UNIVERSITY OF SOUTHERN QUEENSLAND
Faculty of Engineering and Surveying

Developing a Home-Based Functional Application for an EEG-based Brain Computer Interface

A dissertation submitted by
Jeremie Alexis

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Abstract

The brain computer interface (BCI) offers users the potential to gain increased access to environment, particularly those with physical disability or impairment. This technology has attracted focus from many disciplines due to its promising applications such as environmental control, robotic or neuroprosthetic control, gaming, physical rehabilitation and vocational enhancement, not to mention the range of medical benefits offered by this technology.

Despite optimistic expectations for the BCI, this technology has largely been confined to the laboratory. Recent developments over the past few years have seen the production of commercial BCIs intended for general user use. Nevertheless, the presence of such devices raises questions of reliability, cost-effectiveness, user-friendliness, and compactness for the in-home user.

This research found that commercial BCIs do enable usable signal acquisition of raw brain waves. Nevertheless, these systems are limited in terms of spatial resolution, and feature extraction and translation. Results show that two commercially available BCIs in particular offer promising results for the user with moderate to severe physical disability. A suitable imagined music application can be derived using a mix of in-built SDK algorithms, independent signal processing, open sound control and Pure Data for real time processing of brain signals.

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ENG4111 Research Project Part 1 &
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Limitations of Use

Certification

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

Jeremie Alexis
Student Number: 0050085287

Signature

Date

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I would like to thank my supervisor, Dr. John Leis, for his prompt and informative assistance throughout this research project. Thanks for providing clear direction and support.

I am extremely grateful for the long-suffering, love and support provided by my family. My dear wife, you are amazing, wise and very gracious. My children you are inspiring and very dear to my heart.

Thank you to God for the gift of life and the complex challenges of the brain to keep us all ‘guessing’ for a long time to come.

Jeremie Alexis

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Glossary

3D. Three-dimensional

ASCII. American Standard Code for Information Interchange

ABS. Australian Bureau of Statistics

ADC. Analogue-to-Digital Converter

ALS. Amyotrophic Lateral Sclerosis

API. Application Programming Interface

BCI. Brain Computer Interface

BF. Body Floating

Ca^{++}. Calcium

CF. Cardiac Floating

Cl^{-}. Chlorine

COM port. Communication port

DLL. Dynamic Link Library

DSP. Disability Support Pension

EEG. Electroencephalography

ECoG. Electrocorticography

ERP. Event Related Potentials

fMRI. Functional Magnetic Resonance Imaging

fNIR. Functional Near Infrared

HCI. Human Computer Interaction

Hz. Hertz

IR. Intracortial Readings

K^{+}. Potassium

MEG. Magnetoencephalography

μ-rhythm. Mu rhythm

Na^{+}. Sodium

PC. Personal Computer

PET. Positron Emission Tomography

SCP. Slow Cortical Potential

SELV. Safe Extra-Low Voltage

SMR. Sensorimotor Rhythms

SNNAP. Simulator for Neural Networks and Action Potentials

USB. Universal Serial Bus

WHO. World Health Organisation

Chapter 1 Overview

"Knowledge for knowledge sake is just plain knowledge. Knowledge in action for people's sake, well that's just plain compassion." - *Jeremie Alexis*

1.1 Introduction

Science fiction is fast becoming a reality for brain-computer interface (BCI) systems. In a climate where Human Computer Interaction (HCI) has gained increasing focus, the BCI stands out as an apt representation of this complex intersection of disciplines (Allison 2010). The impetus behind this now tangible, sophisticated technology stems from the pioneering research efforts of Hans Berger (1873-1941) and later Dr. Grey Walter (1910-1977). Berger's (1929) research perpetuated the development of encephalographic (EEG) technologies, which subsequently led to Walter's breakthrough development of the first BCI device in 1964 (Graimann et al. 2010).

