PROJECT CAREBRO

A Brain-Computer Interface for use in Home Automation

by
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GRADUATION REPORT

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ABSTRACT

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A brain-computer interface allows communication from the brain to an external device. Carebro is a brain-computer interface using electroencephalography that is being developed by Negotica Development Projects to provide people with disabilities with the ability to control applications and functions in their household. In this research project the hardware availability for consumer EEG monitoring is investigated. Two EEG headsets are used in an experiment with a total of three electrode configurations to analyse the success rate of cognitive command detection of Carebro with different electrode placements. Placement over the parietal lobe does not appear to be as significant a factor as proposed, and per-subject analysis of results implies that training longer in one session does not positively impact success rates but regular training might. Additionally, a Java application has been developed that allows greater adaptability of the user interface and provides additional functionality for Carebro. Finally, research into the effect of EEG hardware on EEG response was conducted, with limited practical results.

DECLARATION

I hereby certify that this report constitutes my own product, that where the language of others is set forth, quotation marks so indicate, and that appropriate credit is given where I have used the language, ideas, expressions or writings of another.

I declare that the report describes original work that has not previously been presented for the award of any other degree of any institution.

Signed,

Jos Albers

ACKNOWLEDGEMENTS

For my graduation for the Bachelor Advanced Sensor Applications I conducted my graduation project at Negotica Development Projects. I would like to thank my company supervisor and the CEO of Negotica, Peter van der Tang, for his supervision and guidance in the project and his keen outlook on the very interesting topic of BCI as well as his readiness to get me involved in several networking opportunities. I would also like to thank Mark de Groot for facilitating the project through answering any questions I had and Annemiek Aarse-Korf and Jitse de Lange, along with Mark and Peter for providing me with a pleasant working environment.

I would like to express my gratitude to my graduation supervisor, Ronald van Elburg, who counselled me over the course of the project and provided invaluable feedback throughout. Finally I would like to thank my friends Max Wessels, Kevin Marczyk and Dennis de Lange for sharing their insights as they were graduation alongside me and my parents and siblings for their unwavering support throughout my graduation period.

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GLOSSARY

BCI	A brain-computer interface is a connection between a computer and a user by measuring brain signals, allowing communication to a nearby device.
EEG	Electroencephalography is a method of monitoring brain activity by measuring potentials at different locations of the brain. This can be done with electrodes on the scalp or with more invasive techniques.
ERP	An event-related potential is a measured response in the brain to a stimulus. Different types of ERPs can be measured using electroencephalography. The magnetoencephalographic counterpart of an ERP is an event-related field (ERF).
ODS	The Open Domotics System by Carebro is an alternative name for the Web of Devices as used by Negotica and is often used internally to connect multiple devices and systems to each other over a local area network or internet connection.
SDK	A software development kit is a collection of tools that is useful in creating application for software packages, frameworks, operating systems etc.
SNR	Signal-to-noise ratio is a term for the relative size of a signal to the background noise. The exact definition of 'noise' differs for different applications, which is handled more in-depth in the conceptual model.
SSVEP	Steady-state visually evoked potentials are brain responses to visual stimulation at specific frequencies. The signal-to-noise ratio of these potentials is usually high, making this a common analytic tool in BCI research.
WBS	A work breakdown structure is a hierarchical structure that decomposes a project into smaller parts with a focus on deliverables. This can be done both from the bottom up where there is no clear end result, and with a top-down approach to describe the important tasks to complete.
10-20 configuration	A widely recognised descriptor of electrode locations, where the distances between electrodes are either 10% or 20% of the total front-back and side-to-side ranges of the skull.

CHAPTER I

RATIONALE

People with certain physical disabilities cannot easily move around in their house and actions that might seem trivial to most people, e.g. opening a window, turning on lights, changing channels on the television and opening the front door, might not come as easily to some people with disabilities. This results in reduced independence as these people cannot easily function without caretakers who check up on them.

The company Negotica Development Projects (Negotica) is a hardware- and software solutions developer with a focus on home automation. In 2009 the company set up a project on using a brain-computer interface (BCI) aimed at making people with disabilities more independent by providing them with the tools to have more control over their living environment. A BCI is a system that allows communication from the brain to an external device. The BCI application that Negotica works on utilizes a consumer-grade electroencephalography (EEG) headset to obtain data - filtered through software provided with the headset - and the main focus of Negotica previously was in developing an interface that allowed control of numerous different actuators with a limited number of actual commands and investigating and translating user requirements to technical solutions. More recently, Negotica has acquired new EEG hardware and would like to investigate the hardware possibilities for Carebro in terms of usability, detection speed, and detection accuracy of cognitive commands.

The research is in the form of a descriptive problem and tries to analyse the issues of using a consumer-grade EEG in BCI for people with disabilities. The main research question is as follows: "What effect does the EEG hardware used for BCI have on data acquisition, signal-to-noise ratio and the success rates of the corresponding SDK algorithms for the classification of a certain amount of commands?"

The intention of continued research and development of Carebro is to set up a new demonstration- and test site where students, companies and health organizations are poised to collaborate.

Sub-questions to this central research question are: "How can the new Carebro best be utilized in the new demonstration- and test platform? What is the best approach to an interface for a flexible (hybrid) BCI application based on cognitive commands for the use of domotics, self-fulfilment and neurofeedback?"

CHAPTER 2

SITUATIONAL & THEORETICAL ANALYSIS

Stakeholders

The aim of Carebro is first and foremost to provide a usable product for people with congenital or non-congenital neuromuscular diseases and disabilities to control various (user-specific) household functions with in an effort to make these people less dependent on caregivers or family members for these functions. For example, currently healthcare organizations often need to send in caregivers to open- or close windows, which undermines the independence of the person with a disability and wastes time for the personnel that could be used in other ways to provide care as well. (Van der Tang, 2016)

Consumer BCIs are available that focus on giving neurofeedback for brain training and relaxation instead of cognitive commands. Neurofeedback for the preservation or restoration of cognitive function is supported by research (Ramar, et al., n.d.) (Otal, et al., 2014), although research on this in recent years is somewhat limited. While not a primary objective in this research it is good to consider that Carebro might provide ways for people with decreased motor functions to rehabilitate using neurofeedback, or for people with disabilities in general to both 'sharpen' their minds and simply entertain themselves.

Electroencephalography

Electroencephalography (EEG) is an electroneurography technique that is used to measure or record electrical activity in the brain and works by reading voltage fluctuations from currents generated by ions moving through neurons (Niedermeyer & Lopes da Silva, 2005). Other methods of (electro)neurography exist as well, such as the more invasive method of electrocorticography (ECoG) – also named subdural or intracranial EEG – in which electrodes are placed underneath the dura mater, the outermost membrane that envelops the brain underneath the skull (Leuthardt, et al., 2006), positron emission tomography (PET), functional magnetic resonance imaging (fMRI) and magnetoencephalography (MEG) (Hämäläinen, et al., 1993).

Historically, EEG has been used for medical purposes in order to diagnose or monitor certain health problems of patients such as seizures and epilepsy (Veisi, 2007), brain diseases (e.g. Alzheimer disease) (Jeong, 2004), changes in body chemistry that affect the brain, head injuries, tumours, infections, temporary memory loss, confusion or fainting, encephalopathy (brain disorders), encephalitis (brain inflammation), strokes or sleep disorders (Attarian & Undevia, 2012), although some of these health problems are not always monitored through EEG (anymore). Another current use for EEG monitoring is in scientific research where observing activity in (parts of) the brain is needed.

In the past, EEG required the removal of the upper layer of skin. Nowadays, commonly a conductive gel or paste is applied to the electrodes or the scalp. Furthermore, dry electrodes can be used that remove the need for a conductive gel.

Electrical activity in the brain for use in BCIs

Brain-computer interfaces work by measuring the electrical or chemical activity in the brain; in any consumer-grade hardware this is done through electroencephalography. In this section the most utilized electrical activities in the brain for BCI applications are detailed.

Evoked potentials (EP) are electric signals from the averaged EEG activity for the time that some stimulus is presented, whether visual, auditory or otherwise (Fisch, 1985). Event-related potentials (ERPs) are more broadly the electrical activity in the brain related to a specific stimulus, response or decision (Luck, 2012). One ERP component is the P300 (P3) wave which can be auditory, visual or somatosensory and is elicited by rare or significant stimuli and in the process of decision making (Beverina, et al., 2003). The P300 wave is quite commonly used in BCI, mostly in an ‘oddball’ paradigm where an unexpected target stimulus gets fired in a regular train of stimuli (Picton, 1992). A general P300 response is illustrated in *Figure 1* with the label *P3*, along with several other ERPs.

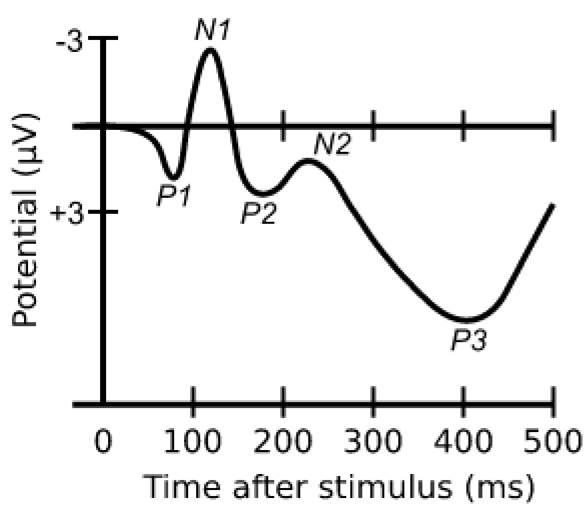


Figure 1 - Response waveform showing several ERP components (RobinH, 2008). P3 indicates the P300 response. Note the inverted y-axis for the potential, which is common in EEG research. Other components are visible in the figure, although these are less reliable for ERP detection than the P300 response for different users and less commonly used in BCI.

Steady state visually evoked potentials (SSVEPs) are the natural responses to visual stimuli at specific frequencies, thus being produced when the patient focuses on an oscillating light or some source that exhibits other wave characteristics. For visual stimuli produced at frequencies of 3.5 Hz to 75 Hz, the brain generates electrical activity at the same frequency (Beverina, et al., 2003). SSVEP signals have a good signal-to-noise ratio (SNR) and are thus often used in research (Ding, et al., 2006). Furthermore, SSVEP does not require user-specific calibration training (Beverina, et al., 2003). The use of SSVEP is also quite common for BCI applications.

β (Beta) and μ (Mu) rhythms are electrical activities in the brain with frequencies ranging from 8 to 12 Hz (Mu) and 12 to 30 Hz (Beta). While these signals are associated with the areas in the brain related to motor control, they can be manipulated by imagining movements (Beverina, et al., 2003). This technique has also been used in BCI applications, although one might expect that imagining motor movements could be difficult for people with certain congenital neuromuscular diseases, which would complicate the use of these signals. If β and μ rhythms are feasible methods this would require additional testing for parts of the target demographic.

One more electrical signal that can be picked up in the brain for use in BCI is slow cortical potentials (SCP). These potential variations are generally produced by muscle movement to produce negative potentials. Positive SCPs are associated with cognitive functions (Beverina, et al., 2003). Researchers have shown in the past that with proper training, paralyzed patients can control SCPs for the use of controlling the movement of a cursor on a screen (Birnbaumer, 2003).

BCI with consumer headset

Medical- or research-based EEG devices are usually too expensive for consumer purchase, or in larger quantities by healthcare organizations. Some EEG hardware has been developed, often with BCI software to go along with it. Among the companies developing BCI targeted for consumers is NeuroSky. This company produces several different affordable EEGs that use ‘dry’ electrodes (without need for a saline solution or conductive gel), albeit for very specific purposes and with only a single electrode. Nevertheless, Neurosky released several products with corresponding Software Development Kits (SDKs) to allow developers to create their own applications.

The chips produced by NeuroSky can also be purchased separately and are featured in several other consumer EEGs. These chips provide low-level signal detection for one EEG channel (with reference and ground signals) and filter the raw EEG data for easier hardware development (NeuroSky, 2016). These chips have also been used by other developers (although most of them partner companies with NeuroSky) to produce their own BCI systems.

Some other BCI systems exist that utilize a low amount of electrodes and focus on meditation, relaxation, sleep and focusing of thoughts. While these can be classified as BCI systems they are not intended to provide a control mechanism but rather provide biofeedback. Examples of these systems are the iFocusBand (FocusBand, 2015), the BrainBand (MyndPlay, 2016), the Muse (InteraXon, 2015) or the Aurora Dream Headband (iwinks, 2016).

On the topic of consumer EEG hardware with a focus on cognitive commands, Emotiv Systems has developed two separate EEG systems. Both of these systems feature a distinct advantages for further development: Both EEGS come with SDK that not only identifies cognitive thoughts by measuring the sensorimotor (SMR) brain wave rhythm but also identifies facial expressions to some extent, which can for many people be used as additional commands.

The first is the EPOC, released in 2009. This device offers the use of electrodes that do not require a conductive gel to be applied and can instead be placed on the scalp 'dry'. However, a saline solution is provided to improve conductivity and from personal experience the sensors still benefit from this solution. The EPOC offers 14 EEG channels that are a subset of the international 10-20 locations detailed in ***Error! Reference source not found.*** nd has a sampling rate 128 samples per second (sequentially, with a single analog-to-digital converter (ADC)). The measured channels are the AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8 and AF4 channels, some of which are 10% electrodes (Emotiv Systems, 2014). The 20% and 10% indicate that the distances between electrodes are either 10% or 20% of the total front-back or right-left distance of the skull (Malmivuo & Plonsey, 1995). Furthermore, the EPOC has Common Mode Sense (CMS) / Driven Right Leg (DRL) reference electrodes at the P3 and P4 locations. CMS is a reference channel which is subtracted from all other EEG signals. DRL brings the potential of the user as far down as possible to the DC 'zero' of the hardware components. The EPOC can also be worn backwards, providing alternate coverage. This has been used in various research setups, although the locations of the electrodes are harder to correlate with certain behaviour of the EEG in this setup. The typical battery life is stated to be 12 hours. Emotiv also released an EPOC+ model that offers a wireless Bluetooth 4.0 LE connection (Emotiv Systems, 2014).

The second system that Emotiv released is the Insight. This EEG measures only five channels, namely AF3, AF4, T7, T8 and Pz following the nomenclature mentioned by Malmivuo and Plonsey (1995). The CMS/DRL reference electrodes are located on the mastoid process of the left temporal bone. The data transmission rate can be 128 or 256 samples per second. The battery life is lower at 4 hours minimum run time, although it can be extended by at least 12 hours with a proprietary external battery back. (The use of other power supplies, including laptops, disables

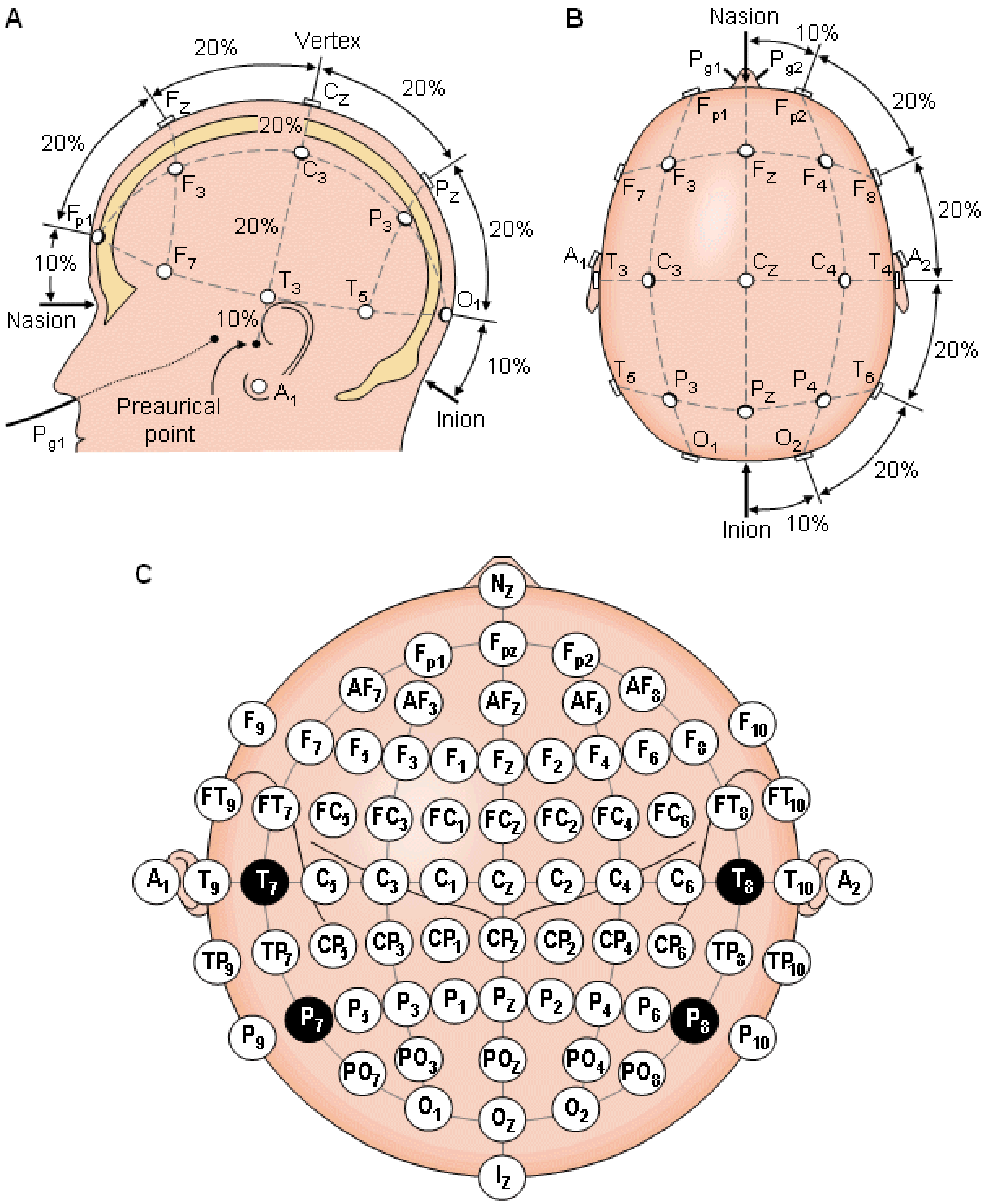


Figure 2 - Reference for electrode locations for the international 10-20 system as seen from the left (A) and top (B) sides of the head. A = ear lobe, C = central, Pg = nasopharyngeal (inserted through the nose), P = parietal lobe (concerning mostly sensory information and spatial sense), F = frontal lobe (concerning motor function, decision making, problem solving, emotions etc.), F_P = frontal pole, O = occipital lobe (concerning mostly visual stimuli and processing).

(C) Locations and nomenclature of the so-called 10% electrodes that lie in between those in the 10-20 configuration (Malmivuo & Plonsey, 1995).

the device for safety reasons, just like for the EPOC). The Insight also works over Bluetooth 4.0 LE Aside from these differences the specifications are very similar to the EPOC model (Emotiv Systems, 2014) (Emotiv Systems, 2014). One large difference between the two devices is that the Insight has sensors that truly function properly dry, without the need for a saline solution. This significantly reduces the setup time and complexity of using the device. Also, aside from SMR rhythm measurement and facial muscle expression measurement the Insight has (or claims to have) software for the detection of mental states of the user, although this functionality remains largely untested. This software might allow mental states to passively influence certain elements of the living environment of the user, such as light.

The BCI systems by Emotiv (or more specifically their Research Edition SDK) and Neurosky, as well as the partner companies using Neurosky chips, allow for the extraction of raw EEG data fed to a computer through their SDK. Emotiv also provides filtered and analysed results for cognitive commands, allowing out-of-the-box control of certain demo applications with BCI. Negotica has already used this SDK to interface the Emotiv EPOC to Java and develop a demonstration application for project Carebro in the past but has not yet worked with the relatively new Emotiv Insight. For the opening of Health-Hub Roden (Health Hub Roden, 2016) work was done to convert this application for use with the Insight and gaining experience with the workings and calibration of the Insight.

BCI software

OpenBCI (OpenBCI, 2015) is an open source BCI platform that is made by a collaborative group of people online, rather than an organization. BCI is used here for various applications, not only as a control interface and mostly as an offshoot of OpenEEG (OpenEEG, 2016), which is simply aimed at creating cheap do-it-yourself EEGs, but OpenBCI also provides the tools and the driven community to develop applications where the brain issues control commands. An example application is the control of a robot using SSVEPs (Audette, 2014).

BCI2000 is another open source project with the collaborative aim to produce a software suite for EEG data acquisition and stimulus presentation. BCI2000 is developed by researchers, for research purposes (Schalk Lab, 2016). This software is not forbidden for use in commercial purposes but its General Public Licence (GPL) imposes the condition that the full source code needs to be accessible (Schalk Lab, 2012). One may still sell EEG hardware in conjunction with the software but this is not an ideal solution for Carebro as one can simply obtain the software themselves.

Other BCI platforms include OpenViBE (Renard, et al., 2010) and a MATLAB toolbox for processing EEG data, EEGLab (Swartz Center for Computational Neuroscience, 2016).

Compatibility

Most of the EEG methods detailed require specific electrodes to work properly. Not all of these electrodes are provided by every consumer EEG headset. Using the Emotiv EPOC to implement an SSVEP-based BCI approach is feasible, although in literature additional EEG electrodes were placed on the parietal and occipital regions of the brain (Liu, et al., 2012) which is close to the visual cortex, which is useful when presenting visual stimuli to evoke a response. Alternatively, the accuracy of detection was significantly lower than using a 'full' EEG setup with more 10-20 electrodes. Furthermore, the C3 and C4 electrodes have been used extensively in research on BCI control for people with severe motor disabilities by Wolfpaw & McFarland (2004) that are not available on most consumer EEG headsets, including the Emotiv EPOC.

The Emotiv Insight has even less electrode locations available with only AF3, AF4, T7, T8 and Pz, likewise lacking electrodes on the occipital lobe and generally leaving few choices for which electrodes to use to obtain optimal signal quality (for the right signals). The sensors are mostly located on the motor cortex and somatosensory areas in the parietal lobe. Currently, raw EEG data from the Insight is sent to the Emotiv Control Panel software, which does behind-the-scenes processing, filtering and analysis of the data. The raw EEG data can be obtained with the Research, Educational or Enterprise Editions; without these the API only allows extraction of the mental commands, along with other data such as facial expressions. This raw data could be useful when fed to and processed with a tool such as BCI2000, OpenViBE or MATLAB, in an effort to get more control over what the user needs to do to have their commands registered.

Hypothesis

Based on the main research question, the hypothesis that this report aims to prove or disprove is described here. The EEG hardware used for cognitive control has a noticeable impact on the success rate of cognitive commands of Carebro, with the electrode configuration of the hardware being the main factor and configurations with electrodes on the parietal lobe performing significantly better than those without.

CHAPTER 3

CONCEPTUAL MODEL

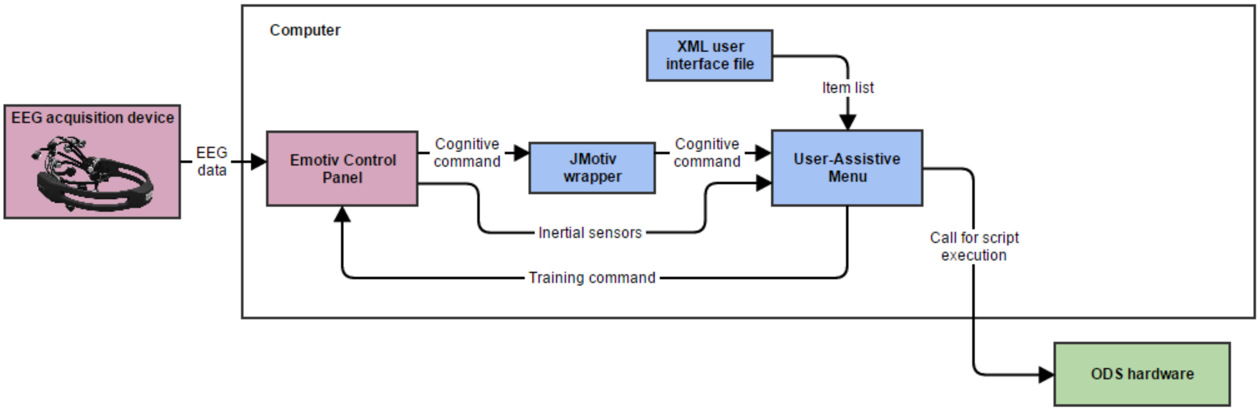


Figure 3 - Flowchart describing the conceptual model for Carebro in its past state. EEG data is acquired using the Emotiv EPOC EEG headset and sent to the computer, where the Emotiv Control Panel software is used to identify if a cognitive command is being issued by the user. A Java application (User-Assistive Menu) detects when a cognitive command is detected by the Emotiv Control Panel via the JMotiv wrapper for Java. The application can also tell the Emotiv Control Panel to start training a cognitive command to allow or improve detection. The XML user interface file provides the item list for the Java application, which provides a user interface that allows interaction with the ODS hardware. Currently the Emotiv Control Panel and the Java application are on the same computer, which has to connect to the Wi-Fi network from the ODS hardware in order to execute scripts there.

Using the EEG headsets and SDK from Emotiv to control domotics applications with the User-Assistive Menu yields the system illustrated in *Figure 3*. The EEG headset that is currently used to acquire EEG data is the Emotiv EPOC, with the Emotiv Insight being capable of interacting with the Emotiv Control Panel software and thus the rest of the system without many alterations. The Emotiv Control Panel is used to identify cognitive commands from the user by using a component analysis algorithm that Emotiv has not disclosed.

