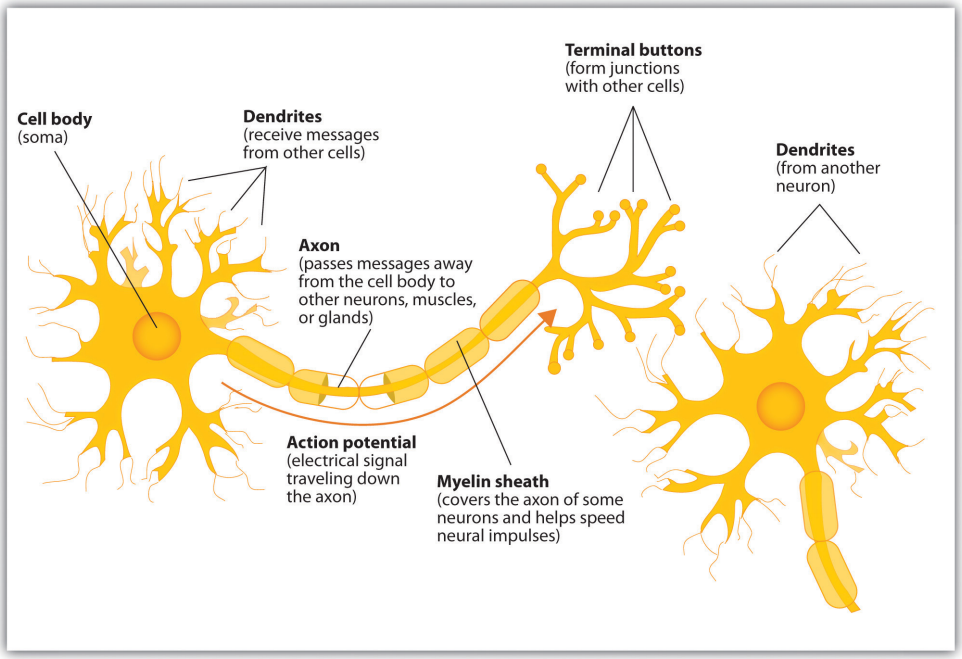

Figure A.1: Structure of a Neuron [34]

Typically, an EEG setup will follow the International 10-20 System (IS 10-20). This setup consists of at least 21 electrodes, of which 2 are reference electrodes attached to the ears [8]. Figure A.2 shows the standard 10-20 system while figure A.3 shows a modified version called the *10-10 system*, which consists of 75 electrodes.

This setup allows easy comparison of data from different subjects and research groups. A greater number of electrodes, like those in the 10-10 system or the proposed 10-5 system (a system that defines 345 positions) allows for

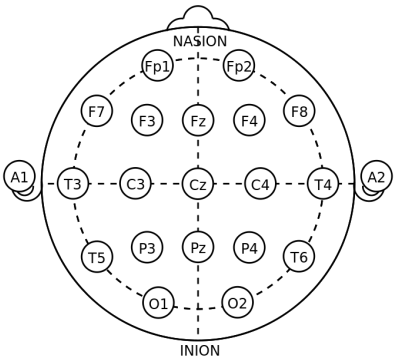

Figure A.2: The International 10-20 System [35]

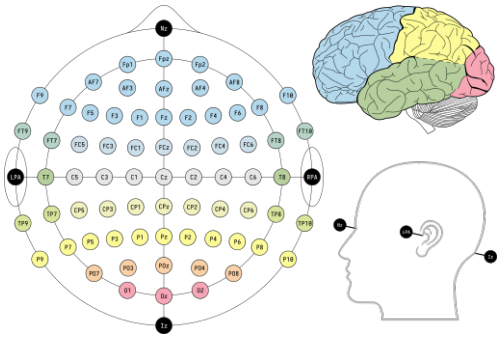

Figure A.3: The modified 10-10 system with coverage for context [8]

more localized data collection and more consistent electrode placement, at the cost of greater setup time [7]. The 10-20 system and its variations depend on three imaginary lines; the *anteroposterior sagittal midline*, the *latero-lateral coronal line* and the *sagittal lateral longitudinal line* [8]. These lines are perpendicular to each other. The anteroposterior line is traced through the *vertex* (top of the head, see point Cz on figure A.2) from the *nasion* (just above the bridge of the nose) to the *inion* (the protuberance on the back of the skull), the latero-lateral line is traced from ear to ear, also through the vertex, and finally the sagittal line is traced from the nasion to the inion but is perpendicular to the anteroposterior line.