In essence, a BCI is a peripheral device that enables a user to communicate with a computer using brain-elicited signals (McFarland & Wolpaw 2011; Hinterberger et al. 2007; Sellers et al. 2007). It should be made clear that BCIs are not 'mind-reading' devices, a common misconception held about this developing technology. BCI technologies lie at the intersection of several fields of study including neurobiology, psychology, engineering, mathematics, computer science, clinical rehabilitation, communications, linguistics, HCI, and human factors (Allison 2010; Mak & Wolpaw 2009). It is noted that a steady increase in specialist knowledge in each discipline and improvements in inter-disciplinary communication will only serve to enhance current BCI systems. In order for a device to be considered a BCI, it must meet four criteria (Pfurtscheller et al 2010). Firstly, a BCI should have a reliance on direct measures of brain activity. Secondly, feedback to the user needs to be provided. This feedback could be visual, auditory, or even haptic. Thirdly, the BCI should operate in real time. Fourthly, the BCI should function as a result of intentional control by the user (Pfurtscheller et al 2010).

Current research offers promising outcomes for users of BCI systems (McFarland & Wolpaw 2011). Some of these benefits include access to control and communication for people with moderate to severe neuromuscular disorders, control of robots or neuroprostheses, enhancement of the gaming industry, enabling PC usage, assistance in physical rehabilitation, and facilitation of environmental control (McFarland & Wolpaw 2011). Yet despite hopeful claims, BCI technology has still predominantly been confined to the laboratory (Sellars et al. 2007). One could infer salient reasons for this slow transition to the public such as reliability, cost-effectiveness, user-friendliness, and compactness (Sellars et al. 2007). Nevertheless, these factors have not prevented a number of international companies, mimicking the promising trends of BCI technology, in releasing several commercially available devices to the general public. To date, a qualitative comparison has been made between BCI devices currently available on the commercial market (Zhang et al. 2010). However, no study has conducted comparative analysis of these devices nor focused on evaluating and improving the efficacy of the same for practical in-home use. As such these gaps in knowledge have informed the focus of this project.

1.2 Aims

With an emphasis on bringing BCI technology out of the laboratory and into the home, this project aims to investigate the potential of producing a reliable, cost-effective and efficient in-home BCI application for users in the general community.

This broader aim is to be accomplished through the comparative analysis of existing, commercially available BCI devices and the testing of these in developing a functional application.

It is anticipated that the device will be useful for people with limited or no physical movement. Yet is benefits are likely to extend to the mainstream population.

1.3 Specific Objectives

The project also aims to address a number of specific objectives in the development of a cost-effective, in-home compatible BCI solution. These objectives have been divided into four primary objectives and one secondary objective as follows:

Primary objectives

1. Research background information relating to brain computer interface (BCI) design, electroencephalography (EEG) signal processing, human factors, and ethics.
2. Use selected software tools for real time acquisition, visualisation and analysis of brain signal inputs.
3. Conduct comparative analysis of selected brain computer interface systems.
4. Establish a framework from which a reliable and robust functional application can be built for use by selected commercial BCIs.

Secondary objective

5. Explore strategies for improving issues of user fatigue, speed, accuracy, consistency, control, user friendliness and convenience, and signal processing algorithms for desired outputs.

1.4 Justification for Research

This section places the research project in context and provides justification for its selection and proposed benefit to society. Discussion is made with respect to benefits for people with disability, benefits for mainstream population and benefits of in-home usage.

1.4.1 Benefits for People with a Disability

In 2009, the Australian Bureau of Statistics (ABS) approximated that 18.5% of the Australian population had a disability (ABS 2010). Disability is defined “as any limitation, restriction or impairment which restricts everyday activities and has lasted or is likely to last for at least six months” (ABS 2010, p.3). Of these people with a disability, the ABS

(2010) estimated that 2.9% had profound limitations, 2.9% had severe limitations, 3.0% had moderate limitations and 5.6% had mild limitations. These limitations refer to core activities of communication, mobility and self care.