The *User-Assistive Menu* block in *Figure 3* is a Java application that uses a custom wrapper class, JMotiv, which Negotica wrote for the Emotiv EPOC in order to inquire if the Emotiv Control Panel detects a cognitive command issued by the user. Furthermore, the Java application can issue a command to the Emotiv Control Panel to train a cognitive command. This will record EEG data for eight seconds to allow or improve detection of cognitive commands using the component analysis algorithm.

The *XML user interface file* provides the content structure of the user interface in a way that allows relatively easy addition of new items and functionality. These items can execute scripts that are stored in the ODS hardware modem that connects several devices (RGB LED beams and a power socket), but only if the computer is connected to the Wi-Fi network from the ODS hardware.

The research in this report will be aimed at the effect of the EEG acquisition device that sends EEG data to the rest of the system. The development of the BCI application is restricted mainly to the *User-Assistive Menu* Java program and the *XML user interface file* seen in the flowchart, with some functionality for local internet browsing and media players added in the Java program. *Figure* 4 illustrates a flowchart of Carebro after the changes made to the *User-Assistive Menu* and with two possible EEG acquisition devices.

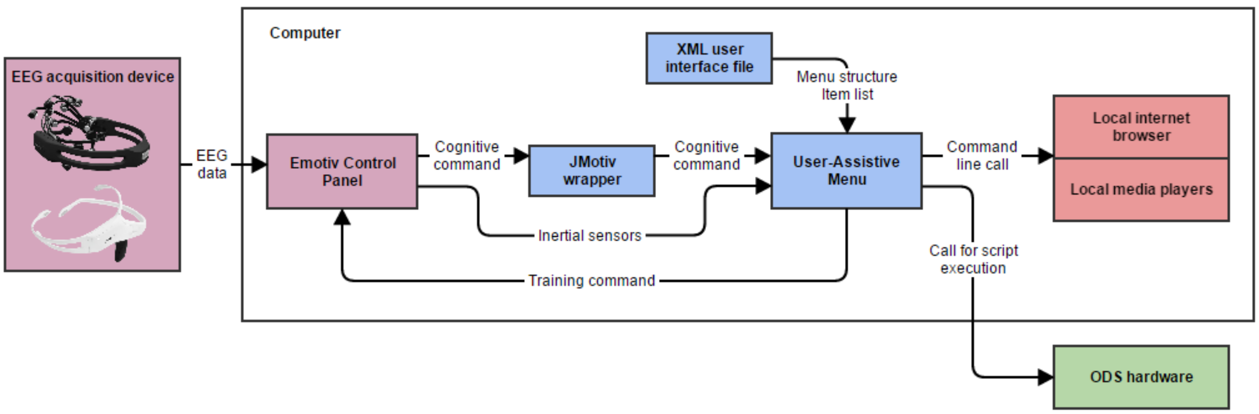


Figure 4 - Flowchart describing the conceptual model for Carebro in its current state, after changes to the User-Assistive Menu and research into the effect of EEG hardware. EEG data is acquired using a consumer EEG headset by Emotiv and sent to the computer, where the Emotiv Control Panel software is used to identify if a cognitive command is being issued by the user. A Java application (User-Assistive Menu) detects when a cognitive command is detected by the Emotiv Control Panel via the JMotiv wrapper for Java. The application can also tell the Emotiv Control Panel to start training a cognitive command to allow or improve detection. The XML user interface file provides the menu structure for the Java application, which provides a user interface that allows interaction with a local internet browser or media player and with the ODS hardware. Currently the Emotiv Control Panel, the Java application and the utilized software are all on the same computer, which has to connect to the Wi-Fi network from the ODS hardware in order to execute scripts there.

For the purpose of this report, the work will be divided into the following categories:

- Research into the effect of EEG hardware used for BCI on the success rate of cognitive detection in the User-Assistive Menu.
- The development of a flexible BCI application that adopts cognitive commands as user input and relates this back to a system useful for the target demographic of people with physical disabilities.
- Research into the effect of EEG hardware used for BCI on data acquisition and signal-to-noise ratio of the corresponding SDK algorithms.

EEG hardware analysis and success rate of cognitive detection

Table 1 - Channel specifications for several BCI systems, not including systems that are only intended to provide biofeedback and not to act as a control mechanism such as the iFocusBand, BrainBand, Muse and Aurora Dream Headband.

	Neurosky (NeuroSky, 2016)	Emotiv EPOC (Emotiv Systems, 2014)	Emotiv EPOC+ (Emotiv Systems, 2014)	Emotiv Insight (Emotiv Systems, 2014)
EEG channels	1	14	14	5
Reference	Not applicable	CMS/DRL	CMS/DRL	CMS/DRL
Reference location	Not applicable (one of the channels)	P3/P4	P3/P4	Left mastoid process (both)
Sampling rate	512Hz	128Hz (2048Hz internal)	256Hz (2048Hz internal)	128Hz
Sampling method	Single channel (application dependent)	Sequential sampling, single ADC	Sequential sampling, single ADC	
Minimum voltage resolution		0.51μV LSB	0.51μV LSB	0.51μV LSB
Frequency range	3-100Hz			
Filtering Partly important for data acquisition	N/A	Built-in digital 5th order sinc filter	Built-in digital 5th order sinc filter	Not made available
Classification algorithm Not important for data acquisition	N/A	Feature reduction, classification using features and channels unique to each person	Feature reduction, classification using features and channels unique to each person	Feature reduction, classification using features and channels unique to each person
Type of electrodes	Saline solution/conductive gel required	Saline solution/conductive gel required	Saline solution/conductive gel required	Dry electrode
Support for facial expression detection	N/A	Included in SDK	Included in SDK	Included in SDK

A side-by-side comparison of all the BCI systems in the situational and theoretical analysis that are not meant solely for the provision of biofeedback can be found in *Table 1*. Although the development of a BCI using low-level Neurosky EEG biosensors may provide a well-suited system for Carebro, this leaves the tremendous task of developing a set of filters and component analysis algorithms that is beyond the scope of this research. The SDK available for the Emotiv EPOC and Insight makes implementations using these systems more practical than other systems. Furthermore, Negotica has already purchased the hardware and research SDK for both of these systems and some development and testing has already been done with the EPOC, including the use of facial expressions for additional commands. For these reasons, it is more practical to use the available systems in order to determine their effect on success rate for the system, where instead of developing a set of algorithms for component analysis, the SDK can be used for detection of cognitive commands. To recap the information from the theoretical analysis, the electrode locations of both the Emotiv EPOC and the Emotiv Insight can be seen in *Figure 5*. A third potential setup for the EEG acquisition comes from wearing the Emotiv EPOC in reverse, leading to the electrode configuration presented in *Figure 6*. This third setup is meant to investigate the effects of electrode configuration instead of channel specifications such as those in *Table 1*.

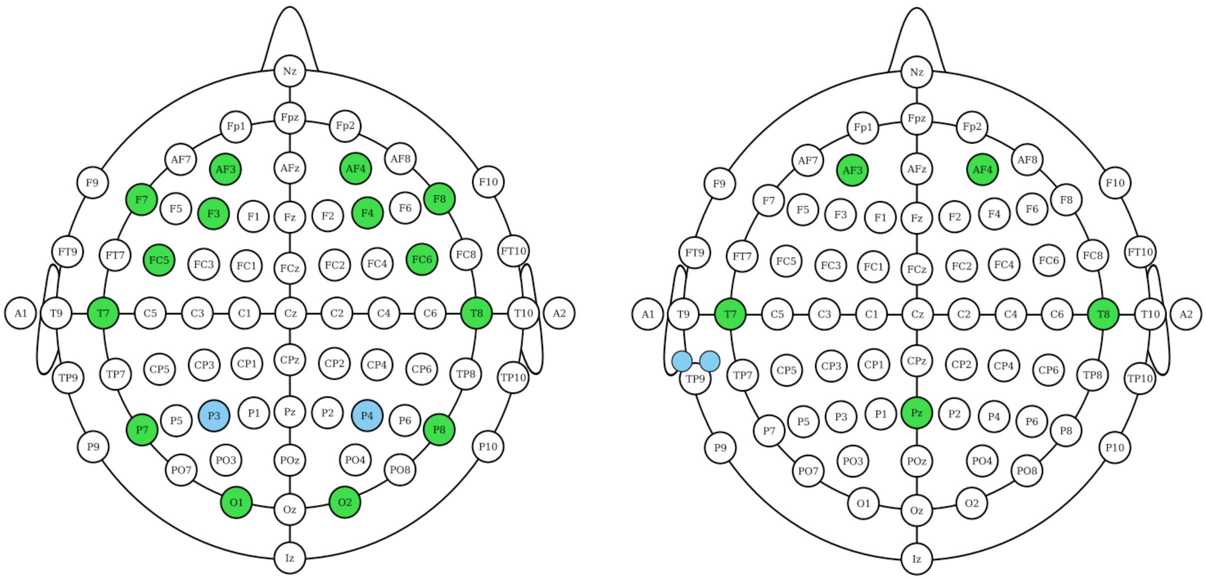


Figure 5 - On the left: electrode configuration of the Emotiv EPOC, using the electrode location scheme for the 10-20 system with 10% electrodes in-between, as seen from the top. EEG channel electrodes used by the Emotiv EPOC are indicated in green, while the reference electrodes are indicated in blue ('t Hart, 2008). On the right: electrode configuration of the Emotiv Insight, similarly indicated in green for EEG channels and blue for reference electrodes.

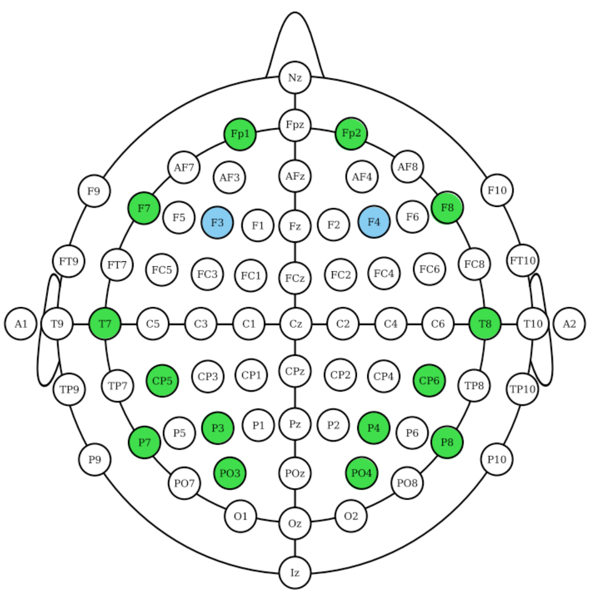


Figure 6 - Electrode configuration of the Emotiv EPOC when worn in reverse, using the electrode location scheme for the 10-20 system with 10% electrodes in-between, as seen from the top. EEG channel electrodes are indicated in green, while the reference electrodes are indicated in blue ('t Hart, 2008). Locations are not precise given the Emotiv EPOC was not intended for reverse configuration.

Prior research with P300 and SSVEP tests (found in *Appendix E*) has indicated that the effect of EEG hardware for the selected headsets is mostly dependent on the configuration of electrodes on the scalp. This is due to the method used for analyzing the EEG data, where the visual cortex and motor neuron cortex play important roles. This carries over to Carebro in the specification of cognitive commands for the Emotiv Control Panel.

To analyze the effects of the electrode configuration on success rate of the overall system an experiment was conducted with three different EEG setups. The details of this experiment are described in the research methodology but the setups that are investigated were chosen because of their ability to connect to the existing application without the need for custom detection algorithms, which would introduce additional variables and are outside of the scope of this research. The EEG setups are:

- Emotiv EPOC. Electrodes are located as on the left side in *Figure 5*.
- Emotiv EPOC worn in reverse. This places the electrodes in a configuration like *Figure 6* resulting in more electrodes surrounding the parietal lobe in the visual cortex. Precise locations cannot be given, however the 10-20 configuration of electrodes is never exact because of differences in scalp size.
- Emotiv Insight. Electrodes are located as on the right side in *Figure 5*.

Performance is measured from the data acquisition to the observed results in the ODS hardware and media players seen in *Figure 4* to give a realistic representation of the success rate of the overall system with the inclusion of hardware. While the success rate should not drop from the detection by the *Emotiv Control Panel* to the *User-Assistive Menu* and from the *User-Assistive Menu* to the *ODS* hardware and media players in theory, it is better for completeness of the evaluation to include all sections of the system in one test. However, possible connectivity issues with the internet browser are ignored, since the stability of the internet connection is not indicative of the reliability of Carebro per se, rather than just the end user's internet connectivity. The *User-Assistive Menu* has several methods in place to regulate command input and prevent rapid re-firing of commands, meaning *Emotiv Control Panel* response is not indicative of the full system response.

<u>Development of a flexible BCI application</u>

A critical part of Carebro as a product is the connection between the acquisition of EEG data and the control given to the user to manipulate the environment by controlling applications in both hardware and software. A work breakdown structure (WBS) has been developed, which can be found in *Appendix B*. This work breakdown structure aims to provide an overview for the long-term development of project Carebro. For the development of the conceptual research setup for Carebro, several tasks have to be completed over the span of the project. There are also tasks related to research and development, usability testing and market research since all of these are required to successfully deliver the project to users. Although some of the work packages in the WBS have become outdated in terms of scope in the time since the development of the WBS, the general outline for the development of Carebro remains intact.

The concept for the BCI application can be found in *Appendix C*. A Java application was developed that used a connection with the Emotiv control panel to control domotics applications over the ODS system from Negotica that is used to connect devices to a network. In *Figure 4* this application is denoted as the *User-Assistive Menu* and interacts with the surrounding blocks.

Effect of EEG hardware used on data acquisition and Signal-to-noise ratio

Aside from the effects of EEG hardware used for BCI on the success rate of the overall application research was done in the effects on signal-to-noise ratio and data acquisition of EEG hardware. This research can be found in *Appendix E* as it was not the main research focus of the experiments, but still contributed to the determination of important characteristics for the EEG hardware. The appendix includes a definition of the signal-to-noise ratio for the EEG data used in the experiment.

CHAPTER 4

RESEARCH DESIGN

The correlation between the EEG hardware used and the success rate of the detection of cognitive thoughts is the main point of interest in the research, although the development of the *User-Assistive Menu* is also significant. The effect of hardware on data acquisition has been analysed through research on EEG acquisition devices and the tools for analysis of EEG data. Some tools may require additional support or signal types, although in the case of the Emotiv EPOC and Insight, the SDK that is provided allows the extraction of EEG channel data to EDF and CSV file types, two common standards in many applications.

Success rate of cognitive detection

The success rate of cognitive detection algorithms can be correlated with the EEG hardware despite the fact that many BCI systems do not utilize the same SDK, as long as raw data can be imported from the device or pre-processing has been well-documented as to account for it in the algorithms. For the two available system, the Emotiv EPOC and Emotiv Insight, the data provided is both available before the application of pre-processing methods and similar for both devices in the SDK. The cognitive detection algorithm in this SDK, while shrouded in secrecy, is similar for both devices as a result of using the same SDK. This makes it possible to investigate the success rate of these devices and compare them to determine their strengths and weaknesses. For the Emotiv EPOC data on success rate is already available, but documentation on experiments with the Emotiv Insight is lacking as a result of it being relative new on the market. Experiments on success rate should therefore first be replicated for the EPOC and then the same test can be conducted for the Insight.

The current build of Carebro utilizes the Emotiv Control Panel software supplied with the Emotiv EPOC and Insight. Research on the success rate of this software has shown that success rate is heavily dependent on the user (Lang, 2012). This is caused in part by the training time required for using the mental commands. More training time causes greater success rates, but for some users training works more efficiently than for others. However, the differences in success rates are also influenced by not having a good control mechanism. The success rate of the mental commands can only be confirmed by the user, with some users being more forgiving for the system than others. One conclusion from Lang is that to achieve reliable accuracy, training sessions take "considerable time, and training can be quite demanding which is especially tiring for disabled users." (Lang, 2012) While this last part is speculative, the time requirement for a somewhat reliable success rate (>70%) is something to keep in mind when developing Carebro based on the Emotiv Control Panel software.

Research by Fakhruzzaman et al. that uses the Emotiv EPOC for Motor Imagery testing also concludes that the success rate of the Emotiv EPOC is heavily dependent on the user. Specifically, the better the user is at replicating the EEG signal with reference training data, the better the success rate (Fakhruzzaman, et al., 2015). The use of the Emotiv EPOC is dissuaded because the device cannot identify patterns from training data when doing another activity at the same time, which Fakhruzzaman et al. mention might be caused by the placement of the electrodes on the device. How this relates to partially or fully disabled users is not investigated in this research.

Important for experiments on success rate of a BCI system is to define how ‘success’ is measured, and to understand how the success rate relates to an application. As mentioned in the conceptual model, performance is measured over the entire system to give a realistic representation of the success rate of Carebro. The *User-Assistive Menu* does not respond to every command issued to the Emotiv Control Panel to prevent rapid re-firing of commands.

For the experiment, four test subjects were used with three headset configurations each as presented in *Figure 5* and *Figure 6*. To aid in providing stable connections between EEG electrodes and the scalp each user wore a beany if necessary, tightening the grip of the headsets. This helps because not everyone has a similar scalp size or shape, meaning not all electrodes are as tightly fitted. The Emotiv TestBench was monitored to ensure each electrode remains connected properly over the duration of each test by looking at the connection indicators and the raw EEG data. An indicator was also present in the *User-Assistive Menu* to help confirm connection stability during the tests.

Although cognitive command training can be done via the *User-Assistive Menu*, this functionality is not complete for three different commands and not necessary for the validity of the tests. The Emotiv Control Panel was used to train three commands: *Push*, *Left* and *Right*. These commands are used to navigate the *User-Assistive Menu* and activate items, allowing access to all necessary functions of Carebro. For some users other commands in the Emotiv Control Panel might prove to be easier to visualize, and the *User-Assistive Menu* does recognize alternative commands. For the success rate experiments, the same commands were used for all test subjects. Each trial (four test subjects, three configurations) trains commands in the same order and for the same duration. The specific order of training was as follows:

- Neutral thought recording for 30 seconds
- Cognitive command training for 8 seconds for *Push*, *Left* and *Right* in sequence. Training was done by

attempting to control the *User-Assistive Menu*, not by looking at the Emotiv Control Panel. The menu was manually controlled during this training by another person to aid in visualization.

- Four times repeated training for above cognitive commands, now without the menu being controlled.
- If any command "skill rating" under the Action panel on the Emotiv Control Panel is lower than 2%, repeat training this command until it reaches 2% or higher.
- Allow time for the subject to attempt each trained command and ask for re-training.

During these calibrations and the subsequent tests users were instructed to try to formulate consistent thoughts over the whole test, and to limit muscle contractions and gestures beyond slight hand gestures to provide aid in visualization. Users were also told not to touch the computer because this can cause noise in the EEG data. After training, the user was instructed to perform an intended action in the menu, including activation of an item (*Push* command) and navigation (*Left* or *Right*) as well as doing nothing. The first command registered was written down as the observed outcome of the trial. If after ten seconds no command was registered the trial outcome was *Neutral*. This way the test not only looked at erroneous command registration but also at unresponsiveness and false positives.

Only ten samples per intended action (Neutral thought, *Push*, *Left* and *Right*) were carried out per test, meaning 40 samples per EEG headset configuration per person. This was done because both prior experience and the tests themselves indicated that sessions of 15-25 minutes of training followed by about 40 minutes of testing (with some discussion of observed results) is very tiring to all test subjects, meaning any more samples would start to be affected by mental exhaustion.

CHAPTER 5

RESEARCH RESULTS

Success rate of cognitive detection

An overview of all data gathered per test subject and per EEG headset configuration in the experiment on the success rate of cognitive detection for the Emotiv EPOC, the reversed Emotiv EPOC and the Emotiv Insight can be found in *Appendix A*. The net response of Carebro for the experiment trials for each EEG headset configuration were recorded in *Table 2*.

Table 2 - Percentages of cognitive detection outcomes for the Emotiv EPOC, the Emotiv EPOC in reverse configuration and the Emotiv Insight for all test subjects. Intended commands are on the left with the observed outcome in percentages. Correct outcomes are highlighted in green. n=40 per intended command.

Emotiv EPOC

		Outcome			
		Neutral	Push	Left	Right
Intended	Neutral	52,5%	10,0%	22,5%	15,0%
	Push	12,5%	57,5%	20,0%	10,0%
	Left	10,0%	22,5%	52,5%	15,0%
	Right	7,5%	20,0%	40,0%	32,5%
	Total	20,6%	27,5%	33,8%	18,1%

Emotiv EPOC (reversed)

		Outcome			
		Neutral	Push	Left	Right
Intended	Neutral	45,0%	15,0%	5,0%	35,0%
	Push	12,5%	62,5%	22,5%	2,5%
	Left	10,0%	32,5%	37,5%	20,0%
	Right	12,5%	15,0%	20,0%	52,5%
	Total	20,0%	31,3%	21,3%	27,5%

Emotiv Insight

		Outcome			
		Neutral	Push	Left	Right
Intended	Neutral	40,0%	22,5%	30,0%	7,5%
	Push	22,5%	62,5%	10,0%	5,0%
	Left	32,5%	25,0%	22,5%	20,0%
	Right	30,0%	17,5%	15,0%	37,5%
	Total	31,3%	31,9%	19,4%	17,5%

Although the results of these experiments in *Table 2* appear to provide a clear overview of success rates, false positives and erroneous responses, the summed data does not show individual performance for test subjects. In terms of the found success rates presented here, the recognition of one or two out of three commands is generally realistic for all configurations and in accordance with or exceeding success rates found in literature on the Emotiv EPOC (Lang, 2012). However, false positives occurred in 50% to 60% of all samples, where each sample lasted ten seconds. While literature results on false positives are limited, these false positives remain problematic for practical use.

For a more precise representation of success rates and the discussion of possible causes of erroneous responses, specific result sets for trials per user should be considered. *Table 3* shows the cognitive detection outcomes for the first test subject, this being the author. The amount of false positives with the trials is relatively low compared to other test subjects, with false positives almost always being *Push* commands. This has to do with the training phase and how commands can ‘overlap’ with others or neutral thought, but for these trials the overlap was generally consistent. *Push* in general was overlapped significantly with other commands, causing erroneous detections of *Push* commands for all intended commands.

Table 3 - Cognitive detection outcomes for the Emotiv EPOC, the Emotiv EPOC in reverse configuration and the Emotiv Insight for test subject one. Intended commands are on the left with the observed outcomes in number of samples (out of ten). n=10 per intended command.

Emotiv EPOC

		Outcome			
		Neutral	Push	Left	Right
Intended	Neutral	9	1	0	0
	Push	3	6	1	0
	Left	3	4	2	1
	Right	2	4	1	3

Emotiv EPOC (reversed)

		Outcome			
		Neutral	Push	Left	Right
Intended	Neutral	6	4	0	0
	Push	1	8	1	0
	Left	1	5	2	2
	Right	3	2	0	5

Emotiv Insight

		Outcome			
		Neutral	Push	Left	Right
Intended	Neutral	6	3	0	1
	Push	4	6	0	0
	Left	5	4	1	0
	Right	5	4	1	0

Table 4 shows the cognitive detection outcomes for the fourth test subject. While the subject had no prior experience with BCI he did understand the logistics of training and component analysis of EEG data. The amount of false positives for the Emotiv EPOC in both configurations is impractical, although other commands score a high success rate. There are a few noteworthy points in these results. Firstly, the Emotiv Insight had no neutral responses, meaning some action was always triggered in the 10 second window given for each sample. For an intended neutral response (no action), all false positives for the Emotiv Insight were *Left* commands, which implies an overlap in the training process for this command with neutral response. Another notable observation is that for every configuration this test subject was able to activate the *Push* command with high chance of success while having (varying) difficulties with distinguishing *Left*

and *Right* commands, which were both trained and tested by rotating the item carousel in the main menu of the *User-Assistive Menu*. Overlap between these commands was visible for other test subjects as well, as seen in *Appendix A*.

Table 4 - Cognitive detection outcomes for the Emotiv EPOC, the Emotiv EPOC in reverse configuration and the Emotiv Insight for test subject four. Intended commands are on the left with the observed outcome in number of samples (out of 10). n=10 per intended command.

Emotiv EPOC

		Outcome			
		Neutral	Push	Left	Right
Intended	Neutral	3	0	5	2
	Push	0	9	1	0
	Left	0	0	8	2
	Right	0	0	3	7

Emotiv EPOC (reversed)

		Outcome			
		Neutral	Push	Left	Right
Intended	Neutral	5	0	1	4
	Push	0	10	0	0
	Left	0	1	6	3
	Right	0	0	3	7

Emotiv Insight

		Outcome			
		Neutral	Push	Left	Right
Intended	Neutral	0	1	9	0
	Push	0	10	0	0
	Left	0	4	4	2
	Right	0	1	4	5

Two of the test subjects obtained somewhat similar observed outcomes. The percentage outcomes of these two subjects are shown in *Table 5*. Although the combination of results tends to favour successful responses, the data in *Table 5* underperforms when compared to the other test subjects for the same test. This is potentially due to the age of these subjects, although the experiment is not conducive to conclusions on correlation between age and success rates. Both users reported that they had difficulties understanding the concept of the cognitive functions used to evoke a command, and both reported being distracted by the things happening on-screen, such as visuals from the Emotiv Control Panel.

Table 5 - Percentages of cognitive detection outcomes for the Emotiv EPOC, the Emotiv EPOC in reverse configuration and the Emotiv Insight for test subjects two and three. Intended commands are on the left with the observed outcome in percentages. n=20 per intended command.