A.2.2 Electrodes

The key components of every EEG are the electrodes. They connect the bioelectrical activity happening withing the skull to the amplifiers and graphing tools that create the encephalograms [7]. An important quality of such electrodes is to not distort the signal they are recording. This is problematic, especially in terms of recording very low-voltage signals like those generated from neural activity. The electric potentials created when the metal of an electrode meets the saline-rich environment of the skin can be enough to throw off measurements significantly [7]. Silver/Silver-Chloride (Ag/AgCl) electrodes used in conjunction with a conductive gel are used to minimize the various measurement distortions and artifacts that would significantly reduce the quality of EEGs, one of which is impedance [7]. A high impedance makes the system more sensitive to movement artefacts and noise [7]. The Ag/AgCl electrodes need to be regularly rechloridated, which is time consuming, or

simply thrown away and replaced [7]. Ignoring that issue, having to apply a conductive gel to each electrode before every EEG recording session means that extra time must be allocated to prepare every subject. Unfortunately, these gels are often toxic and lose their effectiveness as they dry out [7]. Despite these problems, Ag/AgCl electrodes with conductive gels are still almost universally used for EEG recordings in clinical settings, simply because they cannot be matched in signal quality and signal-to-noise ratio (SNR) [7]. But because of their inherent problems, they are inconvenient for long-term EEG monitoring. This is where recent advances in dry and active electrode technology presents new opportunities. The surface-to-skin contact problems described earlier in this section are still present. The connections between dry metals and skin will still have problems with high impedance which may vary greatly depending on conditions (sweat, climate etc.) [7]. This high impedance makes the electrodes more susceptible to noise and movement, something which is likely already higher and more varied compared to a controlled lab environment [7]. But by utilizing advances in other departments such as differential amplifiers, shielding and integrated circuitry, these effects can be minimized just enough to make them useful in certain applications, such as those who depend on regular and/or long-term use [36][37][38].

A.3 Validation of existing devices

Interest among researchers and hobbyists for portable, low-cost EEG systems is high enough to support a growing industry of commercial devices [14]. Many such systems rely on dry, reusable electrodes to make them more user friendly and to increase comfort during long EEG sessions [14][17][16][39]. It does however raise questions regarding their reliability, at least in terms of providing usable data for academic studies.

A.3.1 Methods of validation

Validation studies for portable EEG headsets are few and far between but there are a few notable examples [14][16][17][39]. These studies typically validate headsets using event-related brain potentials (ERPs), where a stimulus (e.g., a visual one) is presented to a subject while wearing an EEG headset. The response on the EEG should be predictable in a healthy subject, see figure A.4 for an example. Of interests to many of these studies were the N2 and P3 peaks, also known as N200 and P300, respectively. The letters indicate whether it is a NEGATIVE or a POSITIVE potential while the

numbers indicate approximately how long after stimulus the peaks appear, in milliseconds. So N200 is a negative peak appearing after ∼200ms and P300 is a positive peak that appears after ∼300ms. N200 is associated with novelty and mismatch detection in the brain while P300 corresponds to cognitive information processing such as those relating to memory, attention and executive functions [40][41]. A test known as the *visual oddball paradigm* is commonly used to induce these peaks and is useful as a validation mechanism [14][42]. A series of dots of the same color are presented, with an occasional "oddball" of a different color presented in between [42]. See figure A.5 for an example.

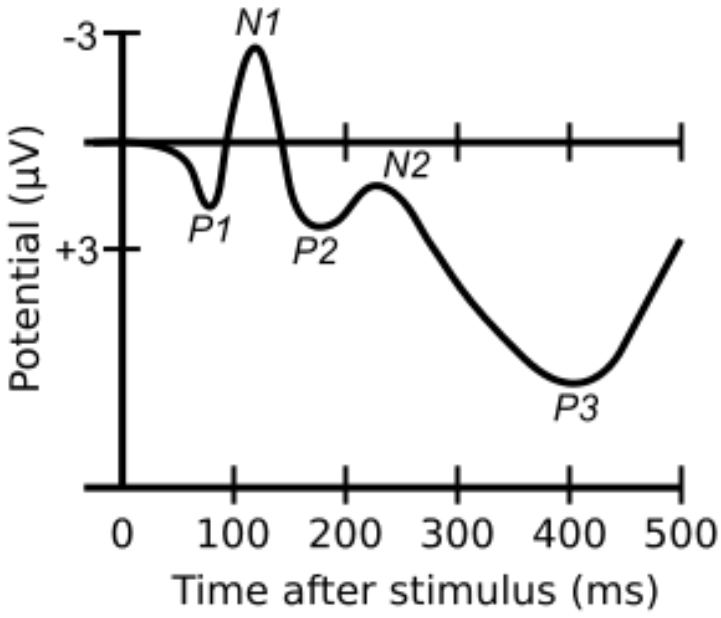

Figure A.4: Event-related brain potentials. Distinct peaks that appear on EEGs after stimulus, often visual ones. The events are also referred to as P100, N100, P200 etc. where the numbers refer roughly to the time that has passed since stimulus [43]