On an international scale, the World Health Organisation (WHO) estimated that 10% of the world's population experience some form of impairment or disability (WHO 2006). Two percent of the global population have a musculoskeletal condition (DCP2a 2007) contributing significantly to global chronic disability. Moreover, neurological disorders (DCP2b 2006) and unintentional injuries (DCP2c 2006) pose a significant health burden to the global community. Of particular interest in this project are those people with disabilities that experience moderate to profound motor impairment.

There are a number of conditions that people that may cause limitations in mobility for at least 6 months duration. These conditions may include but are not limited to (Niestadt & Crepeau 1998; Pedretti 1996):

- Chronic non-progressive neurological conditions: cerebral palsy.
- Progressive neurological conditions: muscular dystrophy, multiple sclerosis, amyotrophic lateral sclerosis (ALS) and other motor neuron diseases.
- Diseases of the circulatory system: heart disease, stroke.
- Cancers, lymphomas and leukaemias.
- Obesity due to diabetes.
- Severe respiratory disorders.
- Injury or other external causes: spinal injury, head injury, acquired brain injury, other accidents causing prolonged bed/chair confinement.
- General ageing process.

People with these disabilities often require moderate to high level modifications to increase independence and maintain quality of life (Pedretti 1996). One such modification relates to access technologies where the relevance of brain computer interfaces (BCI) becomes apparent.

1.4.2 Applications Beyond Disability

BCI systems do not only have the potential to increase the independence and quality of life of people with disabilities. There are target groups that would also find benefit from these systems including (Allison 2009):

- The mainstream healthy: general population
- Those in rehabilitation: stroke, autism, attention deficit
- Gamers
- Those experiencing situational disability: surgeons, drivers, soldiers, mechanics
- Astronauts
- Virtual navigators
- Pilots
- Drivers
- Home automation groups

1.4.3 From the Lab to the Home

Aside from various communication and environmental control applications (Mak & Wolpaw 2009), there are limited alternative home-based BCI solutions that exist for users. In order to realise a viable solution for users it is important that a baseline of reliability be established. This concept is discussed in detail in the chapter on Designing a Robust and Reliable BCI Solution on page 36 below.

1.5 Project Outline

This dissertation is organised as follows:

Chapter One: Introduction and justification of research project.

Chapter Two: Background to BCIs. This chapter discusses pertinent information and background knowledge to the growing BCI area. Topical areas covered include access technologies, the human brain, EEG, BCIs, signal processing, human factors, and ethical considerations.

Chapter Three: Designing a Robust and Reliable BCI Solution. This chapter expounds the underlying research methodology used to develop a functional application of a BCI. It explains reasoning behind particular decisions made throughout the research project and describes an appropriate evaluation of commercial BCIs. Importantly, this chapter provides a clear definition of what constitutes a reliable solution.

Chapter Four: Testing and Evaluation of BCIs. This chapter presents results obtained through the testing of selected BCI devices and software and development tools. These results form a foundation for further discussion in Chapter 5. A comparative analysis of selected BCI devices is provided to identify the robustness of existing solutions and to inform future BCI research.

Chapter Five: Developing the Functional Application. This chapter discusses and critically evaluates the results developed through data collection and analysis of BCI testing. A framework for developing a functional application is discussed as well as strategies for improving BCI performance at home.

Chapter Six: Conclusions and Future Work. This chapter summarises research finding and its contribution to the body of research knowledge. It exposes limitations of this research and suggests areas for future work and improvement on this project.

Chapter 2 Background to BCIs

"If the human brain were so simple that we could understand it, we would be so simple that we couldn't." - *Emerson M. Pugh*

2.1 Background & History

The BCI has shown a rapid transition from a theoretical framework or sci-fi idealism to become a reality. At one time the concept of controlling the environment with the human mind was as far-fetched as time travel is today. Nevertheless, technological innovation and rapid learning in multiple disciplines has seen the BCI materialise within a short space in time (Wolpaw 2002). This chapter explains the underyling theory and knowledge required to develop appropriate BCI solutions for the in-home user. Important topics such as access technologies, human brain anatomy and physiology, EEG, signal processing and ethical considerations are explored in detail.