Emotiv EPOC

		Outcome			
		Neutral	Push	Left	Right
Intended	Neutral	45%	15%	20%	20%
	Push	10%	40%	30%	20%
	Left	5%	25%	55%	15%
	Right	5%	20%	60%	15%

Emotiv EPOC (reversed)

		Outcome			
		Neutral	Push	Left	Right
Intended	Neutral	35%	10%	5%	50%
	Push	20%	35%	40%	5%
	Left	15%	35%	35%	15%
	Right	10%	20%	25%	45%

Emotiv Insight

		Outcome			
		Neutral	Push	Left	Right
Intended	Neutral	50%	25%	15%	10%
	Push	25%	45%	20%	10%
	Left	40%	10%	20%	30%
	Right	35%	10%	5%	50%

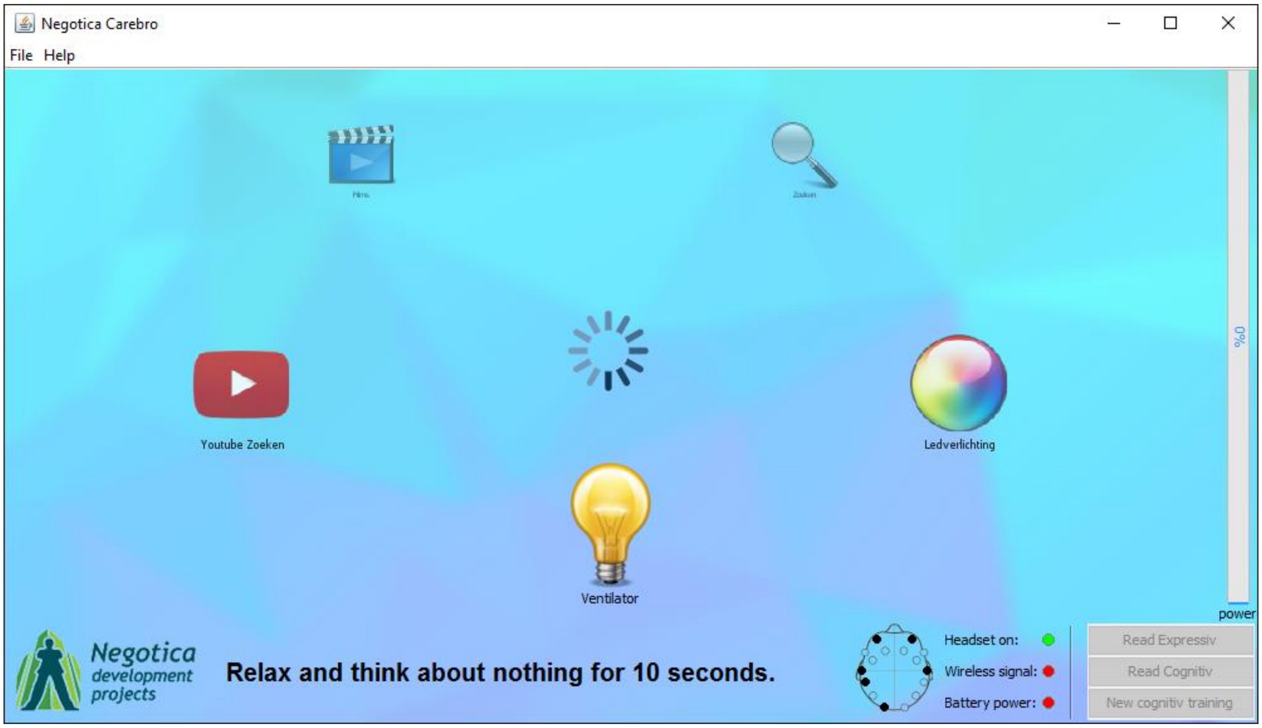
As mentioned earlier, *Appendix A* provides an overview of all data gathered per test subject and per EEG headset configuration in the experiment on the success rate of cognitive detection.

<u>Development of a flexible BCI application</u>

The work that was done on the *User-Assistive Menu* served as an integral part of the overall system of Carebro, and the results from the experiment on the success rate of cognitive detection include all interactions through the *User-Assistive Menu*. This includes test subjects training and testing with the graphical user interface presented and the verification of experiment outcomes through the interactions between the ODS server and the menu.

Appendix D includes a write-up on recent developments and usage instructions of this application that was meant for Negotica but has been translated from Dutch. The most important additions made to the Java program that led to the *User-Assistive Menu* are written here.

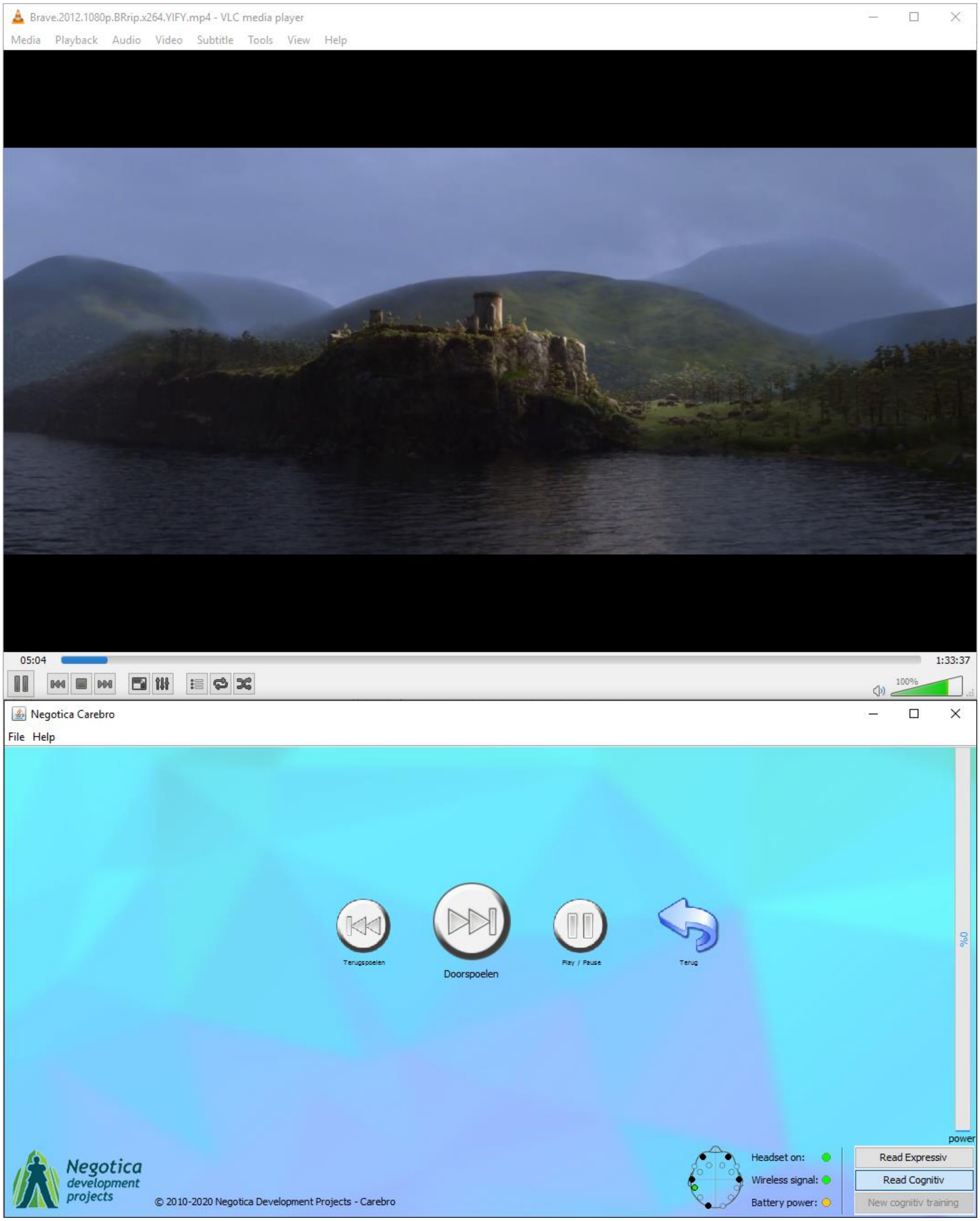
The XML user interface file that provides an item list for the menu can now also make one of three types of submenus. The first is the carousel-style menu that Negotica developed before, where the user navigates the menu by rotating it and the selected item is displayed at the front through a forced perspective. This menu style is also seen in *Screenshot 1*. The other styles display the items in a line or a grid. The line menu is useful for smaller amounts of options where compact, subtle controls are preferred, such as when viewing a video. An example of this situation is shown in *Screenshot 2*. Finally, the grid menu is especially useful when navigating using a cursor, although all menus can technically be navigated with the cursor. The cursor can be combined with e.g. inertial sensors (such as those present on the Emotiv EPOC and Emotiv Insight EEG headsets) or a joystick if the user is capable of using those.



Screenshot 1 - The main screen of a demonstration build of the current User-Assistive Menu that was delivered for Carebro. A carousel-style menu with a forced perspective is displayed with the 'ventilator' item in front and activated. The text at the bottom serves as an instruction for cognitive training, while the display on the bottom right indicates EEG headset and electrode connection status. On the right are options for toggling facial expression and cognitive control and for starting cognitive training. The loading icon in the center illustrates that the system is responding when the user cannot control it.

To reiterate, the *User-Assistive Menu* interacts with other components of Carebro like in *Figure 4* in the conceptual model. The Java program already interacted with the ODS server outside of the computer through a Wi-Fi connection to call for script executions on the ODS system. Additional functionality that has been developed is the interaction through the command line and Windows Powershell to play media files with VLC (VideoLAN organization, 2016) and search web pages online. As mentioned in *Appendix D*, the intention of the web browsing is to connect it to a typing application that was outside of the scope of development.

The headset connection indicator in the bottom right of *Screenshot 1* and *Screenshot 2* has been modified to display only electrodes relevant to the Emotiv Insight to reduce clutter. The location of several menu elements have been moved around the screen as well to better suit the intended layout where the menu occupies the bottom half of a screen, while the top half is reserved for content browsers and displays.



Screenshot 2 - A submenu of a demonstration build of the current User-Assistive Menu that was delivered for Carebro. A line-style menu is displayed with items that allow control of the VLC player at the top. The back button on the right returns the user to the main menu and exits VLC.

The training of cognitive commands through the *User-Assistive Menu* has also been adjusted to allow for the training of both left and right navigation commands. The use of blinking for activation with facial expression commands on remains unchanged. Internally the use of *Push* as a cognitive command for activation has been implemented now, so this can be trained with the Emotiv Control Panel. The whole training process in the menu is too succinct for the separation of three cognitive commands, although it is sufficient for demonstrations. For the experiment on success rate of cognitive detections the training was still done through the Emotiv Control Panel.

The JMotiv wrapper class used for the connection of the Java program to the Emotiv Control Panel remains unchanged for the Emotiv Insight as the interaction between these elements is identical to how cognitive commands are trained and detected for the Emotiv EPOC.

CHAPTER 6

DISCUSSION AND CONCLUSIONS

The research described in the report was aimed at answering the following research question: "What effect does the EEG hardware used for BCI have on data acquisition, signal-to-noise ratio and the success rates of the corresponding SDK algorithms for the classification of a certain amount of commands?"

Sub-questions to this central research question are: "How can the new Carebro best be utilized in the new demonstration- and test platform? What is the best approach to an interface for a flexible (hybrid) BCI application based on cognitive commands for the use of domotics, self-fulfilment and neurofeedback?"

The mission statement of Negotica and the intention of continued research and development of Carebro is to set up a new demonstration- and test site where students, companies and health organizations are poised to collaborate. The questions formulated above are discussed in this section by dividing it in parts.

Success rate of cognitive detection

When drawing up conclusions about this experiment it is important to note that the amount of test subjects is low, so certain statements about the performance of configurations should not be made. More importantly however, each subject performs better for certain commands than others, experiences overlap in commands during training or might get different issues with false positives. It is not sufficient to simply sum up all results and infer that some success rates are better than others. All tests should be examined separately, as was done in the results of this research, to come to conclusions.

As said before, longer sessions of training did not benefit the distinction of cognitive commands in all cases because of a loss of concentration or inconsistent thought patterns. Longer sessions of training and testing were not conducive to stable results, making more samples per test logistically difficult. Again, results are very likely to improve or become more consistent when subjecting users to regular training (or use) over several months.

The overlap of EEG patterns during training that makes the separation of two or more commands with each other or commands with neutral thought so difficult is the largest problem when dealing with the separation of cognitive commands, since there is no good way to know ahead of time that two commands are being trained with the same EEG patterns. This is further aggravated by the way Emotiv keeps the algorithms for component detection a secret. Especially for the fourth test subject it is visible that all false positive responses tend to lead to the same cognitive command. Results for the third test subject also indicate strong overlaps between *Left* and *Right* commands leading to the Emotiv SDK choosing one command over the other. The activation of the cognitive command recognition of the *User-Assistive Menu* in each sample also lead to some possibly trained interactions, where a command was instantly and involuntarily activated by the test subject. Because of this interaction and how it would not appear in practical situations, such an instantaneous command was disregarded and the test restarted, whether it was an unsuccessful response or a successful one.

One more concern with the experiment is with the training procedure changing over time. For later test subjects, experience from past tests changed the way the testing was organized. The training was kept consistent, but during tests with later subjects some distracting element were hidden at all times. Since this was not the case for earlier test subjects, this possibly affected test results in some way, inhibiting success rates. However, the main difference between tests was in the smoothened transition between samples.

Based on the central research question, the hypothesis stated for the effect of the EEG hardware used was as follows: "The EEG hardware used for cognitive control has a noticeable impact on the success rate of cognitive commands of Carebro, with the electrode configuration of the hardware being the main factor and configurations with electrodes on the parietal lobe performing significantly better than those without."

From the test results it appears that the Emotiv EPOC (in standard configuration) did not perform worse than the reverse configuration or the Emotiv Insight for any of the test subjects. This was not as expected, considering the lack of electrodes on the scalp around the parietal lobe (responsible for sensory information, spatial sense and navigation among other things) for this configuration relative to the other configurations. The Emotiv EPOC in reverse configuration did not perform objectively better than the other configurations, even though this configuration boasts the most electrodes around the parietal lobe. The standard configuration does place electrodes on the occipital lobe (responsible mainly for visual processing), which could be cause for better results for test subjects who relied mainly on visual response and stimulation for cognitive commands.

The Emotiv Insight did not perform better than either Emotiv EPOC configurations, although results are also not significantly worse. If test subjects did rely mainly on visual stimulation, the results are skewed somewhat against the Emotiv Insight. All results were from test subjects who had limited (in the case of the first subject) or no prior experience with brain-computer interfaces or Emotiv SDK and hardware, and certainly no experience with separating three different cognitive commands. It is possible – and even likely – that with regular training over a timespan of several months the results would improve dramatically. Especially for the fourth test subject, who was able to separate some cognitive commands with high success but faced some overlap in others, the results seem promising for tests with subjects who have more experience with regular training. An experienced user may also rely less on visual stimulation and more on spatial sense more, which would work better with the Emotiv EPOC in reverse configuration and with the Emotiv Insight, although this is only a postulate and cannot be confirmed with this research.

The hypothesis must be at least partially disproved, since the EEG hardware used did not impact success rate equally for each test subject. Furthermore, while the electrode configuration does seem to play a role in the success rate of cognitive command detection, the optimal configuration of electrodes is not confirmed. The parietal lobe does not seem to be the most important region for EEG patterns.

Development of a flexible BCI application

Based on the ideas of the conceptual menu presented in *Appendix C* a Java program with a user interface was developed for Carebro that could serve the project in the future, providing the benefits of adaptability of menu styles and addition of functions to interact with applications on the computer.

Several example features have been developed such as the ability to use BCI to open up media files or internet web search results. Some of the larger intended functions remain for the future, including a typing interface, which would allow for much more specific (online) content browsing than is currently available, as well as neurofeedback and self-fulfilment through creative applications (such as a painting program). Negotica has displayed interest in presenting neurofeedback to the users in the form of mental state or possibly the level of command training. Some of this functionality might be possible by accessing data from the Emotiv Control Panel but neurofeedback, self-fulfilment tools and a typing interface were considered outside of the scope of development at this time.

The product is not complete yet and Negotica intends to develop this application further as it serves as the backbone of Carebro, but the developments made and the concepts given in *Appendix C* have largely already been adopted with the *User-Assistive Menu*. Different iterations of the program have also been demonstrated several times throughout development in various locations. Most notably a derivative of the application was used in combination with a Winamp visualization controlled by the program to introduce Carebro in Health-Hub Roden at the reopening and more recently a demonstration was held where people could try out Carebro at the Saxion University of Applied Sciences in Deventer.

Effect of EEG hardware on data acquisition and signal-to-noise ratio

The results of the research into the effect of EEG hardware on data acquisition and SNR that is shown in *Appendix E* have led to several new insights about the extraction of EEG data from the Emotiv EPOC and Emotiv Insight for the use of analysis. In terms of literature research, the subject of data acquisition has also provided knowledge on BCI in general. The experiments with SSVEP and P300 response for both headsets have reaffirmed the desire for Negotica to operate without the use of SSVEP for e.g. a spell application for typing since the obtained test data with the Emotiv EPOC and Emotiv Insight showed difficulties of ERP responses for general use without medial-grade BCI. This is different than the reasoning of Negotica that SSVEP and P300 spelling is simply a slow and disorienting process for the user, so there is merit to these results.

However, the results did not provide satisfactory conclusions because of the limitations and mistakes made during the experiments, and do not work toward the common goal of this research to further develop Carebro and allow for better cognitive control of the various applications controlled by the *User-Assistive Menu*. This is why the research has been restricted to *Appendix E*, even though insights during the various ERP experiments and prior literature research have helped provide an understanding of BCI.

CHAPTER 7

RECOMMENDATIONS

Following conclusions on the success rate of cognitive detection in the *User-Assistive Menu*, the effect of the EEG hardware used when comparing the Emotiv EPOC and the Emotiv Insight is not very significant. It is possible that with regular training over a longer time span, results may improve more for the Emotiv EPOC in reverse configuration than the Emotiv Insight, although this is unconfirmed. However, there is a major benefit to the Emotiv Insight because of the use of dry electrodes. For the P_Z electrode the connection is somewhat difficult because of its looseness on the scalp, but this depends on the shape of the head of the user. Furthermore, the experiment found that male pattern baldness, leading to a reduction in hair on the crown of the head, makes this connection easier. Either way, it is certainly easier to connect all electrodes of the Emotiv Insight properly than to do so for the Emotiv EPOC, which requires adding a saline solution on the electrode pads and mounting and dismounting the electrodes on the headset, even though the Emotiv Insight does occasionally – and for some users – benefit from using a saline solution as well. In terms of user benefit the Emotiv Insight is an enormous step forward, as expected, and the drawback of going from 14 electrodes to 5 is surprisingly limited.

Aside from the conducted experiment, the analysis of consumer BCI and the effects of electrode configurations and ERP detection have led to renewed insights on the state of consumer BCI. With the EEG hardware that is currently on the market, the author recommends Negotica stay with the hardware that they have already purchased as the provided component analysis algorithms are not easily replicated for use in BCI applications, leaving ERP detection as the main method of control. Considering the target demographic of Carebro, people who use this device throughout their day might become fatigued faster with the use of SSVEP or P300 spellers and control schemes that with the current system of cognitive command detection.

Another factor to take into account is the life cycle of the product. Right now Negotica is a very early adopter of BCI hardware with the intention of releasing a real product (even after the Emotiv EPOC has been on the market since 2009) and certainly the first when it comes to domotics applications. Market saturation is a potential hazard in this industry but as the only contender on the market there is plenty of room for expansion. My recommendation to Negotica is to find a potential client to actually develop an application for and to perform tests on long-term success rate improvements. Even if this client does not end up purchasing Carebro there are challenges to creating a full domotics application with BCI that are not immediately present when constructing a prototype. Nevertheless, the suggestions posed in the work breakdown structure in *Appendix B* allow for rapid progression on the way to this phase of the product.

Finally, the research into the effect of EEG hardware on data acquisition and signal-to-noise ratio that led to the experiments in *Appendix E* reaffirms the desire of Negotica to develop Carebro without the use of SSVEP or P300 ERP responses for a spell application.

REFERENCES CITED

Attarian, H. P. & Undevia, N. S., 2012. *Atlas of Electoencephalography in Sleep Medicine.* s.l.:Springer Science & Business Media.

Audette, C., 2014. *Controlling a Hex Bug with my Brain Waves.* [Online]
Available at: http://eeghacker.blogspot.nl/2014/06/controlling-hex-bug-with-my-brain-waves.html
[Accessed 15 March 2016].

Beverina, F. et al., 2003. User adaptive BCIs: SSVEP and P300 based interfaces. *PsychNology,* 1(4), pp. 331-354.

Birnbaumer, N., 2003. The thought-translation device (TTD): neurobehavioral mechanisms and clinical outcome. *IEEE Transactions on Neural Systems and Rehabilitation Engineering,* 11(2), pp. 120-123.

Ding, J., Sperling, G. & Srinivasan, R., 2006. Attentional Modulation of SSVEP Power Depends on the Network Tagged by the Flicker Frequency. *Cerebral Cortex,* 16(7), pp. 1016-1029.

Emotiv Systems, 2014. *Emotiv EPOC & Testbench Specifications.* [Online]
Available at: https://emotiv.com/product-specs/Emotiv%20EPOC%20Specifications%202014.pdf
[Accessed 17 March 2016].

Emotiv Systems, 2014. *Emotiv Insight Product Sheet.* [Online]
Available at: https://emotiv.com/product-specs/Emotiv%20Insight%20Product%20Sheet%202014.pdf
[Accessed 17 March 2016].

Emotiv Systems, 2014. *Epoc.* [Online]
Available at: https://emotiv.com/epoc.php
[Accessed 17 March 2016].

Emotiv Systems, 2014. *Insight.* [Online]
Available at: https://emotiv.com/insight.php
[Accessed 17 March 2016].

Fakhruzzaman, M. N., Riksakomara, E. & Suryotrisongko, H., 2015. EEG Wave Identification in Human Brain with Emotiv EPOC for Motor Imagery. *Procedia Computer Science,* Volume 72, pp. 269-276.

Fisch, B. J., 1985. Introduction to EEG and Evoked Potentials. *Neurology,* 35(2), pp. 289-289.

FocusBand, 2015. *FocusBand - Mind Training Headset.* [Online]
Available at: http://www.ifocusband.com/
[Accessed 15 March 2016].

Hämäläinen, M. et al., 1993. Magnetoencephalography—theory, instrumentation, and applications to noninvasive studies of the working human brain. *Reviews of Modern Physics,* 65(2), p. 413.

Health Hub Roden, 2016. *Health Hub Roden.* [Online]
Available at: http://www.healthhub-roden.nl/english
[Accessed 29 May 2016].

InteraXon, 2015. *Muse - Meditation Made Easy.* [Online]
Available at: http://www.choosemuse.com/
[Accessed 15 March 2016].

iwinks, 2016. *Aurora.* [Online]
Available at: https://iwinks.org/
[Accessed 15 March 2016].

Jeong, J., 2004. EEG dynamics in pateints with Alzheimer's disease. *Clinical Neurophysiology,* 115(7), pp. 1490-1505.

Lang, M., 2012. *Investigating the Emotiv EPOC for cognitive control in limited training time,* Canterbury: Department of Computer Science.

Leuthardt, E. C., Miller, K. J., Schalk, G. & Rao, R. P. N., 2006. Electrocorticography-based brain computer Interface-the seattle experience. *IEEE Transactions on Neural Systems and Rehabilitation Engineering,* 14(2), pp. 194-198.

Liu, Y. et al., 2012. Implementation of SSVEP Based BCI with Emotiv EPOC. *Virtual Environments, Human-Computer Interfaces and Measurement Systems (VECIMS), 2012 IEEE International Conference on,* pp. 34-37.

Luck, S. J., 2012. An introduction to the event-related potential technique. In: H. Cooper, ed. *APA Handbook of Research Methods in Psychology.* Washington, DC: MIT Press.

Malmivuo, J. & Plonsey, R., 1995. Electroencephalography: EEG Lead Systems. In: *Bioelectromagnetism.* New York: Oxford University Press, pp. 258-260.

MyndPlay, 2016. *BrainBandXL & MyndPlay Pro Bundle.* [Online]
Available at: https://myndplay.com/products.php?prod=9
[Accessed 15 March 2016].

NeuroSky, 2016. *Electroencephalogram sensor - BCI.* [Online]
Available at: http://neurosky.com/biosensors/eeg-sensor/
[Accessed 2016 March 15].

Niedermeyer, E. & Lopes da Silva, F. H., 2005. *Electroencephalography: Basic Principles, Clinical Applications and Related Fields.* 5th ed. Philadelphia, PA: Lippincott Williams & Wilkins.

OpenBCI, 2015. *Open Source Biosensing Tools.* [Online]
Available at: http://openbci.com/
[Accessed 16 March 2016].

OpenEEG, 2016. *Welcome to the OpenEEG project.* [Online]
Available at: http://openeeg.sourceforge.net/doc/index.html
[Accessed 15 March 2016].

Otal, B., Vargiu, E. & Miralles, F., 2014. *Towards BCI Cognitive Stimulation: From Bottlenecks to Opportunities.* Graz, Graz University of Technology Publishing House.

Picton, T. W., 1992. The P300 wave of the human event-related potential. *Journal of Clinical Neurophysiology,* 9(4), pp. 456-79.

Ramar, S., Bose, A., Smida, J. & Vaiyapuri, A., n.d. *Effect of Brain Computer Interface (BCI) in stress induced loss of cognition in hippocampus of wistar albino rats.* [Online]
Available at:
https://www.researchgate.net/profile/Sivanandan_Ramar2/publication/295626416_Effect_of_Brain_Computer_Interface_BCI_in_stress_induced_loss_of_cognition_in_hippocampus_of_wistar_albino_rats/links/56cc13db08aee3cee5426a64.pdf
[Accessed 25 May 2016].