Another commonly used ERP is feedback-related negativity (FRN) [14][40] [44]. FRN occurs when individuals are exposed to stimuli (e.g. auditory) that they associate with reduced performance [44]. An example of this is playing a certain tune when a subject loses points while playing a game. Approximately 250 milliseconds after stimulus, the FRN should be measurable [14][40][44]. In a neurologically healthy subject, the peaks are expected to be there after a

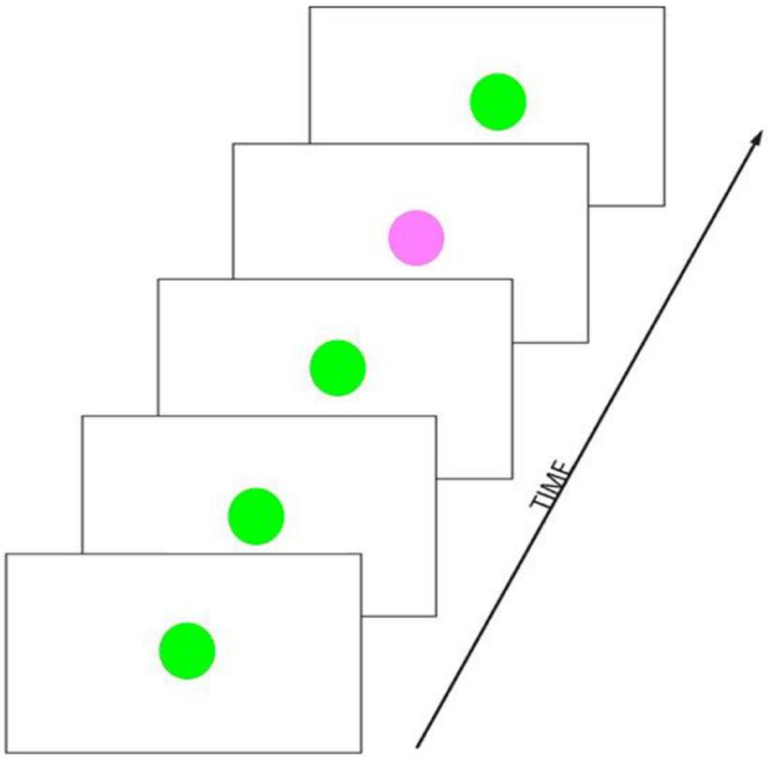

Figure A.5: One version of the visual oddball paradigm. A series of dots of the same color, in this case green, are presented to a subject. Occasionally, a different colored ball is presented, in this case a purple one [42]

relevant stimulus is given so an EEG headset that consistently fails to detect them is not considered very useful in academic studies.

A.3.2 Device examples

The Emotiv EPOC EEG headset (EPOC) is a subject of a few studies [14][16][17], but the results were mixed. While it managed to detect the peaks of interest consistently, the quality of the signal was often poor. The bulkiness of the headset and its high maintenance cost also negatively impacts its supposed usefulness as a device for commercial and long-term use [17]. It should be noted that the device used in these studies is an old, discontinued model. However, no reliable validation studies were found for the newer models.

An alternative to the Emotiv EPOC EEG headset (EPOC) is the Muse 2 Brain Sensing Headband (Muse), which is the device chosen for this thesis. While advertised as a tool for meditation, it has shown promise as a system for use in ERP research [14]. The Muse has significantly fewer electrodes than the EPOC (5 on the Muse compared to 14 on the EPOC). Despite this, the Muse 2 Brain Sensing Headband (Muse) performed admirably in the only validation study available on the headset [14]. The Muse only has electrodes in the Fpz (a reference electrode) AF7, AF8, TP9, and TP10 locations* (see figures A.3, A.6 and A.7). To put that into perspective, P300 is typically measured from electrodes placed above the parietal lobe (the yellow part of the brain in figure A.3), which the Muse does not cover, although frontal lobe P300 measurements are not unusual [45]. While it could never come close to the quality of clinical EEG systems, it does however show its potential for use in studies where N200, P300 and FRN are of particular interest [14]. No studies that compare the performance of the Muse with the EPOC were found, but its minimalist design certainly makes it more desirable when user comfort is an important factor.