2.2 Access Technologies

People with moderate to profound motor impairment require an alternate form of access or channel to interact with the external environment (Memarian et al. 2009). Memarian et al. (2009) defines this means of capturing a user's intent as an access pathway. Access technologies can be categorized into two main groups, pertaining to the physical abilities of potential users. These groups include those access technologies suitable for people with some physical movement and those suitable for people with no physical movement (Tai et al. 2008).

Table 2-1 below illustrates the breakdown of access technologies with respect to physical ability.

Table 2-1: Access technologies relevant to physical ability (Tai et al. 2008).

Access Technology		
Some Physical Movement		**No Physical Movement**
At least one reliable access site from the neck or below	**A reliable access site above the neck**	
• Mechanical switch • Electromyography • Infrared sensing	• Mechanical switch • Electromyography • Oculography • Computer vision	• Electroencephalography (EEG) • Electrocorticography (ECoG) • Intracortical recordings (IR) • Electrodermal activity (EDA)

As the severity of physical impairment increases particular access technologies become more useful than others. Specifically, EEG, ECoG, and IR emphasize cortical control with minimal to no reliance on motor activity. Electrodermal activity (EDA) operates in a distinct fashion by detecting changes in the user’s skin conductivity. When considering BCIs, advancing research on additional sophisticated access technologies can also be taken into consideration. These comprise Functional Magnetic Resonance Imaging (fMRI), Magnetoencephalography (MEG), Positron Emission Tomography (PET), and Functional Near Infrared (fNIR) (Allison 2009; Pantazis & Leahy 2006). Nevertheless, these latter technologies are more expensive and tend to be restricted to laboratory environments (Sellars & Donchin 2006). Moreover, EEG has been a long time established and reliable technology in a variety of medical applications and has particular relevance to non-invasive BCIs.

2.3 The human brain

The human brain is a complex mass of neural tissue that is essential for survival and function. An adult brain typically weighs 1.4 kg with a volume of 1200 cc (Martini 1998). The brain facilitates physical movement (motor control), interprets sensation, regulates life-dependent activities such as breathing, and enables higher order cognitive skills, to name a few functions. At its most basic functional unit, the brain and other neural tissue are made up of individual neurons (Martini 1998). Neurons have a number of structural and functional classifications; however in general, they are comprised of a body, dendrites and axon (Martini 1998). Dendrites are tree-like processes that extend from the body and receive information from other neurons. The axon is a long process that has connection points to pass on information to other cells. Inter-cellular communication is achieved via specialized sites called synapses (Martini 19998). As there is a gap (neuroeffector junction) between cells, the information from a neuron (pre-synaptic cell) is converted to chemical form (neurotransmitters), which are expelled into the gap between two cells. The neurotransmitters can then activate another post-synaptic cell.

2.3.1 Action potentials

The inside of a neuron (brain cell) is slightly negative in charge compared to its outside (Martini 1998). This negative charge results in a potential difference called a transmembrane potential. When measuring the transmembrane potential of an undisturbed nerve cell, this is known as its resting potential and equates to -70 mV (Martini 1998). Any transmembrane potential shift towards 0 mV or above is termed a depolarisation (Martini 1998). Information to be propagated along neurons is largely accomplished in one of two ways, namely via graded potentials or action potentials.