Renard, Y. et al., 2010. OpenViBE: An Open-Source Software Platform to Design, Test and Use Brain-Computer Interfaces in Real and Virtual Environments. *Presence : teleoperators and virtual environments,* 19(1).

RobinH, M., 2008. *The components of Event Related Potentials,* s.l.: English Wikibooks.

Schalk Lab, 2012. *BCI2000 Licensing.* [Online]
Available at: http://www.bci2000.org/wiki/index.php/BCI2000_Licensing
[Accessed 17 March 2016].

Schalk Lab, 2016. *BCI2000.* [Online]
Available at: http://www.schalklab.org/research/bci2000
[Accessed 17 March 2016].

Swartz Center for Computational Neuroscience, 2016. *EEGLAB.* [Online]
Available at: http://sccn.ucsd.edu/eeglab/
[Accessed 18 March 2016].

't Hart, M., 2008. *The 10-20 system.* [Online]
Available at: http://www.mariusthart.net/?e=200
[Accessed 4 April 2016].

Van der Tang, P., 2016. *Interview with Negotica Development Projects* [Interview] (8 February 2016).

Veisi, I., 2007. *Fast and Robust Detection of Epilepsy in Noisy EEG Signals Using Permutation Entropy.* Boston, IEEE.

VideoLAN organization, 2016. *VideoLAN - Official page for VLC media player.* [Online]
Available at: http://www.videolan.org/vlc/index.html
[Accessed 21 August 2016].

Wolpaw, J. R. & McFarland, D. J., 2004. Control of a two-dimensional movement signal by a noninvasive brain-computer interface in humans. *Proceedings of the National Academy of Sciences of the United States of America,* 101(52), pp. 17849-17854.

APPENDIX A

EXPERIMENTAL RESULTS FOR SUCCESS RATE OF COGNITIVE DETECTION

Test subject #1

Headset configuration: Emotiv EPOC

		Outcome			
		Neutral	Push	Left	Right
Intended	Neutral	9	1	0	0
	Push	3	6	1	0
	Left	3	4	2	1
	Right	2	4	1	3

Headset configuration: Emotiv EPOC (reversed)

		Outcome			
		Neutral	Push	Left	Right
Intended	Neutral	6	4	0	0
	Push	1	8	1	0
	Left	1	5	2	2
	Right	3	2	0	5

Headset configuration: Emotiv Insight

		Outcome			
		Neutral	Push	Left	Right
Intended	Neutral	6	3	0	1
	Push	4	6	0	0
	Left	5	4	1	0
	Right	5	4	1	0

Test subject #2

Headset configuration: Emotiv EPOC

		Outcome			
		Neutral	Push	Left	Right
Intended	Neutral	4	2	3	1
	Push	2	4	3	1
	Left	1	4	3	2
	Right	1	2	4	3

Headset configuration: Emotiv EPOC (reversed)

		Outcome			
		Neutral	Push	Left	Right
Intended	Neutral	3	1	1	5
	Push	2	6	2	0
	Left	0	7	1	2
	Right	0	4	1	5

Headset configuration: Emotiv Insight

		Outcome			
		Neutral	Push	Left	Right
Intended	Neutral	5	1	2	2
	Push	2	7	1	0
	Left	6	2	1	1
	Right	6	1	0	3

Test subject #3

Headset configuration: Emotiv EPOC

		Outcome			
		Neutral	Push	Left	Right
Intended	Neutral	5	1	1	3
	Push	0	4	3	3
	Left	0	1	8	1
	Right	0	2	8	0

Headset configuration: Emotiv EPOC (reversed)

		Outcome			
		Neutral	Push	Left	Right
Intended	Neutral	4	1	0	5
	Push	2	1	6	1
	Left	3	0	6	1
	Right	2	0	4	4

Headset configuration: Emotiv Insight

		Outcome			
		Neutral	Push	Left	Right
Intended	Neutral	5	4	1	0
	Push	3	2	3	2
	Left	2	0	3	5
	Right	1	1	1	7

Test subject #4

Headset configuration: Emotiv EPOC

		Outcome			
		Neutral	Push	Left	Right
Intended	Neutral	3	0	5	2
	Push	0	9	1	0
	Left	0	0	8	2
	Right	0	0	3	7

Headset configuration: Emotiv EPOC (reversed)

		Outcome			
		Neutral	Push	Left	Right
Intended	Neutral	5	0	1	4
	Push	0	10	0	0
	Left	0	1	6	3
	Right	0	0	3	7

Headset configuration: Emotiv Insight

		Outcome			
		Neutral	Push	Left	Right
Intended	Neutral	0	1	9	0
	Push	0	10	0	0
	Left	0	4	4	2
	Right	0	1	4	5

APPENDIX B

WORK BREAKDOWN STRUCTURE CAREBRO

WORK BREAKDOWN STRUCTURE

Project Carebro: A Brain-Computer Interface for Use in Home Automation

By Jos Albers
March 2016

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Introduction

This work breakdown structure aims to provide an oversight for the long-term development of project Carebro. For the development of the conceptual research setup for Carebro, several tasks have to be completed over the span of the project. There are also tasks related to research and development, usability testing and market research since all of these are required to successfully deliver the project to users.

Any tasks that are relevant to the advancement of Carebro over the next five years are discussed in the work packages (WPs) in this document, where for each WP the general objectives are listed, a description of the goal is provided, the deliverables that are produced by the work package are listed and the extent at which the work package is in the scope of this graduation research is discussed. Moreover, several tasks are continuous processes, not something that can be 'completed' and forgotten. For these WPs, this is therefore indicated in the scope.

To summarize the scope of the graduation research project, the mind map in *figure 1* is displayed. A more detailed discussion of scope is available for each work package.

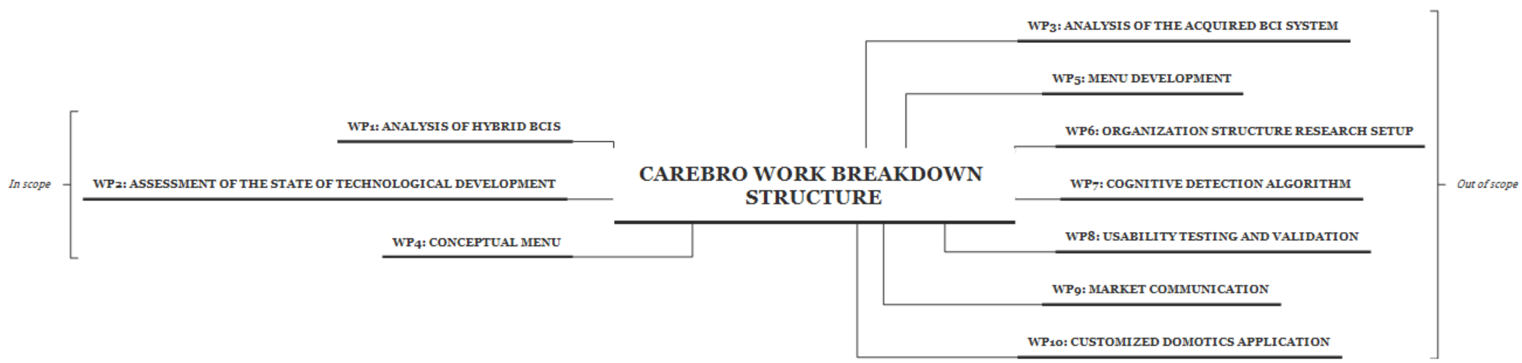

Figure 7 - Mind map of the work breakdown structure, indicating which work packages lie within the scope of this graduation research project.

WP1: Analysis of hybrid BCIs

Objective(s)

- Gain an understanding of the possibilities of hybrid BCI systems
- Determine the requirements for input in the adaptive menu

Description

Various different forms of hybrid BCI systems exists. In this work package the different menu style possibilities that exist can be investigated with literature research to develop insights into both the ease of setting up such a hybrid BI and the usefulness. The implications of the additional input method or peripheral are important to consider for the user interface in WP4; that is to say, would the additional input take over as the main form of navigation and relegate the EEG data to complimentary functions, or would it just provide an additional command, leaving encephalography to be the most important form of control?

Deliverables

- Report describing the advantages and disadvantages of various hybrid BCI systems and the required connections for each

Scope

Developing a hybrid BCI system depends on and should be tailored to the individual using Carebro. However, it is important to gain an understanding of the possibilities of hybrid systems relatively early on in development, before the menu is really developed. This means that WP1 should remain in the scope of the research.

WP2: Assessment of the state of technological development

Objective(s)

- Determine developments in BCI hardware and applications since 2014
- Determine the current state of the consumer EEG devices and BCI software
- Predict upcoming technologies in BCI
- Provide advice on the acquisition of new hardware and/or licenses

Description

This work package is focused on gaining an understanding of the more recent developments that relate to Carebro since the project was shelved in 2014 and includes both technological advancements in (consumer) EEG devices and other peripherals such as eye tracking hardware and software and speech recognition software.

The assessment of the current state of technology and developments for certain peripherals will provide insights that are helpful in determining which peripherals to use in hybrid BCIs for Carebro. Conversely, it is useful to know which peripherals can make interesting combinations with BCI to narrow down the scope of the research in current technology.

Deliverables

- Literature research report describing the ongoing and past developments of consumer EEG devices and other peripherals useful for Hybrid BCI systems
- Advice report on the acquisition of new hardware and software licenses

Scope

To understand the requirements of other aspects of the project better, including the other work packages, it is important to get reacquainted with the technology that is on the market or coming up by the time a custom request for a Carebro application comes in. Therefore this work package is one of the most important things to have in the scope of the research. Important to note that WP2 is a continuous task, since the assessment of current technology has to be done regularly to keep up with trends and interesting new methods of detection.

WP3: Analysis of the acquired BCI system

Objective(s)

- Test the acquisition of EEG data
- Analyze the success rate or quality of potential provided classification software
- Establish the tradeoff between training and command classification

Description

While Carebro currently relies on the use of the Emotiv Epoc and Insight, the plan is to be flexible in terms of the headset used for EEG acquisition. When another headset is picked out, this work package is relevant for the verification of the headset. The acquisition of EEG data has to be tested to see if the data includes any artefacts related to motion, connectors, muscle movements, etc. If the headset includes software for the classification of cognitive commands, the success rate of this software and the overall detection quality need to be evaluated as well. One metric often used when assessing the performance of a BCI is the information-transfer rate. The tradeoff between training/calibration time and the number of commands that can be classified effectively will have to be tested. Literature indicates that the optimum number of commands that can be classified was three or four in 2005. Since then, BCI has developed further but one cannot simply assume the gain increases with more commands to classify.

Deliverables

- Comparison report on the analysis of the Emotiv EPOC and Insight
- Additional comparisons of other acquired EEG devices – when available

Scope

This work package is difficult to place in or out of scope as a whole. On one hand, the analysis of the Emotiv Epoc and especially the Emotiv Insight that are available now is lacking in these specific points. But since no other headsets have been acquired yet the analysis of those BCI systems is out of scope of this research. In a way, WP3 is a continuous because of the intended flexibility of Carebro in which BCI system to use.

WP4: Conceptual menu

Objective(s)

- Conceptualization of the adaptive menu
- Breakdown of menu styles for different selection methods

Description

This work package relates to general concept of creating an interface where different input sources can be used in conjunction with EEG data to form a complete BCI system. Various menu styles and the way these are interconnected to provide a system that relays freedom of input peripheral use are considered. Other considerations for such a menu are also considered before the project can move on. The specifics of the software used do not belong in this work package.

Deliverables

- Document detailing the conceptual model and menu styles
- Prototype of adaptive menu

Scope

While a conceptual model can still be changed significantly over the course of project development, the conceptual model is important to have at this stage of the project, with a prototype of the menu following this concept. The menu can then be used for the implementation of other input methods to test hybrid BCI approaches, making it one of the bigger priorities in getting the research setup off the ground and within the scope of the research. Since the development of the prototype is software development, this aspect of the work package is likely outside of the scope of the graduation project.

WP5: Menu development

Objective(s)

- Develop a fully functional menu following the conceptual model from WP4

Description

This work package includes the development of the conceptual model from WP4 following the prototype. This work package is mainly continuous with the adaptive menu being tailored to (most) Carebro users with additional input methods and perhaps different EEG headsets connected to the system.

Deliverables

- Fully functional adaptive menu

Scope

This work package is out of the scope of the project since it requires the completion of all previous work packages and likely involves work done in the research platform created in this project.

WP6: Organization structure research setup

Objective(s)

- Providing a hierarchical structure for operations in the research setup where Carebro can be further developed

Description

For the students and staff of the possible start-up company dedicated to Carebro to know who to report to and where to find guidance, communication pathways have to be established, such as a connection to the skype and caller ID network of Negotica and Brin and the connection to their parent company, Remmin BV.

Deliverables

- Document suggesting the communication pathways between the Negotica office and the research setup or possible start-up company

Scope

The organizational structure requires a lot of business administration knowledge and likely requires a larger overview of the situation than is available in this graduation project, so it is presumably out of scope.

WP7: Cognitive detection algorithm

Objective(s)

- Development of a custom cognitive detection algorithm

Description

Preprocessing, filters and component analysis of EEG data. Meant to work more reliably than currently available software that comes with consumer products.

This work package includes the implementation of filters and the development of a detection algorithm for EEG data. The hardware from which to acquire the EEG data signals and the software that could be used to process this data, filter it and perform component analysis will be determined based on the outcome of the advice report from WP2. Nevertheless, the current hardware, the Emotiv EPOC and Insight, could be used to evaluate how well such algorithms could work with existing consumer EEG setups with certain electrode placements.

The reason that it might be beneficial to develop a custom algorithm is because many of the consumer EEG headsets on the market, including the products by Emotiv, do not provide insight into the workings of their own algorithm, and in the case of Emotiv it is generally considered likely – or even common knowledge – that their algorithm also relies on the use of facial expressions, even for their cognitive recognition suite. While tests have been conducted by Negotica on people with neuromuscular diseases, the claims by Emotiv that people with locked-in syndrome can use their headsets with accurate detection cannot easily be verified. Essentially, a custom algorithm could prove to be more reliable for cognitive detection for Carebro than the algorithms provided in standard software. More importantly, however, different headsets with similar electrode placements could be interchangeably connected to the algorithm developed in this work package and the algorithm can be adjusted, whereas standard software cannot be used with other consumer EEG devices.

Deliverables

- Cognitive detection algorithm

Scope

This work package is considered out of scope for the near future, mainly because the task is not completed easily in a short time period and because Negotica wishes to focus more on the implementation of the research platform in Health-Hub Roden and the setup for future research possibilities.

WP7 is arguably continuous as the algorithm will likely have to be adjusted over the validation phase and any alterations in electrode placement or headset accuracy will have to be taken into account for the algorithm.

WP8: Usability testing and validation

Objective(s)

- Determine the success rate of the cognitive detection algorithm from WP7
- Analyze the ergonomics of the EEG hardware and electrode placement used in conjunction with the algorithm from WP7

Description

Usability testing relates to the ease of using the device during calibration and normal activity, how precise the headset has to be placed, how comfortable it is, as well as the ease of issuing a cognitive command and the method used for this. Validation testing will determine the statistical success rate of issuing commands correctly and sensor drift, although it remains impossible to use a reference EEG with the same electrode placements at the same time as the EEG that is validated, for obvious reasons.

Deliverables

- Usability advice report
- Validation report

Scope

This work package is considered out of the scope of the project since it requires the completion of WP3, WP7 and possibly other work packages. Since WP7 is out of scope the validation of its deliverables will also be out of scope.

Similar to WP7, this work package is continuous, since the validation will have to be repeated when adjustments are made to the algorithm, and usability may increase of decrease with different electrode placements.

WP9: Market communication

Objective(s)

- Deploy a demonstration setup of Carebro
- Writing documentation for the use of Carebro
- Further usability testing with the target demographic

Description

This work package is targeted at gathering clients for Carebro by expanding interest through means of a demonstration setup. Documentation can help make the product more understandable to clients and increase usability. Furthermore, with potential clients testing the system for themselves, the usability of Carebro for its target demographic can also be evaluated, and steps can be taken to ease the learning curve for this demographic, through documentation, tutorials and extensive support.

Deliverables

- Demonstration setup
- Documentation
- Updated usability advice report from WP8

Scope

The market communication process is continuous and some networks have already been established by Negotica. The documentation and usability testing with the target demographic are not feasible at this stage in development, however, and therefore out of scope.

WP10: Customized Carebro application

Objective(s)

- User-based requirement specification and functionality inventory for custom applications

Description

This work package focuses on the delivery of custom-made Carebro applications for clients by expanding the functionality of the menu from WP5 and the actuators and sensors connected to it. This work package requires communication with individual clients or organizations in the same way that Negotica does business with current clients for various other projects. Customization is a key aspect of Carebro, making this step – and the ability of Carebro to be adaptable to individual demands and variations – critical for its success in fields such as home automation and self-fulfillment and potentially neurofeedback.

Deliverables

- Customized Carebro application that controls home automation system functions that correspond to the wishes of a specific client

Scope

The customization of applications for Carebro in home automation, self-fulfillment and neurofeedback is a continuous process, and is a necessary component for Carebro for as long as the product exists. Without the customization and client communication the product cannot be used by many people. This work package is out of the scope of the research project as essentially all of the other work packages have to be completed (or started, in the case of continuous processes) before starting with this one.

APPENDIX C

ADAPTIVE MENU CONCEPT

ADAPTIVE MENU

Project Carebro: A Brain-Computer Interface for Use in Home Automation

By Jos Albers
March 2016

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Introduction

The development of the research setup in Health-Hub Roden will focus partly on development of a user interface that allows relatively easy implementation of new input sources (e.g. a joystick, eye tracking software, speech recognition, Leap Motion etc.) and creation of signals that can be used for new applications and can be reached in a logical sequence of commands that fit with the needs of a particular user for these applications. While many interviews that Negotica has had with people in the target demographic in the past have showed that people value not only independence in as many basic actions as possible, but also having ways of entertainment and self-actualization in the form of creative expression. This means that Carebro should be capable of catering to specific individuals instead of offering a one-size-fits-all solution. This requires close communication with the user, something with which Negotica is already very familiar for its other product and projects.

The user interface that is suggested in this document is still tentative and can be changed over the course of the development of Carebro. However, the development of a conceptual model for the creation of a prototype that can service the implementation of new input sources and connection to new applications is important to have at a relatively early stage in development. The menu can then be used to test hybrid BCI approaches and control of various applications. As such, it is one of the bigger priorities in getting the research setup in Health-Hub Roden off the ground.

Conceptual menu

For this system, I propose a Java application – like the current user interface utilized by the Emotiv hardware – with multiple menu styles that can be easily selected in Java for each submenu. These different menu options would allow for the most optimal selection method for certain amounts of actions and give freedom in developing applications or hybrid BCI systems that are tailored to specific users. While it is not possible to consider every possible actuator or action that could be controlled with Carebro, consider the following example:

A man with partial locked-in syndrome (who can still move his eyes) can rely on both cognitive control (with an EEG headset) as well as eye movements and blinking (which are often unaffected, unless the user has total-locked in syndrome), so it would be inconvenient to only rely on EEG data. Several eye-tracking techniques exist. Electric potential measurement or electrooculography (EOG) can be used to track the direction of the eye but can drift and is therefore not the most stable solution for selection of menu options. Considering the fact that someone with locked-in syndrome is not very mobile, it is feasible to use more accurate camera tracking methods that require the head to be stable. Whatever the method of oculography, there menu should function in a way more akin to using a mouse with EEG data serving as clicks and perhaps quick options/navigation. In this example, the man wants to control not only his window, lights and heater but also be able to play music on Spotify. These activities could realistically be placed on one grid menu, although depending on the wishes of the user it might be more suitable to turn the control of a Spotify application into a set of commands in a submenu.

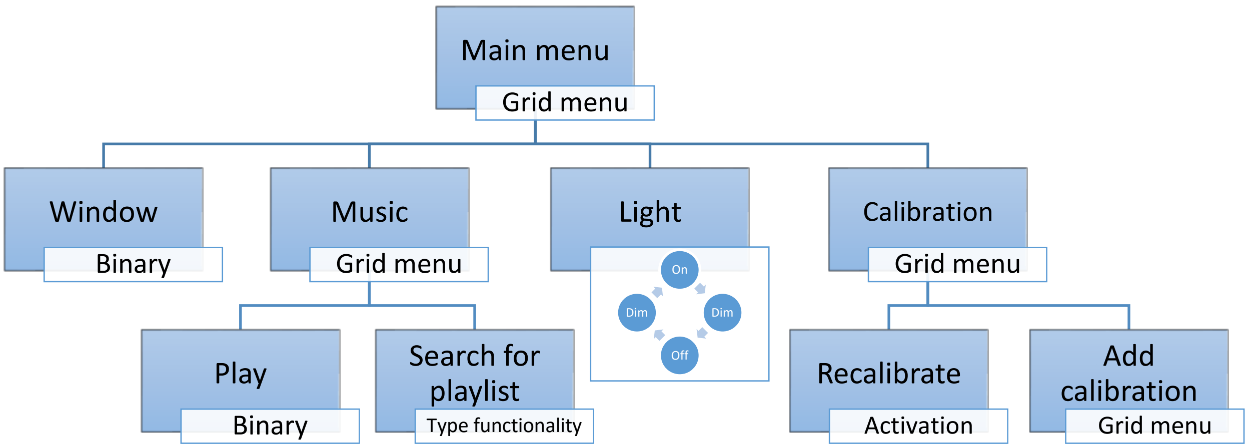


Figure 8 - Conceptual menu for the example of control with a combination of oculography (OG) and electroencephalography (EEG) as input methods.

In the above example, EEG is used for only two commands: select the method under the cursor, and return to the parent menu. Both of these commands are very important to access easily and reliably, and with only two mental commands to differentiate accuracy should not be a problem. Depending of the preferences of other users who have the same input methods, additional use can be made of mental commands by adding functionality, such as a quick option to reach a command prompt or add a calibration trial to the current calibrations. Alternatively, EEG could even be relegated to the use of quick command selection as a way to complement a control system of oculography. This only works if the eye tracking method used proves to be reliable and precise enough to select menu options from a grid but frees up the use of BCI for more intuitive browsing of the menu.

Considerations

Dominant input method

The most important things to consider for the user interface when implementing a hybrid BCI system are the implications of adding an additional input method to only EEG. The input method could completely take over as the main navigation input of the menu, such as for eye tracking, or it could be just one additional command. An example of the latter is when someone with ALS can only make slight movements with one finger. This movement could be used to activate something in the menu but it cannot easily navigate through any type of menu alone with only one trigger. It is still technically possible, by using a cyclical navigation wheel where one tap moves through the menu and two consecutive taps activate something for example, but utilizing EEG data to be the main navigation method would be more logical in this example.

Below are some selection options for different setups. The exact visuals of the interface are not the key takeaway from these figures; instead, the concept of the navigation technique used is more important.

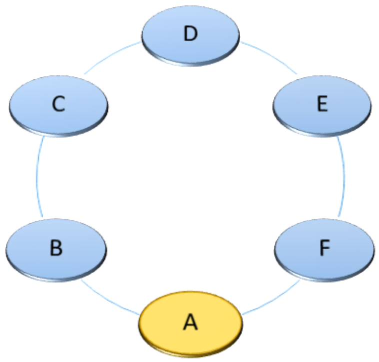


Figure 9 - Cyclical menu. Useful for methods where only a few commands are available / preferred, including cognitive commands.

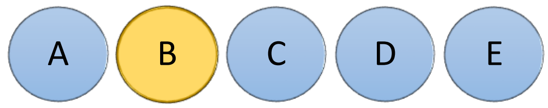


Figure 10 - Line menu. Similar to the cyclical menu in that there is only horizontal scrolling through options. This menu simply offers a different presentation that could prove easier to visualize with cognitive commands.

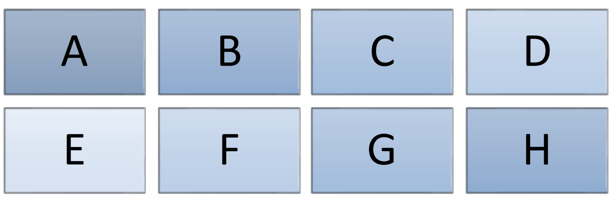


Figure 11 - Grid menu. Instead of the previous menu styles, the grid menu does not work by scrolling through the options (although this is possible) but by moving a cursor over the screen. This cursor can be operated by various input methods, e.g. a cursor, a touchpad, oculography or BCI using slow cortical potentials. (Birnbaumer, 2003)

User interaction

There are other important considerations for the user interface aside from the means of moving through the menu. The electrodes of the EEG device need to make optimal contact with the skin to register potentials in the brain properly. If one electrode does not make proper contact and the signal quality is reduced or unusable, the cognitive recognition may fail to work entirely. Without the user knowing why, this can be very frustrating. This is why it would be a good idea to display the connection of every electrode at all times. This should be close to location that the user should focus on (or look at, in the case of oculography) so that a loss in connection quality can be easily picked up on.

Something else to consider is the potential combination of Carebro with the Web of Devices and its sensors that can measure various abiotic factors (e.g. temperature, humidity, oxygen concentration or daylight) or biometric data (e.g. heartrate, blood sugar or other things users like or need to measure). It could potentially be beneficial or desirable for the user to see graphs or figures on the measured data in the menus, in the same places where they control things to suit their needs. An example could be keeping the room temperature in the same general area as the control for the heater, or oxygen concentration as the control for the window. It is important to differentiate the useful display of this data from actual medical information. The system would need to be a lot more reliable and well-validated for each individual variation of Carebro as tailored to a user when medical factors that determine the health of a user are put on display, which would be best to consider out-of-scope of Carebro in general.