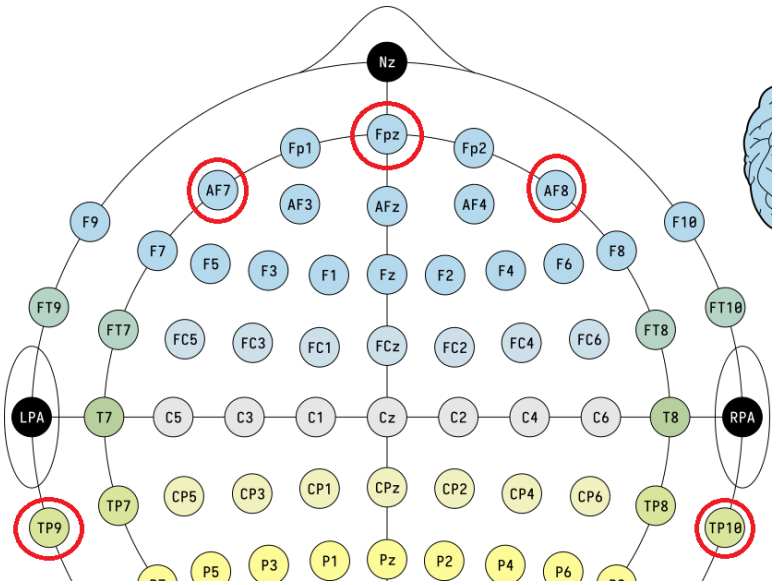

Figure A.6: Locations of the Muse's electrodes, circled in red.

* It should be noted that the Muse appears to have five forehead electrodes in addition to the two behind the ears. All documentation found indicates a total of five EEG electrodes with only three on the forehead, so the exact purpose of the extra electrodes is unclear.

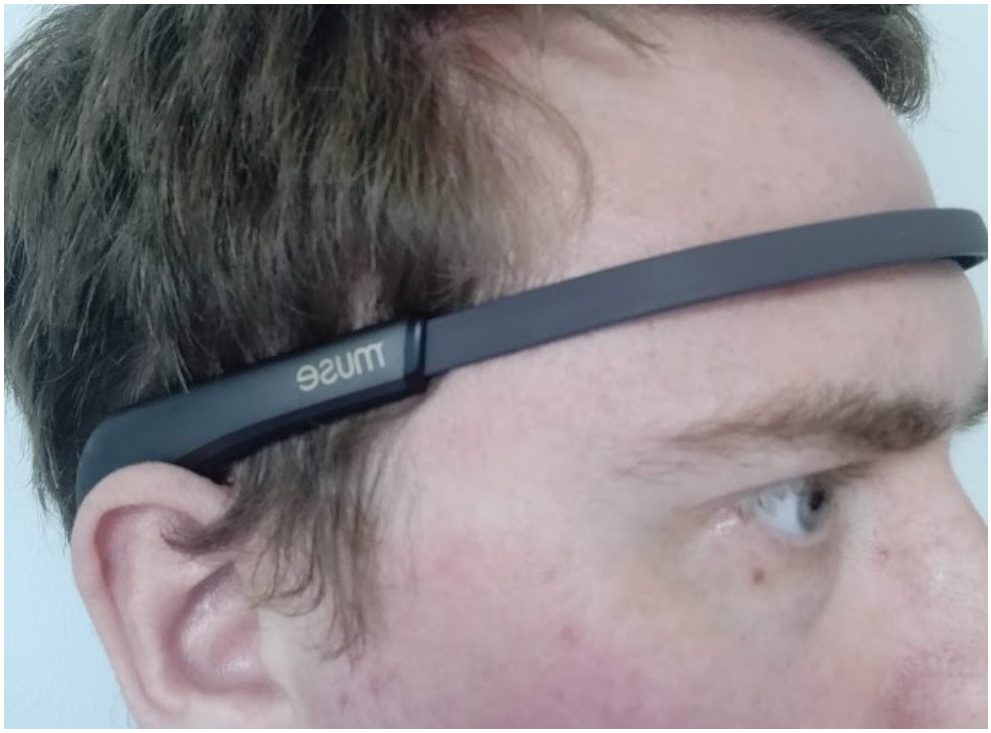

Figure A.7: The Muse 2 Brain Sensing Headband (Muse) in use. A reference electrode is positioned in the middle of the forehead (Fpz position), between two active electrodes (AF7 and AF8 positions). One electrode is position behind each ear (TP9 and TP10).

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