Another consideration is simplicity. Ideally, for a BCI system, the user is presented with as few options as possible while not limiting control. Nesting options inside of submenus is a great tool to keep the amount of options on the screen at the same time limited and allow easy navigation to the option the user wants access to. If all possible options were presented on the same screen this could overwhelm the user or get them lost in the interface and makes scrolling to the desired option a chore with BCI.

Aside from nesting menus the options presented should also be as streamlined as possible, and clear in which way they operate. For instance, if a window does not really need five different settings for the angle at which it is open, it is useful to limit the command on the screen to a simple switch that switches between open and close commands with enough clarity that the user can see it is a binary operation. This consideration also somewhat discredits the use of typing commands for everything as simple buttons serve their purpose just as well, without the user getting frustrated that their command was mistyped.

Alternative User Control

Direct control from results

Looking at a user interface with menu 'buttons' that all operate in fixed ways can be useful to easily connect to as many applications as wanted, and is suitable for software applications in particular. For the control of actuators and effects that are clearly visible to the user upon activation or deactivation, such as actuators in lights, windows or doors, the use of a user interface on a screen is not so important, as long as these mental commands used can be recognized and distinguished clearly. In the case of a setup with only a few different actuators, this might lead to an application where no screen is needed and the user can simply use mental commands as they move around freely.

One thing that can contribute to this model is the concept of complex thoughts where a combination of visual, auditory and perhaps even olfactory and tactile stimulation is stored in a memory that can be evoked to control an action. As an example of a real application, the opening of a window can be associated with more than the β (Beta) and μ (Mu) rhythms (related to motor control, manipulated by imagining movements) if the olfactory and tactile imagination of outside air getting into the room can be measured, perhaps as an evoked potential. The same complex thoughts could possibly be utilized for playing music, since music can be tied to a lot of memories and emotions.

Past research on BCI has not focused on the specific use of emotions and sensations evoked from memory, however, and the likelihood of a successful, reliable implementation of complex thoughts in direct user control is not high when more than a few commands are involved, in my view. This is why the focus is put on a menu that allows versatile control of many applications using a limited set of input commands and that can increase its effectiveness clearly with other peripherals. The addition of peripherals for direct control with complex thoughts is not intuitive and easily definable.

Evoked potentials

BCI research relating to control with the brain often focuses on evoked potentials (EP) in the form of P300 or SSVEP. These methods have been described more in the graduation definition. To summarize, evoked potentials (EP) are electric signals from the averaged EEG activity for the time that some stimulus is presented, whether visual, auditory or otherwise. Event-related potentials (ERPs) are more broadly the electrical activity in the brain related to a specific stimulus, response or decision.

One ERP component is the P300 (P3) wave which can be auditory, visual or somatosensory and is elicited by rare or significant stimuli and in the process of decision making. The P300 wave is quite commonly used in an ‘oddball’ paradigm where an unexpected target stimulus gets fired in a regular train of stimuli.

Steady state visually evoked potentials (SSVEP) are the natural responses to visual stimuli at specific frequencies, thus being produced when the patient focuses on an oscillating light or some source that exhibits other wave characteristics. For visual stimuli produced at frequencies of 3.5 Hz to 75 Hz, the brain generates electrical activity at the same frequency, or multiples of that frequency. SSVEP signals are often used in research because of their good signal-to-noise ratio. Furthermore, SSVEP does not require user-specific calibration training.

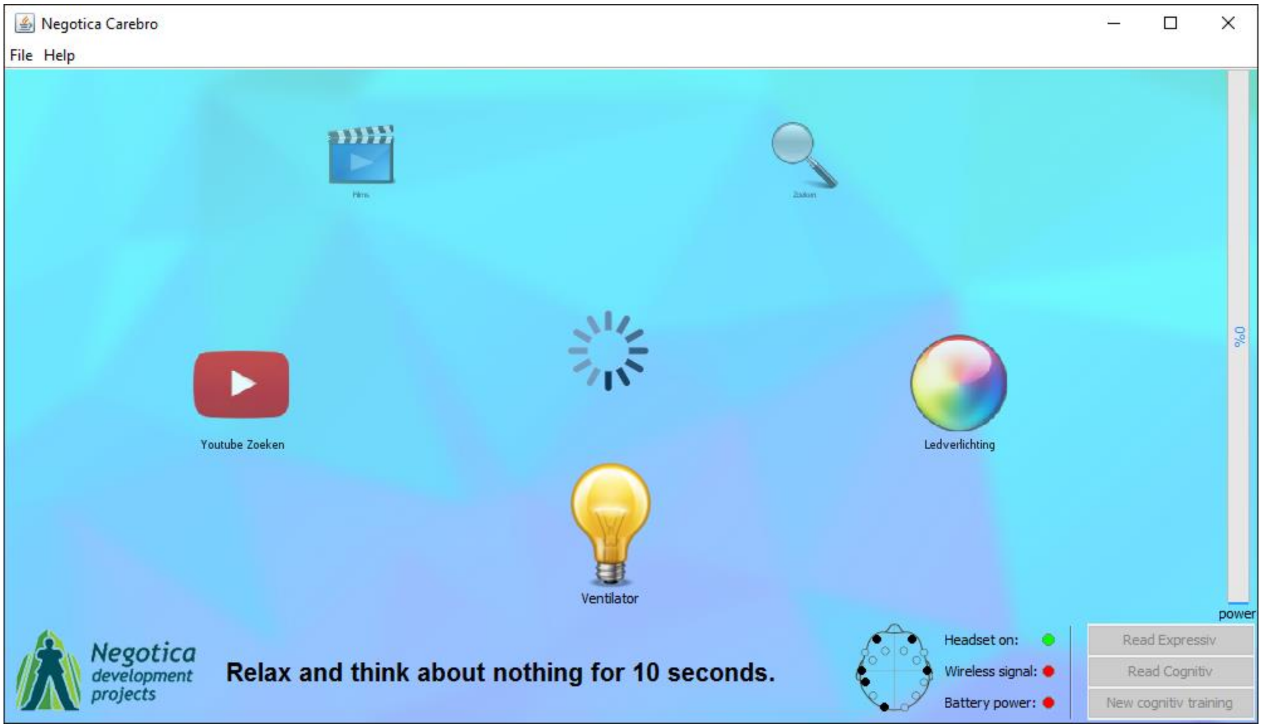
Both of these methods – P300 and SSVEP – rely on the user looking at an interface and processing often visual stimuli in the form of blinking lights. The application of these potentials is straightforward and relatively reliable. However, previous investigations by Negotica have deemed both methods too unfriendly to use. The way these methods are presented can require a lot of concentration and wear out the user and their eyes. A more passive menu in which the user has to evoke a mental image or imagination of motor control as presented in the conceptual menu above can circumvent these issues.

APPENDIX D

ADDITIONS TO THE USER-ASSISTIVE MENU

[The following document has been translated from Dutch]

Carebro User-Assistive Menu



Recent adjustments

Sub-menus and menu types

Now the XML-file that is called in the Main of the Java program can be used to indicate which type of menu an item is and different types can be used in combination. Nesting menus is recommended when there are too many applications for a single Carousel, Grid or Line menu. This can then be adjusted easily in the XML-file to the wishes each user. For example, a Line menu is clearer for less options and a Grid menu is usable with cursor control (which can in turn be controlled by e.g. joystick or inertial sensors).

Design

Adjustments to the look-and-feel are mainly some new icons for several new applications, the adjustment of the layout (to provide more space to e.g. video the application had to fit in a section of the screen, Peter [author's note: Peter is the company leader] had the idea to tilt a 16:9 monitor and display the User-Assistive Menu on the bottom half) and the addition of a logo and background. Naturally, the background can be changed, the current background was simply chosen for demonstration purposes and as a proof-of-concept.

Changed headset display

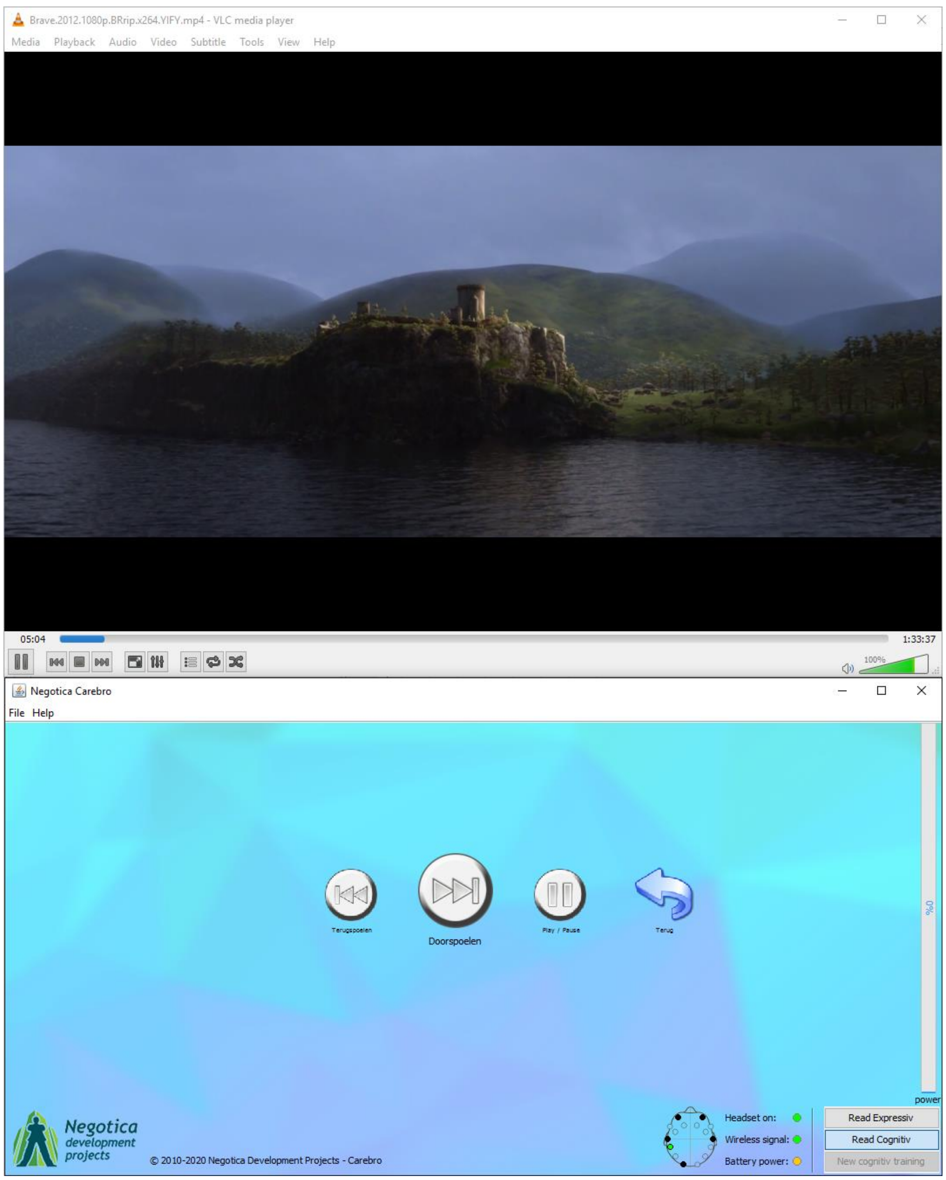
To accommodate the Emotiv Insight the electrode indicators are not all provided anymore, only those relevant to the Emotiv Insight

Calibration phase

The calibration of the brain control now works for two directions instead of just one. The use of blinking for activation remains unchanged and possible. Internally the use of *Push* as a cognitive command for activation has been implemented now, so this can be trained with the Emotiv Control Panel. The whole training process in the menu is too succinct for the separation of three cognitive commands, although it is sufficient for demonstrations.

Example applications

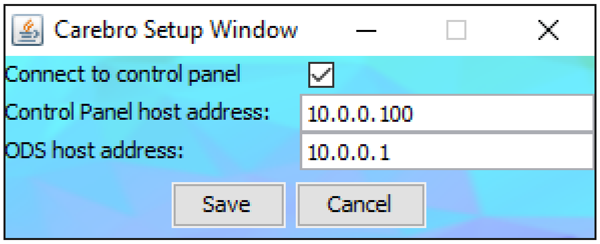
- Existing scripts that are executed through the server in the ODS suitcase.
- Local video files with a submenu for control that are played via VLC. With the back button VLC is closed as well.
- Google-search command that returns the first result from YouTube and so plays a video to the user. This command is intended for use with a typing application.
- Google-search command that also needs to be controlled by a typing application. This simply returns the first webpage found.



To make the system ready for use

ODS system

Connect to the ODS system of the suitcase. The Control Panel host address can differ, open the command line and look at ipconfig. The use of internet is not done through the suitcase, so for internet a second network needs to be connected to (likely through an Ethernet cable).

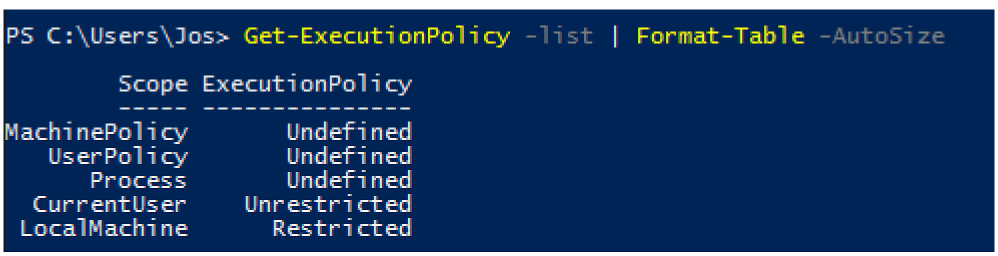


Powershell

Windows Powershell is called through the command line for the use of keystrokes, and can generally do more than the command line, making it a good starting point for the addition of applications and advanced commands.

Powershell cannot be called through the command line to run a script, because for most users this is only dangerous and not at all useful. Calling Get-ExecutionPolicy in Powershell likely returns Restricted. If this is the case, the following command has to be executed:

Set-ExecutionPolicy –Scope CurrentUser –ExecutionPolicy Unrestricted.



File paths

All icons and scripts are under the folder in the application and do not need to be referenced again for the correct file path. However, the example application for local video files refers to files that are not present, namely example video files.

VLC preferences

To let VLC close correctly it is important to go to preferences and check "Allow only one instance".

APPENDIX E

SSVEP AND P300 RESPONSE EXPERIMENTS

SSVEP and P300 response experiments

This research is based off of the same situational and theoretical analysis as the graduation report. Furthermore, some sections are meant to replace parts of the chapters they appear in, not the entire chapter. That is to say, these are actually outdated and relegated segments of those chapters.

CONCEPTUAL MODEL

Definition of signal-to-noise ratio

The aim of this research is research into the effect of EEG hardware used for BCI on data acquisition and signal-to-noise ratio of the corresponding SDK algorithms.

For the signal-to-noise ratio, it is important to decide what constitutes noise for the EEG data. For EEG data, the most common definition of signal-to-noise ratio of an ERP is the size of the signal relative to the size of the noise, that is, the background signal amplitude of the EEG. It should be noted however, that the component detection algorithm used by Emotiv for the creation of a cognitive command is not only based on the greatest ERPs. This makes it harder to identify what is a signal and what is background EEG data. For this, a look into the frequency spectra of EEG data for both ‘active’ thoughts and ‘neutral’ thoughts was made to determine if certain characteristics are evident. Additionally, disregarding the component detection algorithm the ERP response will be analysed for both EEG devices to determine the signal-to-noise ratio by the definition of the signal relative to the size of the noise. For this research, tests will be conducted for both EEG headsets by conducting a test on ERP response with multiple triggers and averaging this data in order to get a general response curve for the potential. The precise experiment conducted for this ERP response can be found in the research design.

RESEARCH DESIGN

The correlation between the signal-to-noise ratio (SNR) of the EEG hardware used and the success rate of the detection of cognitive thoughts are the main points of interest in the research, although other points are also significant. The effect of the hardware on data acquisition is analysed through research, and finding the proper tools for the analysis of EEG data. Some tools may require additional support or signal types, although in the case of the Emotiv EPOC and Insight, the SDK that is provided will allow the extraction of EEG channel data to EDF and CSV file types. EDF stands for European Data Format, which is a standard in many applications.

Data analysis of BCI systems

As mentioned in the conceptual model, for the identification of the channel noise of both EEG devices the frequency spectra of EEG data is inspected. A division is made in the EEG data samples between samples where 'active' thoughts are maintained and the Emotiv component analysis algorithm detects a command is being transmitted, and samples where 'neutral' thoughts are maintained. The latter is more difficult to maintain but the samples show a clear split between what is considered an active thought and what is considered neutral behaviour. Each sample taken has a length of approximately 45 seconds to allow extraction of only relevant data by rejecting data related to muscular movement. For each sample at least 20 seconds are made to remain and the frequency spectrum is analysed.

Success rate of cognitive detection

The success rate of cognitive detection algorithms can be correlated with the EEG hardware despite the fact that many BCI systems do not utilize the same SDK, as long as raw data can be imported from the device or pre-processing has been well-documented as to account for it in the algorithms. For the two available system, the Emotiv EPOC and Emotiv Insight, the data provided is both available before the application of pre-processing methods and similar for both devices in the SDK. The cognitive detection algorithm in this SDK, while shrouded in secrecy, is similar for both devices as a result of using the same SDK. This makes it possible to investigate the success rate of these devices and compare them to determine their strengths and weaknesses. For the Emotiv EPOC data on success rate is already available, but documentation on experiments with the Emotiv Insight is lacking as a result of it being relative new on the market. Experiments on success rate should therefore first be replicated for the EPOC and then the same test can be conducted for the Insight.

The current build of Carebro utilizes the Emotiv Control Panel software supplied with the Emotiv EPOC and Insight. Research on the success rate of this software has shown that success rate is heavily dependent on the user (Lang, 2012). This is caused in part by the training time required for using the mental commands. More training time causes greater success rates, but for some users training works more efficiently than for others. However, the differences in success rates are also influenced by not having a good control mechanism. The success rate of the mental commands can only be confirmed by the user, with some users being more forgiving for the system than others. One conclusion from Lang is that to achieve reliable accuracy, training sessions take “considerable time, and training can be quite demanding which is especially tiring for disabled users.” (Lang, 2012) While this last part is speculative, the time requirement for a somewhat reliable success rate (>70%) is something to keep in mind when developing Carebro based on the Emotiv Control Panel software.

Research by Fakhruzzaman et al. that uses the Emotiv EPOC for Motor Imagery testing also concludes that the success rate of the Emotiv EPOC is heavily dependent on the user. Specifically, the better the user is at replicating the EEG signal with reference training data, the better the success rate (Fakhruzzaman, et al., 2015). The use of the Emotiv EPOC is dissuaded because the device cannot identify patterns from training data when doing another activity at the same time, which Fakhruzzaman et al. mention might be caused by the placement of the electrodes on the device. How this relates to partially or fully disabled users is not investigated in this research.

Important for experiments on success rate of a BCI system is to define how ‘success’ is measured, and to understand how the success rate relates to an application. To determine success rates for EEG hardware with a reliable control mechanism, one technique is to use signals to stimulate the P300 wave, since such an ERP can actually be observed in the channel waveforms as seen in *Figure 1*. For Carebro, which utilizes Motor Imagery, such a study would be somewhat futile. However, for the measurement of the signal-to-noise ratio such ERP response may still prove fruitful. This knowledge has led to the setup of two experiments on ERP response. The first on the SSVEP response of the EEG hardware and the second on the P300 response. The latter is also the most developed experiment because of its promising results.

P300 response

For the ERP response of both EEG devices a test has been constructed using a P300 speller visualisation. Recourses for this test were taken from Visaduma (Ekanayake, 2012) although the theory behind this test was discovered by Jaeyoung Park (Park & Kim, 2012). OpenViBE version 1.1.0 was used to execute a program found with this experiment called P300New (Ekanayake, 2012) with the structure seen in *Figure 12*. This program opens a speller visualization that displays a grid of letters and numbers found in *Figure 13*. By using a serial port driver program called a null-modem emulator (com0com) (vfrolov, 2015) two COM ports on the computer running the experiment are paired. Modifying the code for the P300New program to send a value to one of the paired COM ports allows the other port to receive this value. In the Emotiv Xavier TestBench that is provided with the SDK for the Emotiv EPOC and Emotiv Insight a COM port can be connected to add signal markers. Connecting to the paired COM port allows the P300 speller to send a marker value when certain events are triggered which are then included in the EDF file that the TestBench can generate. For reference, the version of TestBench that was used for this experiment was 3.1.19 and the version of the null-modem emulator was 3.0.0.0.

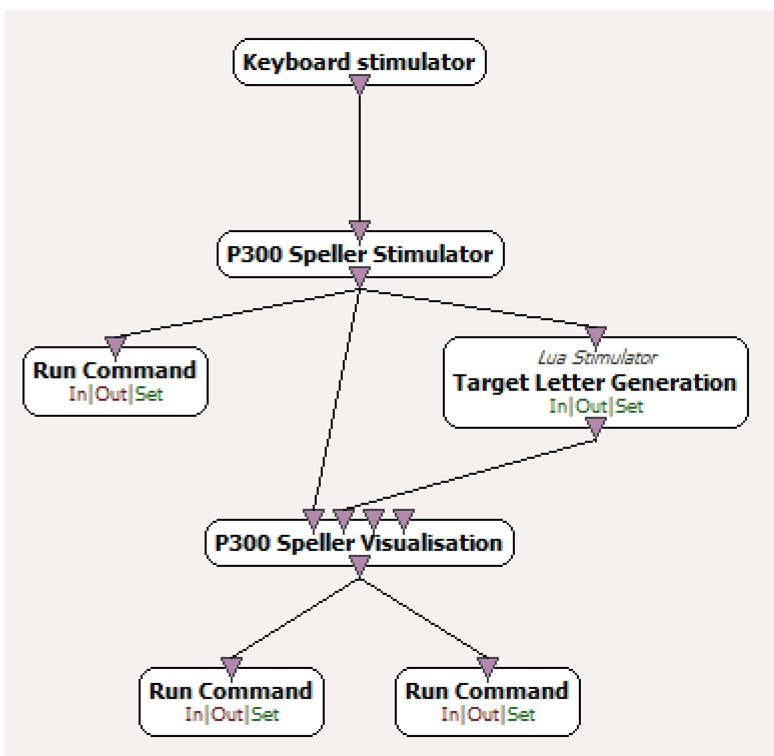


Figure 12 - The OpenViBE Designer visual representation of the P300 speller XML file. The “Run Command” block sends a value to the specified COM port that is paired with the COM port read by the TestBench application.

Figure 13 - The visual representation of the P300 speller. Random highlights of rows and columns are used in sequence to evoke an P300 ERP.

Upon starting the OpenViBE application one random letter or number in the P300 speller is highlighted in green for a moment. Row and columns are then flashed at random in rapid succession, where the test subject is focusing on the indicated letter or number. These random flashes sometimes trigger the target, eliciting a P300 response in the brain through the use of the oddball paradigm (Picton, 1992). After 24 triggers of the target a new target is appointed and the experiment repeats itself, with a few seconds of respite for the test subject in between. For every non-target stimulus a value of ‘2’ is sent to the COM port that is paired to the TestBench COM port, generating a marker with that value. For every target stimulus a value of ‘1’ is sent. The resulting EDF file generated by the TestBench after ending the experiment trial is full of markers.

RESEARCH RESULTS

Data acquisition

The acquisition of test data for the Emotiv EPOC was already a priority from the beginning of the research, since furthering the development of Carebro requires at least an understanding of past knowledge and progress on the project. Initial tests with the Emotiv EPOC revealed they did not function after several years of inactivity due to the batteries. Communications with Emotiv support informed that the battery could require draining and recharging for several days to function again, although this proved fruitless. Disassembly of one EPOC and investigation of its battery revealed the battery to be swollen, indicating failure. A new battery was ordered from a local retailer to quickly get one EPOC running again and the battery was replaced. Later communications with Emotiv to see into battery replacement for the other models were not productive, but the device with the replaced battery served to investigate the current state of Carebro and the support packages provided by Emotiv for their product. In the process of setting up a demonstration for Carebro for the opening of Health-Hub Roden, the SDK for the Emotiv EPOC was used in combination with Java to develop an application based on an existing program for Carebro. Health-Hub Roden is a learning organization and collaborative platform where businesses, government bodies and students (mainly of the Hanzehogeschool) are aiming to do research and development in various health-related fields together (Health Hub Roden, 2016). Moreover, while the library for the EPOC was used to connect to Java, the used EEG hardware was the Insight. The reason for using the libraries for the EPOC was that the libraries for the Insight were released very recently before starting the demonstration application and the development of a custom wrapper was not feasible in the available time.

After the demonstration at the Health-Hub Roden, research was done to determine the software that could be used to not only visualize, but also analyse the EEG data provided by both BCI systems. The internal filtering of the Emotiv algorithms was investigated. The Emotiv EPOC and Insight both utilize a built-in digital 5^{th} order sinc filter. A sinc filter is an ideal low-pass filter that can only be approximated with time-truncated values, so it is not likely ideal for real-time processing. This means the specifications for the systems only specify the use of a low-pass filter. The filters used and the component analysis algorithms are kept secret, although Emotiv claims the classification uses features unique to each person.

After extensive research into various EDF readers and editors EEGLAB was chosen to visualize the data files generated by the EEG hardware. EEGLAB is a MATLAB toolbox specifically for EEG recordings.

Data analysis of BCI systems

After obtaining the EEG data in EEGLAB by importing the EDF files saved with the Emotiv TestBench, the data first needed to be preprocessed. The EDF data received from the first test with the Emotic Insight is shown in *Figure 14*. Channel spectra and maps are shown in *Figure 15*, displaying event-relate potential (ERP) averages for single epochs.

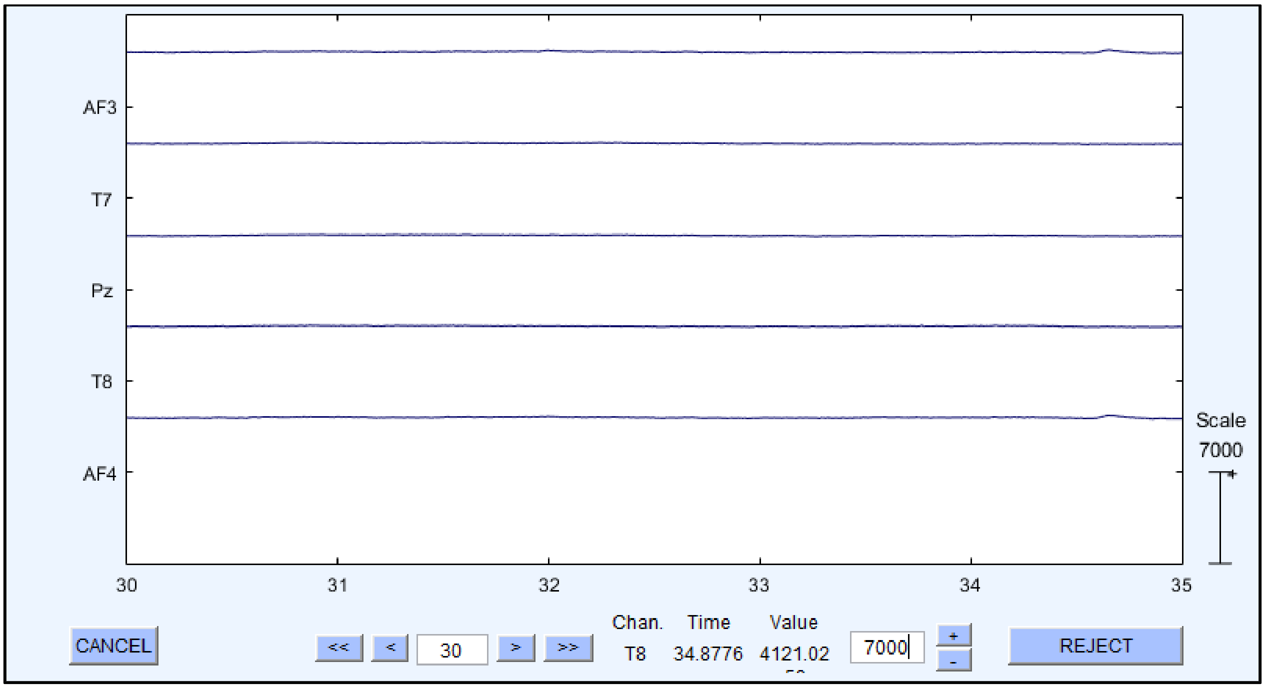


Figure 14 - Emotiv Insight EEG data from the first of four samples with 'neutral' behavior. The value indicator at the bottom indicates EEG values of over 4000µV. At a scale of 7000, the channel spacing is 7000µV and the channel data can be vizualized.

Figure 14 indicates that the raw EEG data from the Emotiv Insight contains values of over 4000µV. The large size of these values is because of a DC offset in the EEG channels. This offset can be removed in two different ways. The first is to normalize the data by subtracting the mean of each channel. The offset can also drift over time, however, due to changes in the potential of the body. This drift van be prevented by applying a high-pass filter, which is another way to remove the DC offset. The Emotiv preprocessing algorithms also utilize a high-pass filter to remove the offset. The frequency spectrum in *Figure 15* shows the highest voltages under 1Hz, followed by many harmonic frequencies.

Implementing a high-pass FIR filter at 1Hz produces the channel output shown in *Figure 16*, with spectra and ERP activity maps for 5, 10 and 20Hz in *Figure 17*. The scale for the EEG data has been significantly less enlarged since the EEG potentials are not offset by DC anymore. The channel spectra are also significantly improved, with noise below 1Hz and harmonics cancelled out. Notably, the spectral ERP maps in *Figure 17* for 5, 10 and 20Hz remain consistent with those from *Figure 15*, suggesting only noise has been filtered out and the distribution of power remains the same.

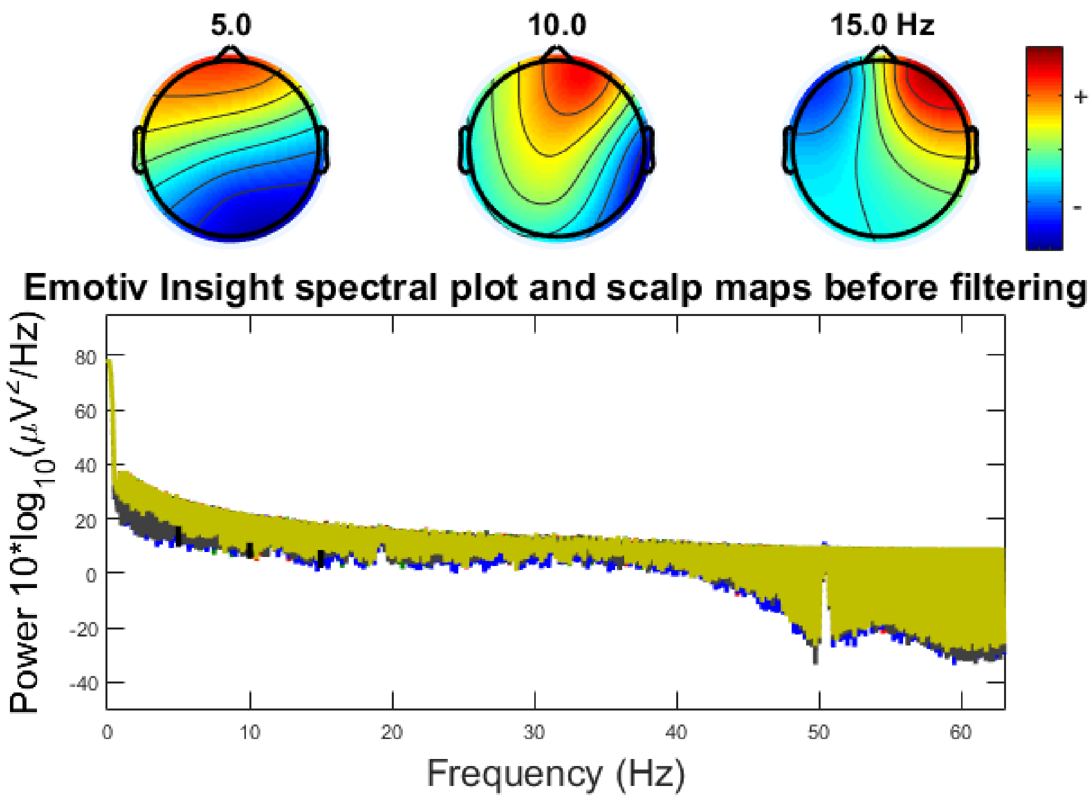


Figure 15 - Channel spectra and activity maps showing the distribution of power at frequencies of 5, 10 and 20Hz for the EEG data from the first sample with 'neutral' behavior for the Emotiv Insight.

The technical specifications listed on the Emotiv website for their product lists the frequency response of the signal to be from 1-43Hz. From *Figure 15* it looks as if the power of the spectra at certain frequencies can no longer exceed a power of 13 $10 * log_{10}(\mu V^2/Hz)$ which is seen in *Figure 17* as a drop of power in the higher frequencies. Furthermore, there is a disturbance around 50Hz, likely caused by the power line hum or mains hum.

While the frequency response of both the Emotiv Insight and the Emotiv EPOC goes up to 43Hz, it is also common to filter out signals over 20Hz (Ekanayake, 2012). Implementing a low-pass FIR filter at 20Hz produces the channel output shown in *Figure 18*, with spectra and ERP activity maps for 5, 10 and 20Hz in *Figure 19*.

Implementation of different filters in EEGLAB showed that the resulting signal is dependent on the order of filtering. Using a high-pass filter at 1Hz followed by a low-pass filter at 20Hz produces different results that using one pass-band filter from 1-20Hz, likely due to the way the filters are applied in EEGLAB. The frequency responses of the high-pass and pass-band filters (seen in *Figure 21*and *Figure 22* respectively) show how the pass-band is stricter, causing the differences in the resulting signal. Note that if the MATLAB Signal Processing Toolbox is present, as was the case for this research, EEGLAB uses the MATLAB routine *filtfilt()* which applies filtering both forward and backward to nullify any phase delays introduced by the filter. If this Toolbox is not present, EEGLAB uses a more rudimentary filtering method involving the inverse Fourier transform (Swartz Center for Computational Neuroscience, 2014).

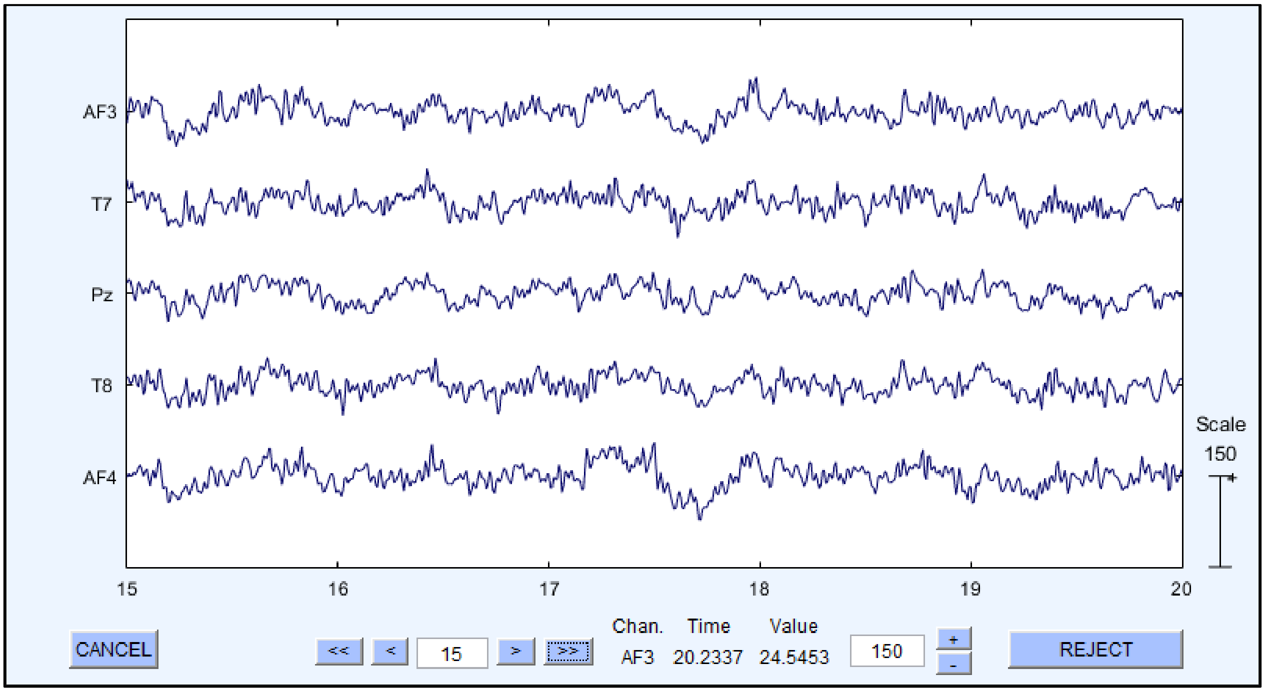


Figure 16 - Emotiv Insight EEG data from the first sample with 'neutral' behavior after implementing a high-pass filter at 1Hz. The channels are not DC-offset anymore and can be displayed on a larger scale.

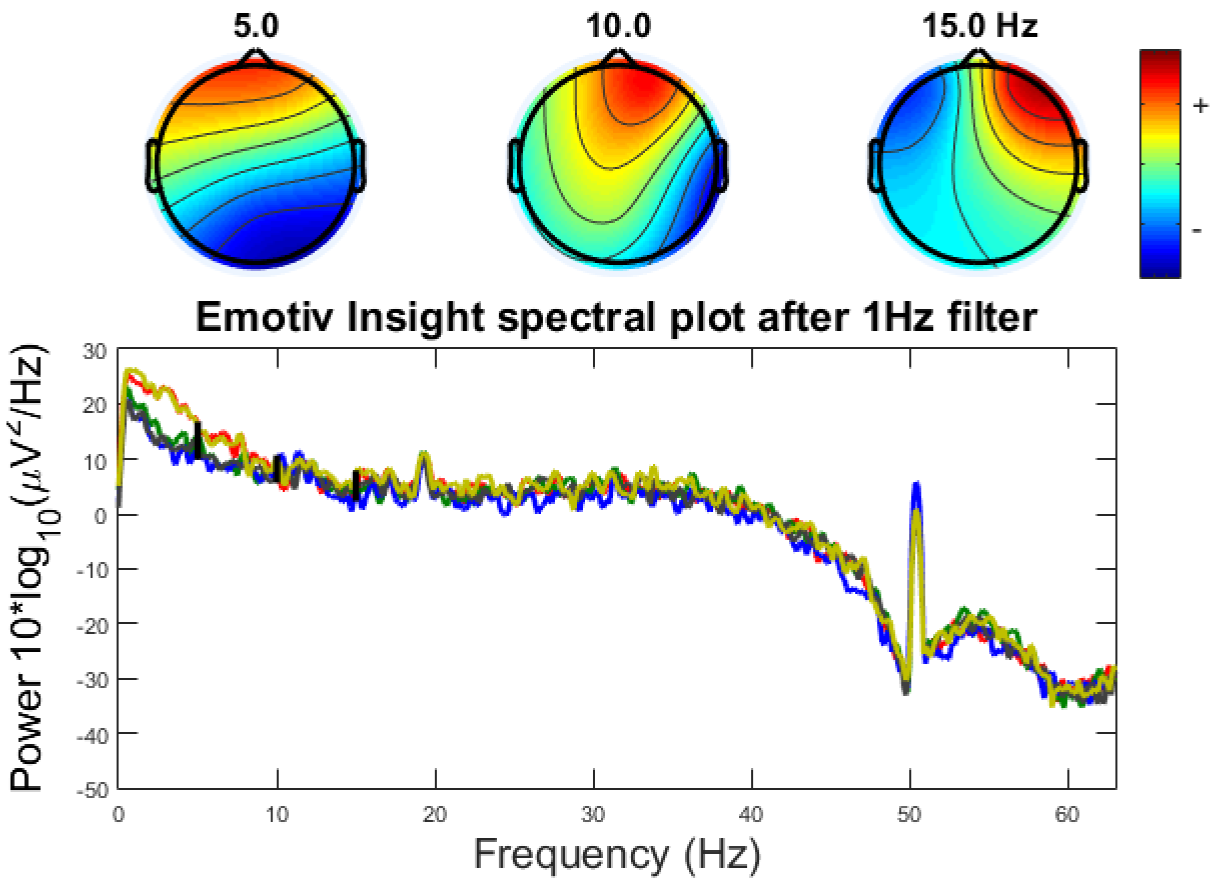


Figure 17 - Channel spectra and activity maps showing the distribution of power at frequencies of 5, 10 and 20Hz for the EEG data from the first sample with 'neutral' behavior for the Emotiv Insight after implementation of a high-pass filter at 1Hz.

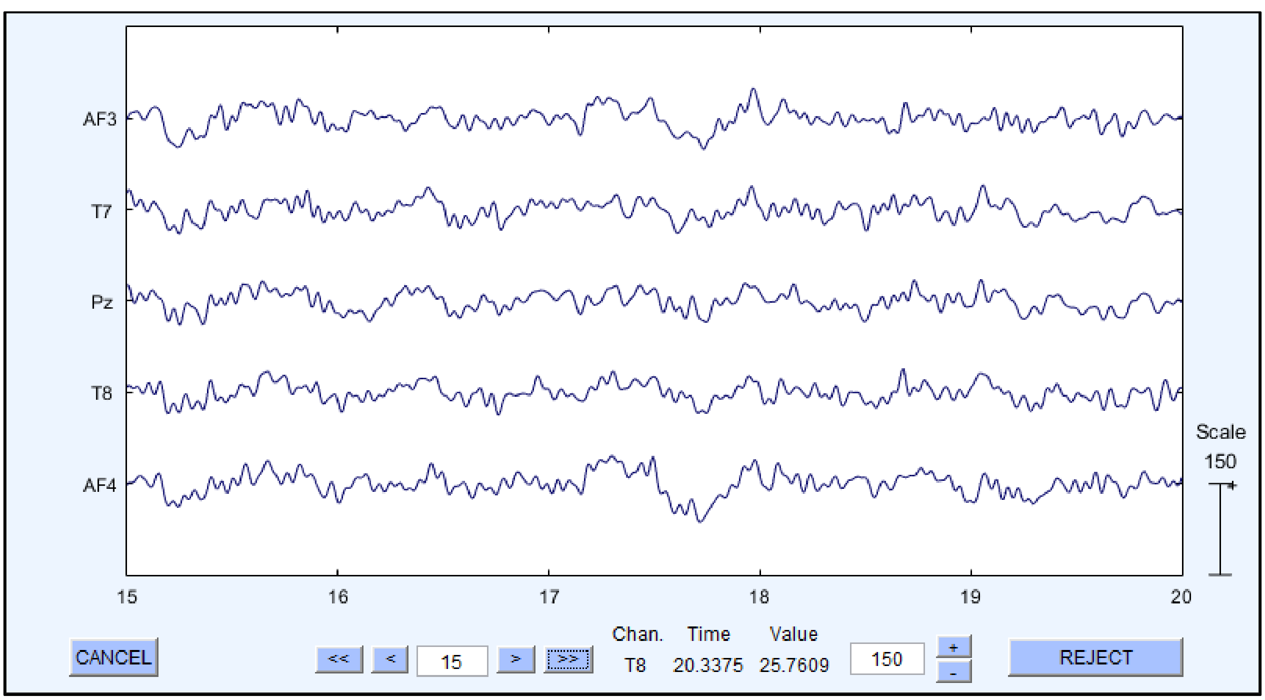


Figure 18 - Emotiv Insight EEG data from the first sample with 'neutral' behavior after a low-pass filter at 20Hz.

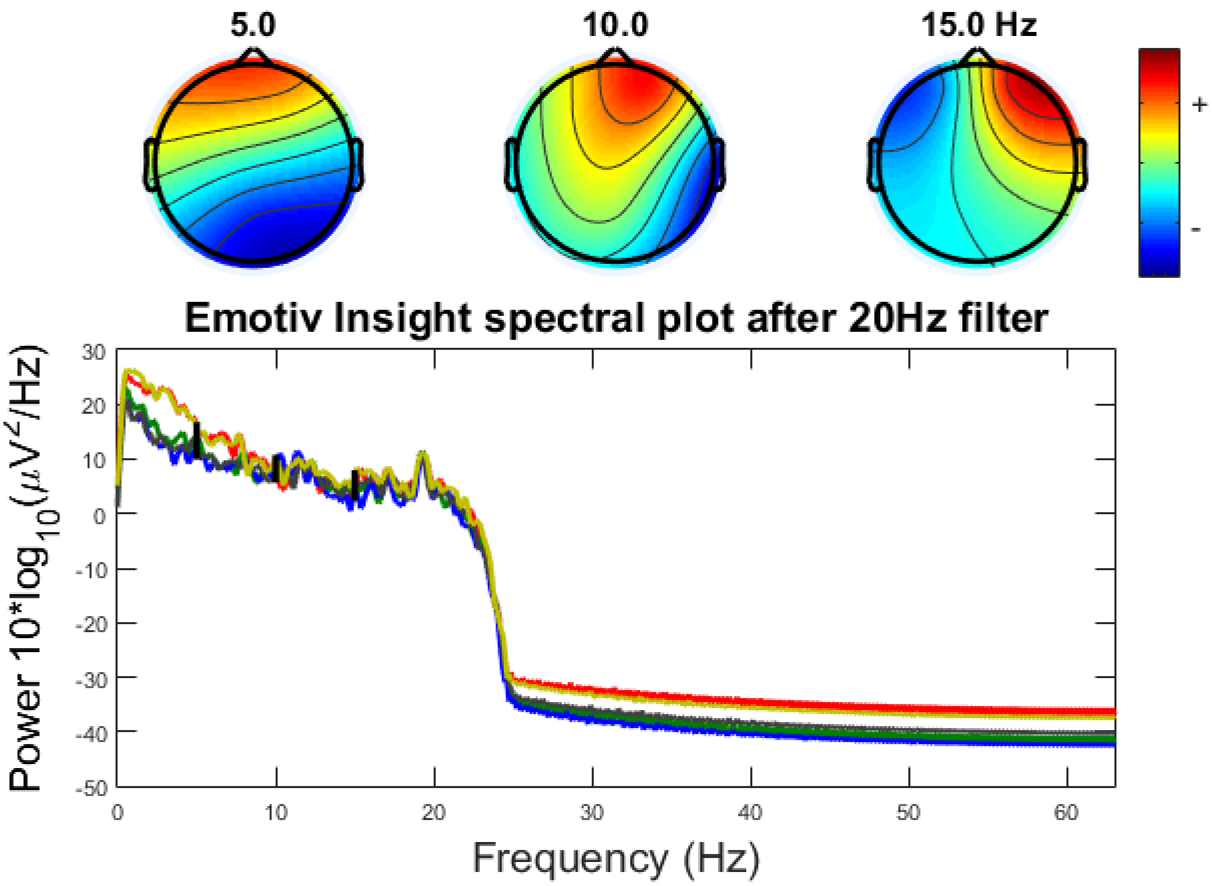


Figure 19 - Spectral data after 20Hz low-pass FIR filter.

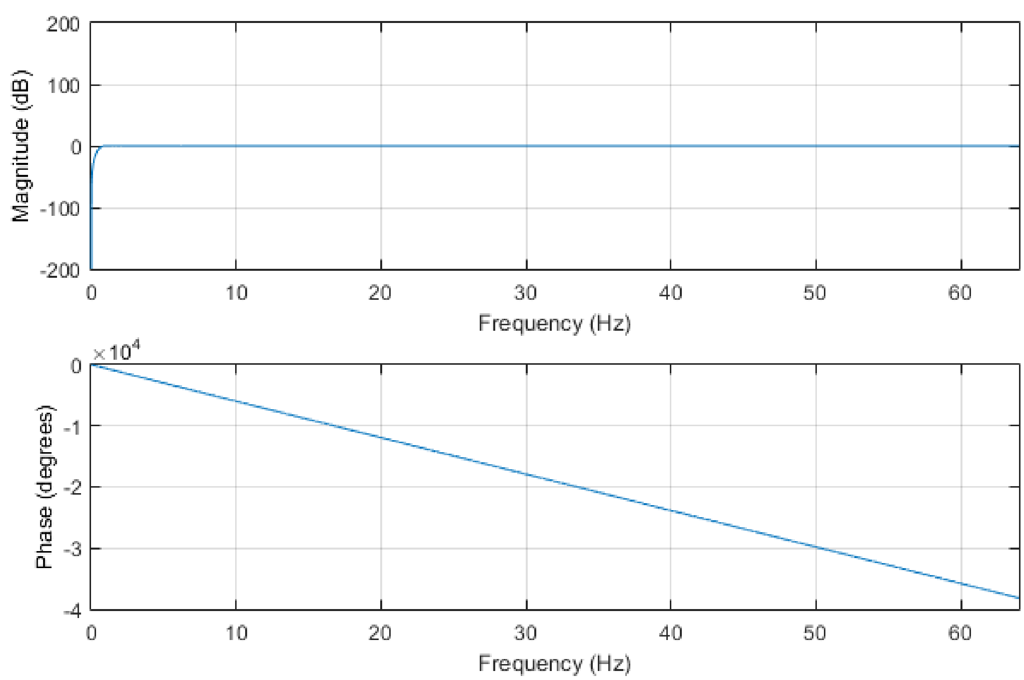


Figure 20 - Frequency response for a high-pass filter at 1Hz as implemented with EEGLAB.

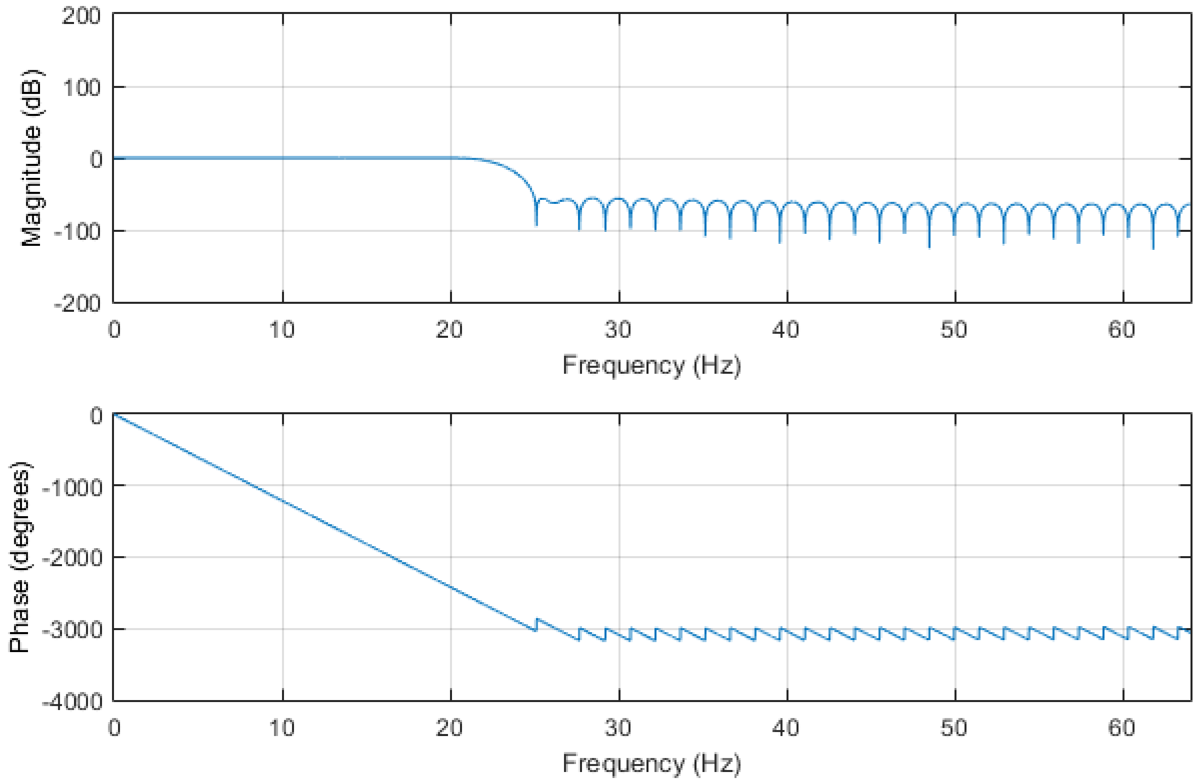


Figure 21 - Frequency response for a low-pass filter at 20Hz as implemented with EEGLAB.

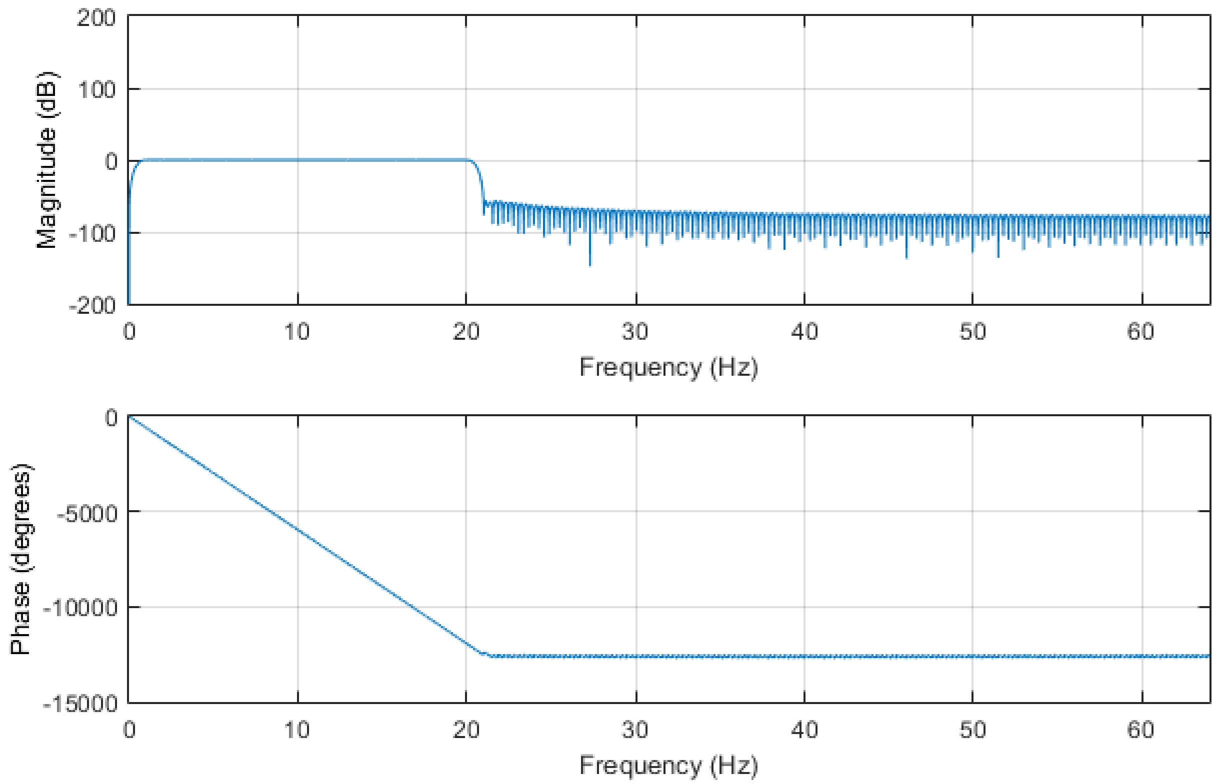


Figure 22 - Frequency response for a pass-band filter from 1-20Hz as implemented with EEGLAB

SSVEP response of the Emotiv Insight

For the determination of SSVEP response of the Emotiv Insight a rudimentary test was conducted where a video of a flickering visual stimulus is displayed with the sound turned off (Max13924eva, 2006). The data from this test was compared with a test without stimuli to see if a possible peak would be caused by the visual flickering stimulus. The frequency response of the high-pass filter at 1Hz that is implemented in this experiment is seen in *Figure 20*. The results from the test without stimuli can be seen in *Figure 23*, *Figure 24* and *Figure 25* and the results from the test visual stimulus at 5Hz can be seen in *Figure 26*, *Figure 27* and *Figure 28*.

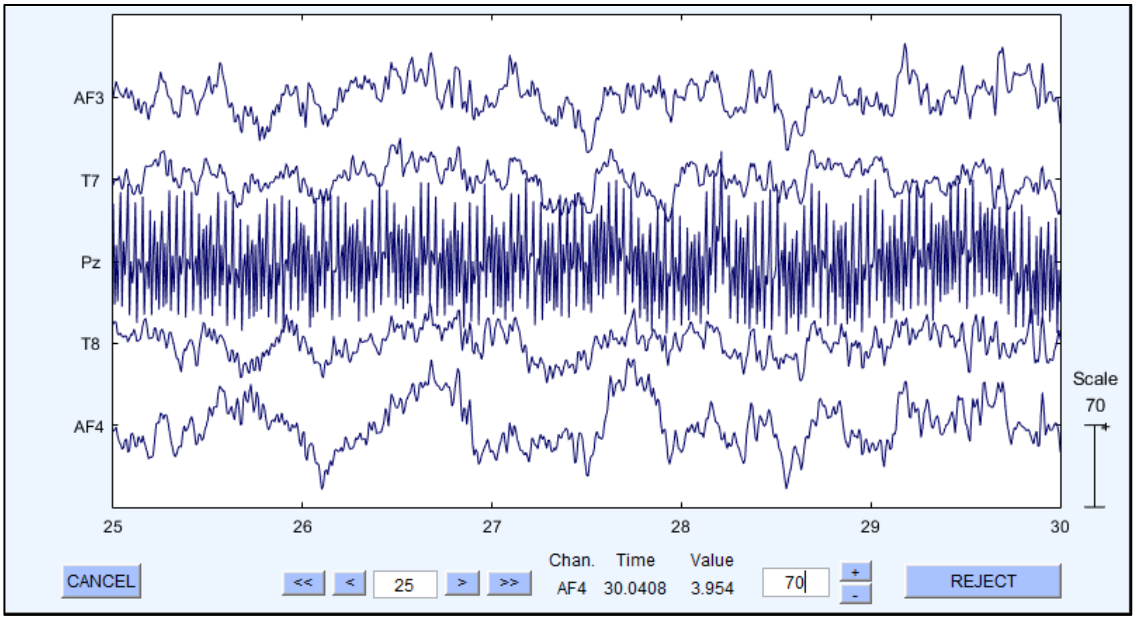


Figure 23 - Emotiv Insight EEG data from SSVEP trial without stimulus after implementing a high-pass filter at 1Hz. Channel data for P_Z is clearly erroneous due to a faulty connection, generating noise.

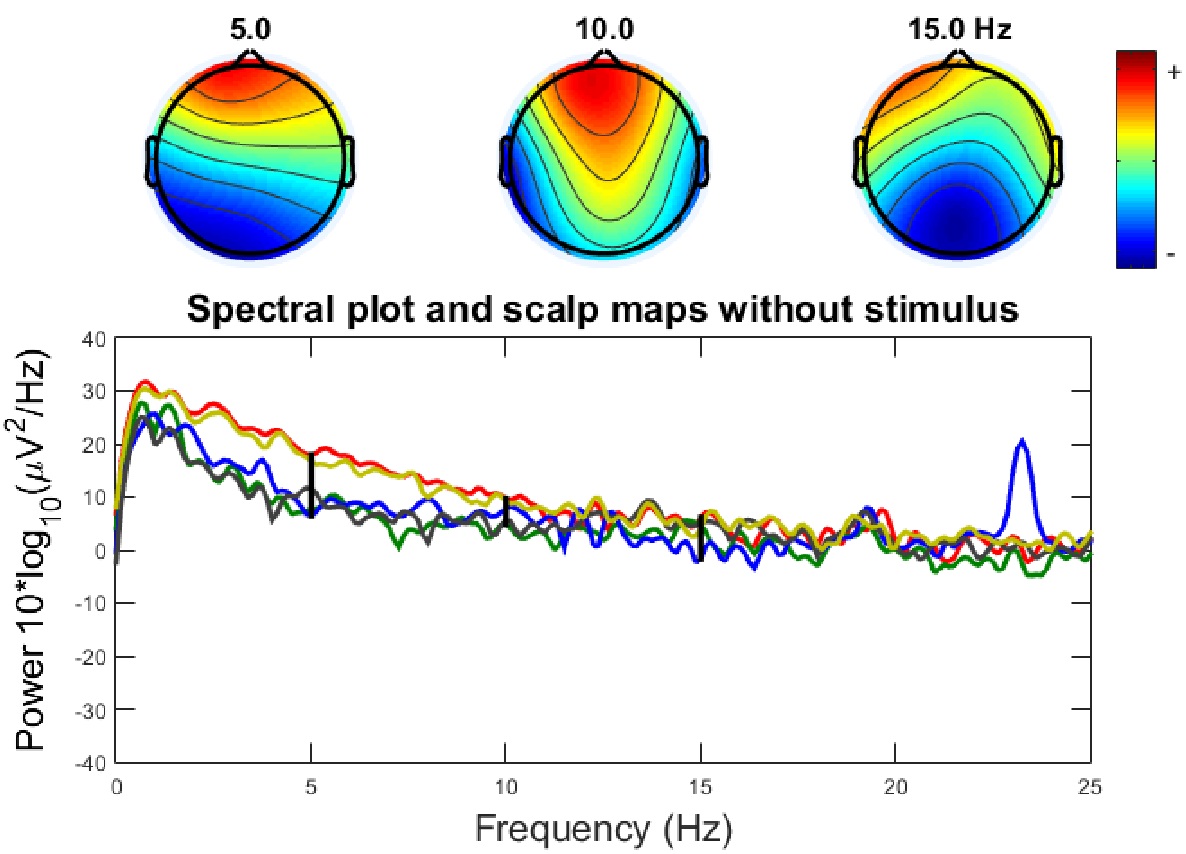


Figure 24 - Channel spectra and activity maps showing the distribution of power at frequencies of 5, 10 and 15 Hz for the EEG data from the same trial without stimuli at *Figure 23*. A strange peak is detected at 23,5Hz, not related to any visual stimulus.

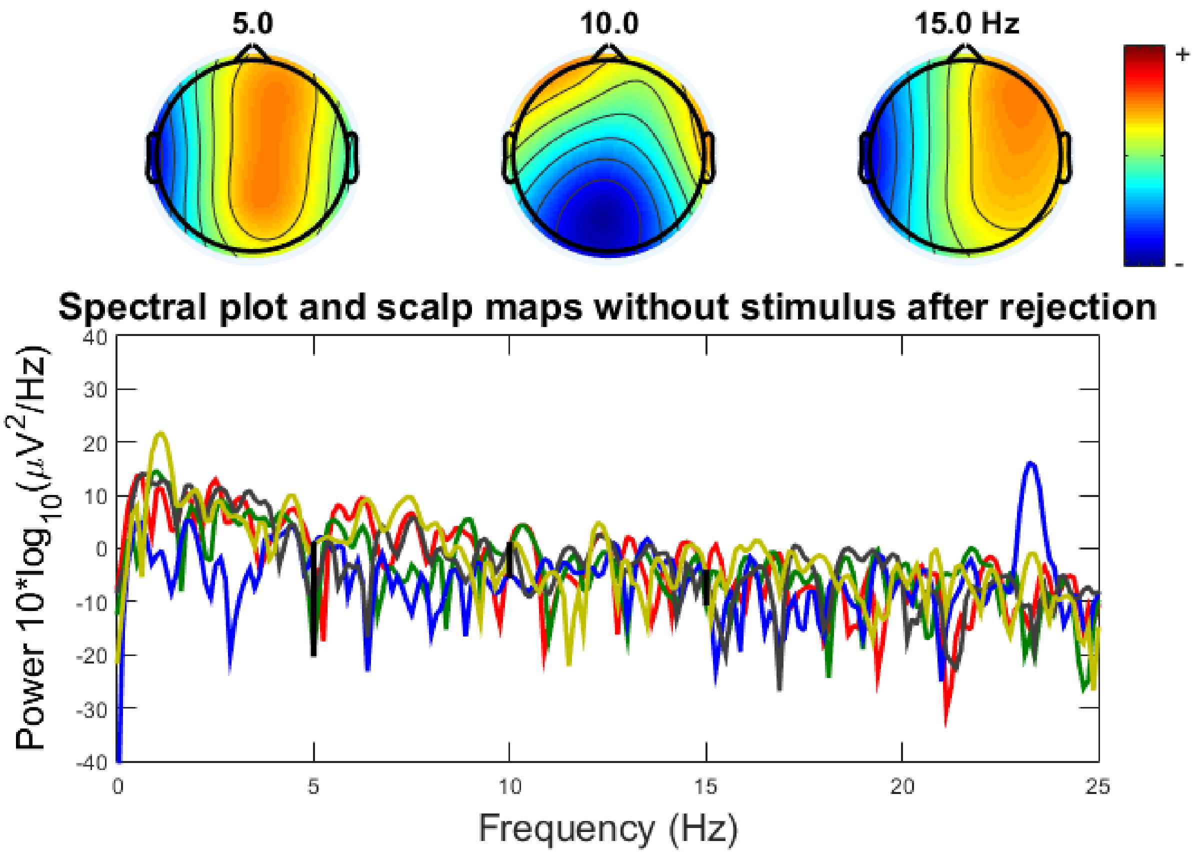


Figure 25 - The same channel spectra and activity maps as for *Figure 24*, this time after rejecting data related to movement by hand.

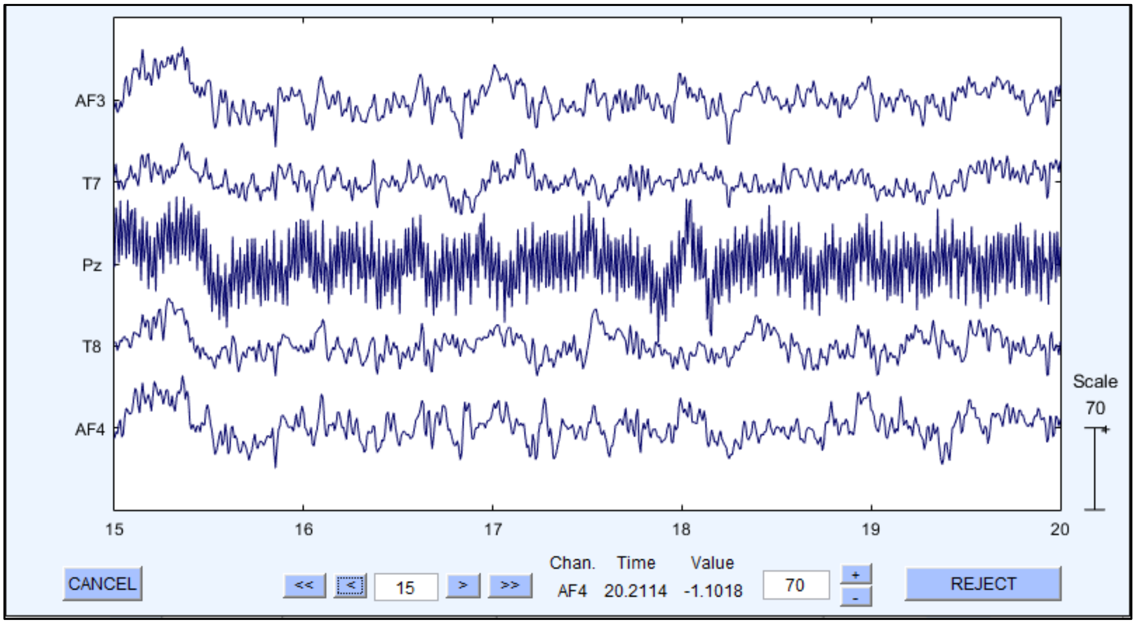


Figure 26 - Emotiv Insight EEG data from SSVEP trial with a ~5Hz visual stimulus after implementing a high-pass filter at 1Hz. Channel data for PZ is clearly erroneous due to a faulty connection, generating noise.

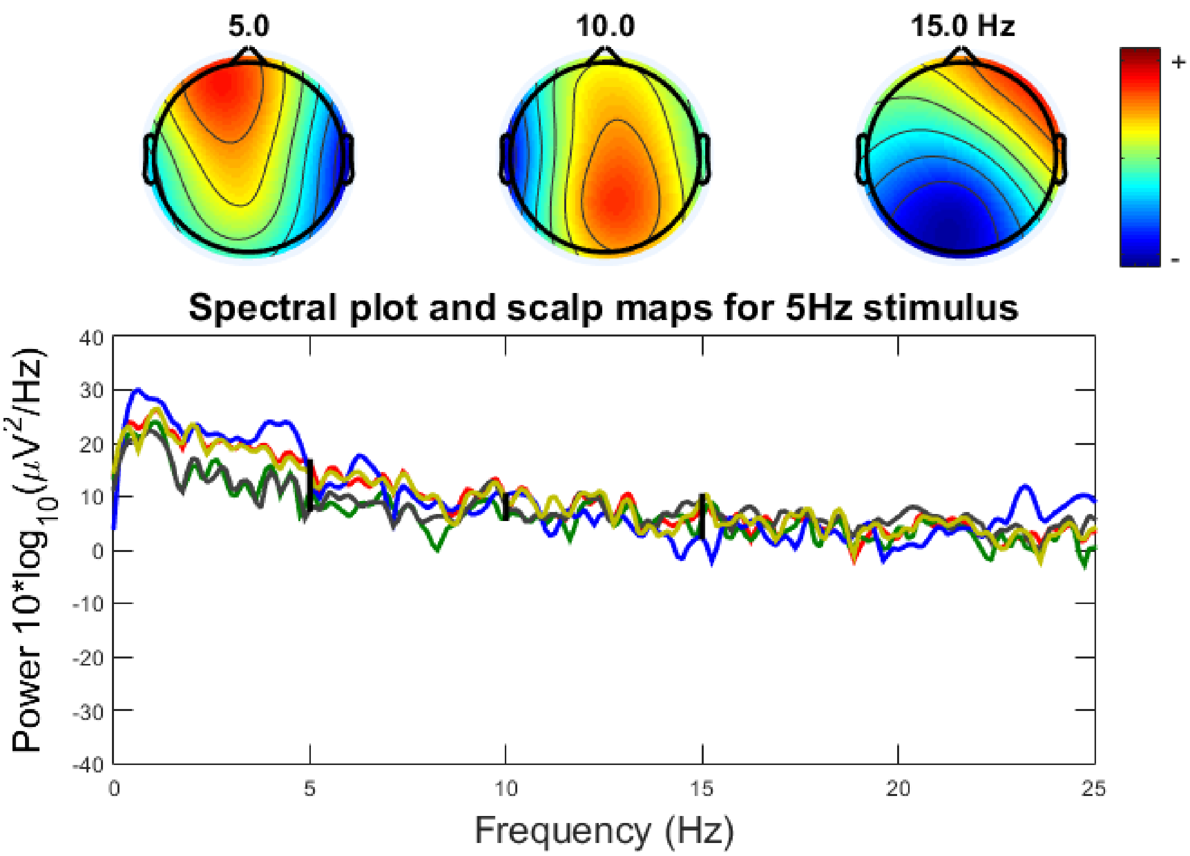


Figure 27 - Channel spectra and activity maps showing the distribution of power at frequencies of 5, 10 and 15 Hz for the EEG data from the same trial with a 5Hz visual stimulus at *Figure 26*. The 23,5Hz peak from the trial without stimuli is still present, although not as pronounced because of the base power being higher across the frequency spectrum for all channels. A peak is seemingly visible near 5Hz, which coincides with the visual stimulus presented.

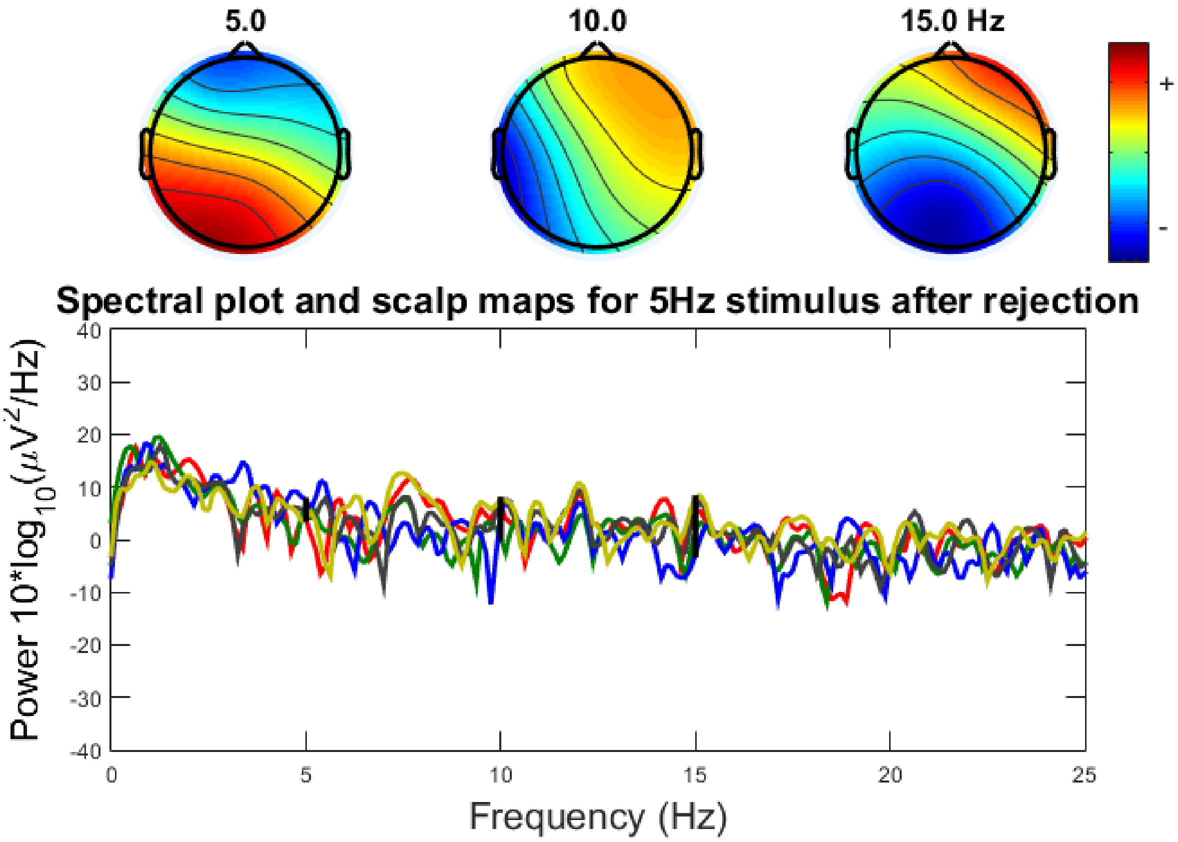


Figure 28 - The same channel spectra and activity maps as for *Figure 27*Figure 26, this time after rejecting data related to movement by hand. The peak around 5Hz has almost entirely disappeared.

From this exploratory experiment is appears as if the Emotiv Insight does not capture SSVEP response at all when presented with a visual stimulus at 5Hz. However, with the role played by the parietal and occipital lobes in the detection of visual stimuli and the lack of electrodes on the Emotiv Insight this is not really surprising.

P300 response with a speller visualization

Several different trials have been conducted for the P300 response with the speller visualization mentioned in the Research Design. In *Figure 29* the ERP waveforms for target stimuli can be seen for the P300 detection of the first trial with the Emotiv Insight. This P300 detection trial is identical to the one given in the results section of the main report and serves to indicate how improper connections of the electrodes to the scalp and muscle movement can disturb the trials, even after rejecting data. For this trial over 38 out of the 81 seconds recorded for the trial have been rejected by hand because of disturbances in the channel data, yet the resulting ERP analysis produces no clear P300 response.

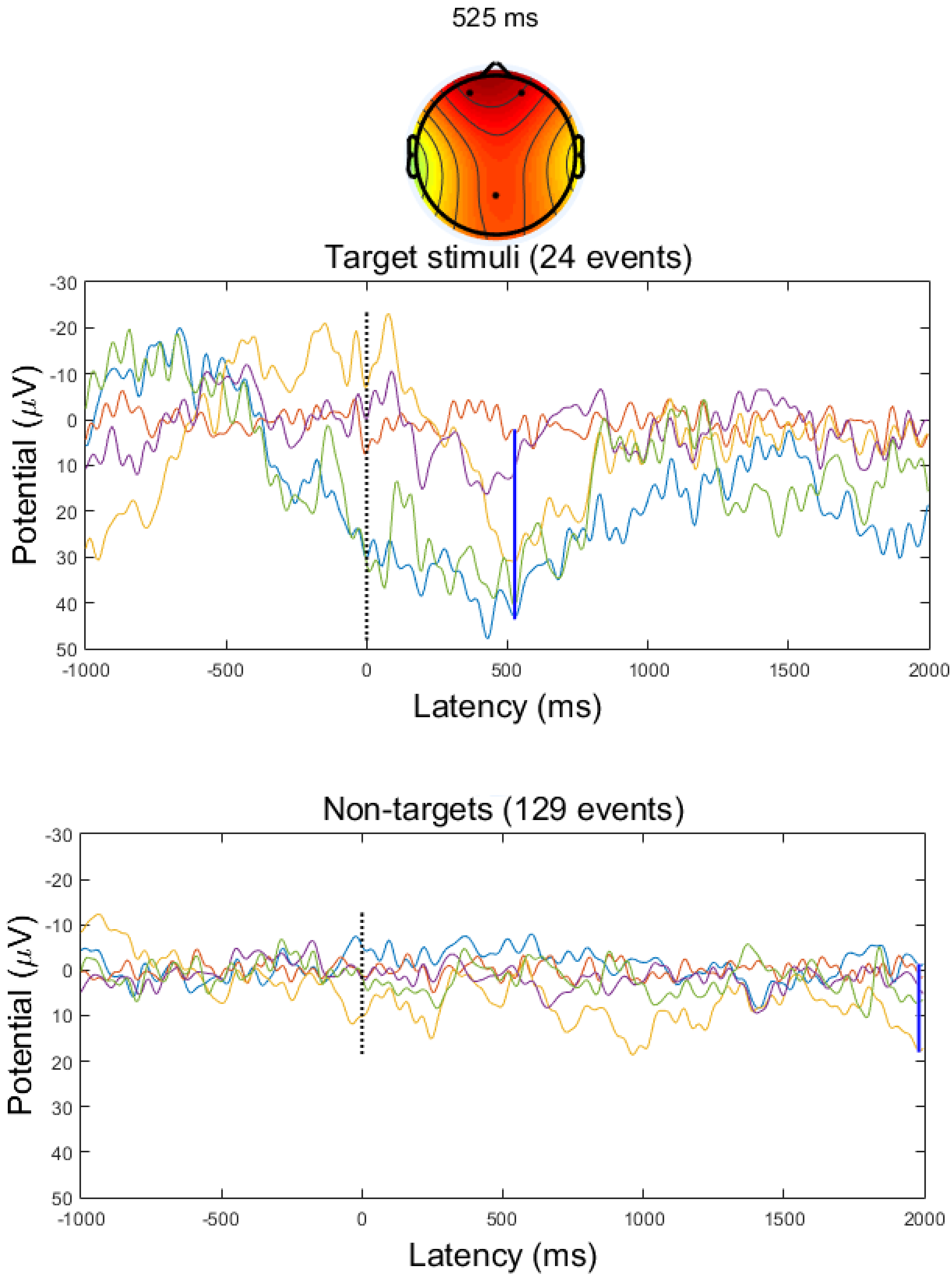


Figure 29 - Above: ERP waveforms for all channels for target stimuli, with the highest RMS highlighted with a scalp map. Below: ERP waveforms for all channels for non-targets. The same scale is used to illustrate the differences in potential.

Aside from the amount of disturbances that had to be rejected, the base number of target and non-target events is low compared to results from literature (Ekanayake, 2012), which may be the reason for not seeing a clear P300 response in this trial.

For the brevity of this report, not every intermediate trial will be discussed here as the amount of events for each of these was not high enough to extract meaningful data from the epochs. The results described here are from experiments with more events. All trials were made using the same test subject except for *Figure 32*, which is the result of a trial with a different test subject to see if this had any effect on the data.

For the calculation of signal-to-noise ratios for the Emotiv EPOC and Insight with the use of P300 ERPs obtained in these experiments, using the qualification of noise and signal obtained in the conceptual model we can observe the EEG potentials for non-target stimuli as noise. From the target stimuli in *Figure 30* and *Figure 31*, however, the range of the potentials increases due to the variability of the EEG data around the target epochs and the P300 response signal is nowhere near as pronounced as in literature (Ekanayake, 2012). This is discussed further in the conclusion.

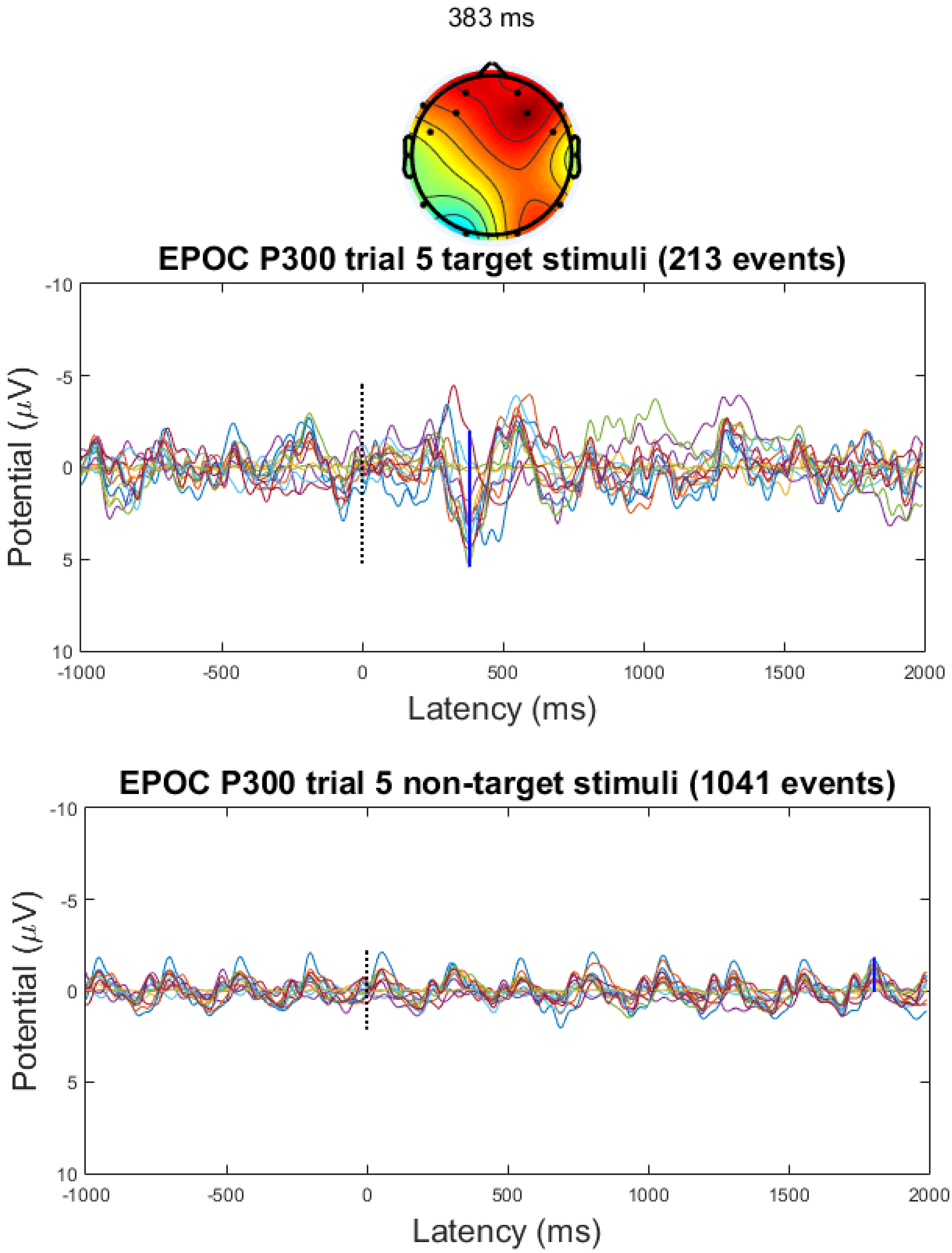


Figure 30 - Above: ERP waveforms for all channels of the Emotiv EPOC for target stimuli, with the highest RMS highlighted with a scalp map. Below: ERP waveforms for all channels for non-targets. The same scale is used to illustrate the differences in potential.

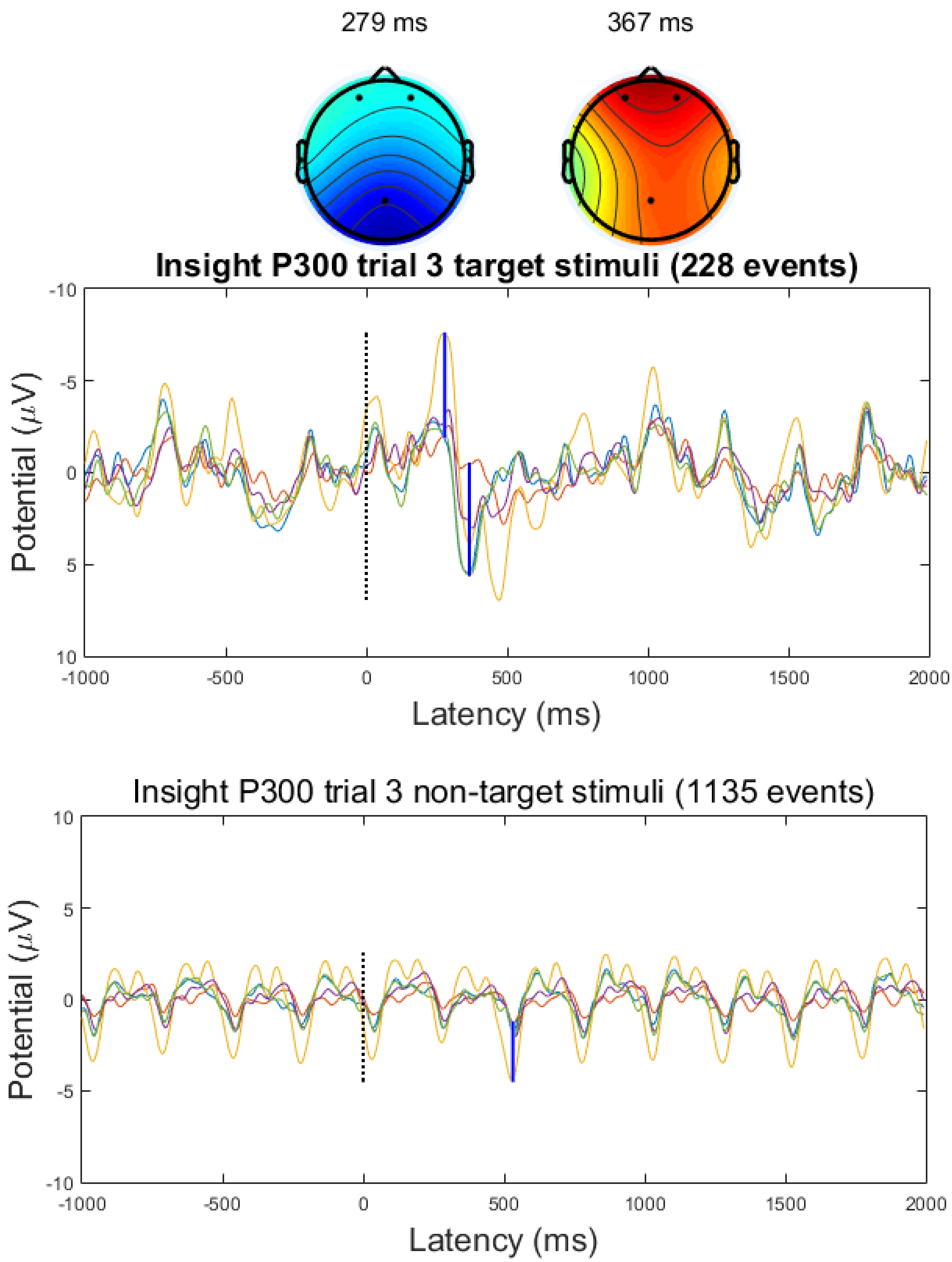


Figure 31 - Above: ERP waveforms for all channels of the Emotiv Insight for target stimuli, with the highest RMS highlighted with a scalp map. An additional scalp map was created for the first peak (297ms) to determine the latency of this response. Below: ERP waveforms for all channels for non-targets. The same scale is used to illustrate the differences in potential.

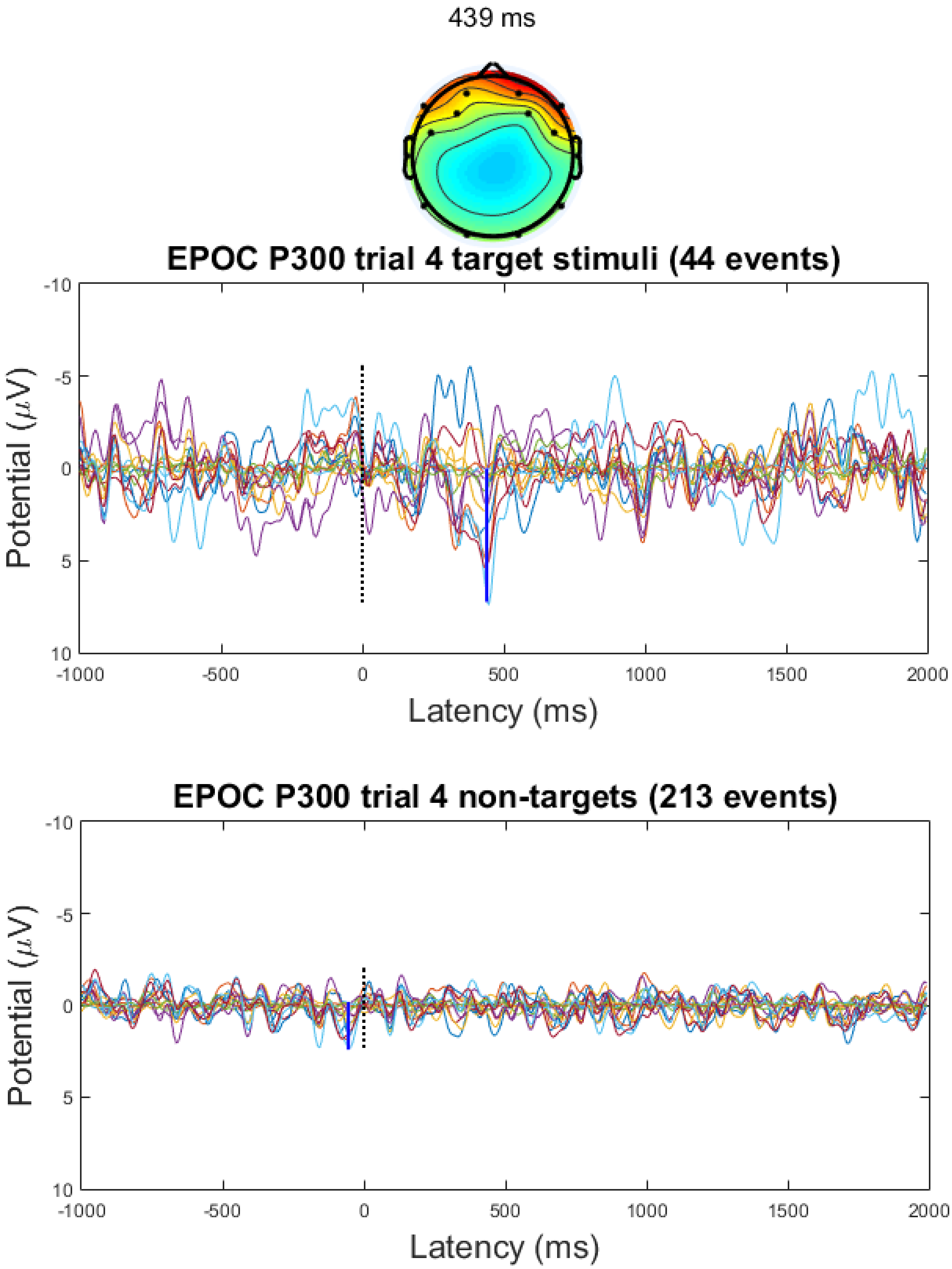


Figure 32 - Trial data with a different test subject. Above: ERP waveforms for all channels of the Emotiv EPOC for target stimuli, with the highest RMS highlighted with a scalp map. A noticeable peak is visible at 439ms which fits within the P300 response curve. Below: ERP waveforms for all channels for non-targets. The same scale is used to illustrate the differences in potential.

DISCUSSION AND CONCLUSIONS

The effect of EEG hardware used on data acquisition and signal-to-noise ratio

The hardware that was evaluated in this research was selected because of its availability at Negotica and more importantly because of the existing research SDK that came with the Emotiv EEG headsets. This eliminated the need of developing a set of filters and component analysis algorithms, and the experience that Negotica had with this SDK gave the company a preference for these devices.

For the extraction of raw EEG data from the Emotiv EPOC and Emotiv Insight research was done in literature and the resulting method of obtaining usable data required implementing software filters in MATLAB to replicate the techniques performed in the Emotiv SDK. Because of the proprietary filter and component analysis methods of the SDK being kept a secret, a great deal of time was lost investigating why channel data seemingly didn't appear, how exactly the data could best be filtered without losing critical signals and what data should be manually rejected in EEGLAB. The analysis of the eventually filtered data was done by investigating the frequency spectra of channel data from several trials. With the component analysis algorithms from Emotiv kept in secrecy and the signal strength not being influenced by measuring 'mental commands' as classified by these algorithms this method of analysis proved unsuitable for the determination of signal-to-noise ratios for either EEG headset. As mentioned in the conceptual model, the signal-to-noise ratio depends significantly on the qualification used to describe noise. Over the course of the project this definition was repeatedly modified as EEG data was analysed. For EEG data, a thought does not manifest itself as a peaking signal or frequency, which was evident from research but it required some first-hand data processing before truly understanding the nature of these signals.

The experiments on the ERP response of the hardware were instead set up to determine a quantifiable SNR. Some mistakes were made in the assumptions for this research that may well explain the inconclusive results of these experiments. For the SSVEP response a visual mode of stimulation was used. The main reasons for this SSVEP experiment were the simplicity of running a rudimentary test and the usually pronounced SNR (Ding, et al., 2006). However, as was mentioned in the theoretical analysis this often required additional electrodes to get (Liu, et al., 2012) a stable detection accuracy. These electrodes are placed on the parietal and occipital regions of the brain, which are close to the visual cortex. The experiment ran in this research utilized visual stimuli to evoke a response, which without these extra electrodes has proven to not be feasible.

One benefit of this find is that it reaffirms the desire of Negotica to operate without the use of SSVEP for e.g. a spell application, since the current hardware (both the Emotiv EPOC and the Emotiv Insight) do not possess enough electrodes on the right regions of the scalp to do this visually. This is different than the reasoning of Negotica that this is simply a slow and disorienting process for the user, so there is merit to knowing this.

An additional flaw in the SSVEP experiment was the acceptance of noise in the P_Z electrode, which hands-on research has shown is the most unreliable connection for the Emotiv Insight because of how loose it is around the scalp, but it is also the most critical electrode location for the Insight for this experiment as it is located on the parietal lobe. The noise caused by this electrode undermined the potential success of the detection of an SSVEP response and is likely the cause of the signal peak around 23,5Hz.

The P300 speller visualization was likewise a visual stimulus. This test evidently provokes some the most pronounced responses in the F_Z P_Z and C_Z electrode locations in the 10-20 configuration, which are not used by the Emotiv EPOC and only C_Z is used by the Emotiv Insight. This explains the lack of good responses visible in the results for this experiment. The difference between literature examples of the P300 response for the Emotiv EPOC was surprising, however, and it is unlikely only the number of events in the trials determined this difference since the last trials for both the EPOC and the Insight had a sufficient number of target events. The P300 responses found in the experiment did fall within realistic ranges as can be seen in *Figure 33*.

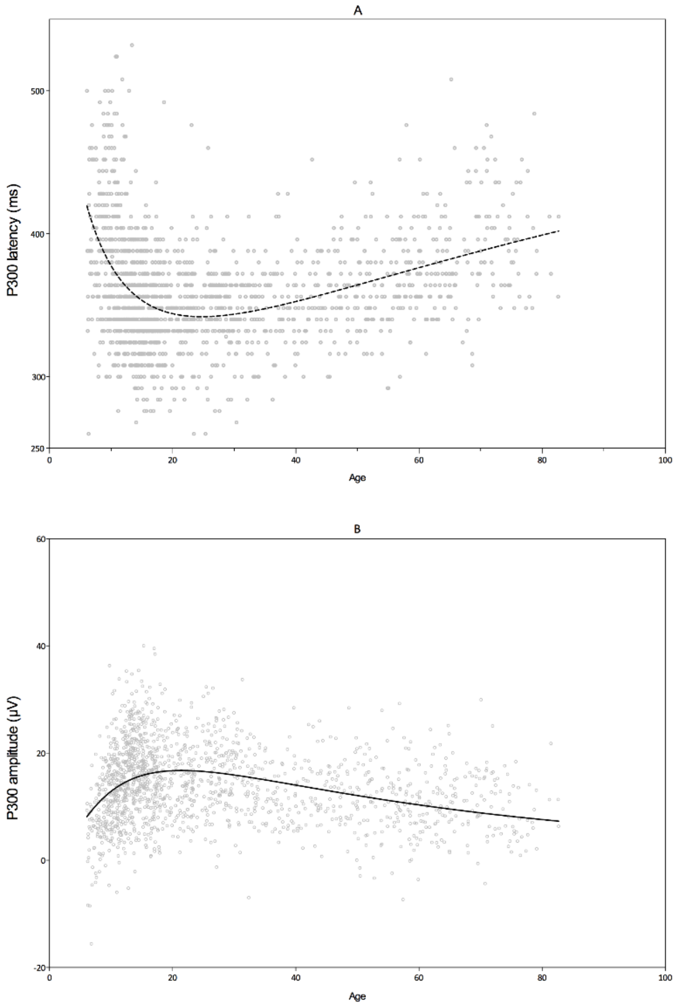


Figure 33 - P300 latency and amplitude trajectories (van Dinteren, et al., 2014).

The effect of EEG hardware used on success rates and calibration time

Findings on the success rate of the Emotiv EPOC were mostly found alongside research into the data acquisition of these devices, and although methods of determining detection success rate were found in literature, the experiments were held off by the acquisition of accurate EEG data. Regretfully, this research was not able to provide a meaningful cause-effect relationship between the hardware used and the detection accuracy of the Emotiv SDK. Instead, the focus was shifted to the determination of a reliable SNR.

For the Emotiv SDK, calibration time has been found through literature, which was determined to suffice for this specific topic. The software used for both evaluated EEG headsets is the same, this question would simply become more interesting when developing custom component detection algorithms for alternative hardware.

RECOMMENDATIONS

The results of the hardware analysis of the Emotiv EPOC and Emotiv Insight mostly explain the overall problems with the experiments. Nevertheless, throughout the project both EEG devices were used extensively for experimental data acquisition, development of the User-Assistive Menu and even repairs to an aged model where the internal battery was replaced. The differences in detection of mental commands using the detection suite provided by Emotiv with its products are minimal, with a similar component detection algorithm being present and facial expressions and gyro- and accelerometer data being present on both devices.

As mentioned in the results, the greatest benefits of these experiments for direct use in Carebro were in the analysis of the electrode configurations and the effect of this on using ERP detection for control. With the EEG hardware that is currently on the market, I recommend Negotica stay with the hardware that they have already purchased as the provided component analysis algorithms are not easily replicated to be used in a BCI application, leaving ERP detection as the main method of control. Considering target demographic of Carebro, people who use this device throughout their day might become fatigued faster with the use of SSVEP or P300 spellers and control schemes.

REFERENCES CITED IN APPENDIX E

Ding, J., Sperling, G. & Srinivasan, R., 2006. Attentional Modulation of SSVEP Power Depends on the Network Tagged by the Flicker Frequency. *Cerebral Cortex,* 16(7), pp. 1016-1029.

Ekanayake, H., 2012. *Research Use of Emotiv EPOC.* [Online]
Available at: http://neurofeedback.visaduma.info/emotivresearch_o.htm
[Accessed 18 06 2016].

Fakhruzzaman, M. N., Riksakomara, E. & Suryotrisongko, H., 2015. EEG Wave Identification in Human Brain with Emotiv EPOC for Motor Imagery. *Procedia Computer Science,* Volume 72, pp. 269-276.

Health Hub Roden, 2016. *Health Hub Roden.* [Online]
Available at: http://www.healthhub-roden.nl/english
[Accessed 29 May 2016].

Lang, M., 2012. *Investigating the Emotiv EPOC for cognitive control in limited training time,* Canterbury: Department of Computer Science.

Liu, Y. et al., 2012. Implementation of SSVEP Based BCI with Emotiv EPOC. *Virtual Environments, Human-Computer Interfaces and Measurement Systems (VECIMS), 2012 IEEE International Conference on,* pp. 34-37.

Max13924eva, 2006. *Flashing screen.* [Online]
Available at: https://www.youtube.com/watch?v=HIEa_UujP4Q
[Accessed 2016 June 19].

Park, J. & Kim, K.-E., 2012. A POMDP Approach to Optimizing P300 Speller BCI Paradigm. *IEEE Transactions on Neural Systems and Rehabilitation Engineering,* 20(4), pp. 584-594.

Picton, T. W., 1992. The P300 wave of the human event-related potential. *Journal of Clinical Neurophysiology,* 9(4), pp. 456-79.

Swartz Center for Computational Neuroscience, 2014. *Chapter 04: Preprocessing Tools.* [Online]
Available at: http://sccn.ucsd.edu/wiki/Chapter_04:_Preprocessing_Tools
[Accessed 19 June 2016].

van Dinteren, R., Arns, M., Jongsma, M. L. & Kessels, R. P., 2014. P300 Development across the Lifespan: A Systematic Review and Meta-Analysis. *http://dx.doi.org/10.1371/journal.pone.0087347.*

vfrolov, 2015. *Null-modem emulator download.* [Online]
Available at: https://sourceforge.net/projects/com0com/
[Accessed 18 06 2016].