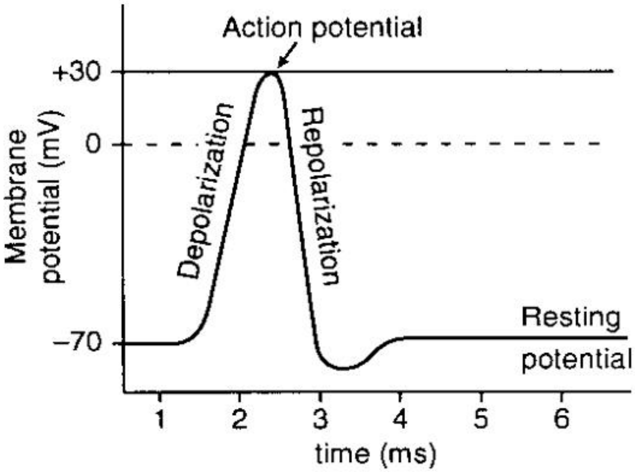


Figure 2-1: Depiction of action potential inside neuron (ODSSM n.d.).

A graded potential tends to be a localised spread of information (current) where the site of stimulation is most affected (Martini 1998). In contrast, action potentials spread across the entire neuron via an “all-or-none” principle (see Figure 2-1). The all-or-none principle simply means that unless depolarisation of a particular segment reaches a threshold value between -60 mV to -55 mV then the charge will not be spread. It can be helpful to imagine a typical axon divided into smaller segments. Each segment needs to reach the threshold in order to pass the information forward. When this chain reaction completes successfully so that information is passed to the cell synapses and on to another cell, this is called continuous propogation (Martini 1998). Table 2-2

Table 2-2 below shows the difference between these two potentials.

Table 2-2: Comparison of graded potentials with action potentials

Graded Potentials	Action Potentials
Depolarises or hyperpolarises	Only depolarises
No threshold value	Threshold must be reached before potential begins
Amount of polarisation is dependent on intensity of stimulus	Identical potential. All-or-none
Stimulation spreads passively	Adjacent site causes next to depolarize to threshold
Strength of signal dissipates over distance	Same strength propagated over entire membrane surface
No refractory period	Refractory period
Most cell membranes	Only in excitable membranes of specialised cells including neurons

An understanding of the underlying human brain's biological processes can help to inform appropriate BCI practices.

2.3.2 Neural activities

The brain uses a complex ion pumping system to produce current. These ions include sodium (Na^+), potassium (K^+), calcium (Ca^{++}) and chlorine (Cl^-). A collection of multiple currents produced by neuronal activity results in signal patterns for further processing (refer to section 2.6 below on Signal processing).

2.3.3 Structure of the brain

The nervous system is divided into two main areas. These areas include the peripheral nervous system and the central nervous system. Of particular relevance to BCIs is the central nervous system as this encompasses the brain and the spinal cord. The brain is comprised of 6 major regions including the cerebrum, cerebellum, diencephalon, mesencephalon, pons and medulla oblongata. These regions can be placed within one of 3 general basic units of the brain, namely the forebrain, midbrain and hindbrain (Luria 1973).

The cerebrum is part of the forebrain, which is the bulk of the brain mass. The cerebrum is divided into two, left and right, hemispheres and is covered by a neural cortex called the cerebral cortex. As the cerebrum is the central hub for “conscious thoughts, sensations, intellect, memory, and [the origins of] complex movements” (Martini 1998 p. 445), this region of the brain has been the focus of BCIs.

2.3.4 Functional areas of the cerebrum

The cerebral cortex has four main lobes, on each hemisphere, that serve different functions. As per Figure 2-2, these lobes include the frontal, parietal, occipital and temporal lobes (Martini 1998). The frontal lobe is associated with higher order thinking skills and voluntary skeletal muscle control. The parietal lobe relates to “conscious perception of touch, pressure, vibration, pain, temperature, and taste” (Martini 1998, p.459). The occipital lobe is associated with the interpretation of visual stimuli. Finally, the temporal lobe is related to interpreting auditory and olfactory stimuli (Martini 1998).

The human brain depends on electrical events generated by billions of neurons. This activity creates an electrical field, which is measured via electrodes placed on the skull or brain (Martini 1998). It is noteworthy, that these electrical events are attenuated by the skull, which implies that great numbers of electrical events are needed to generate a recordable signal (Sanei & Chambers 2009).

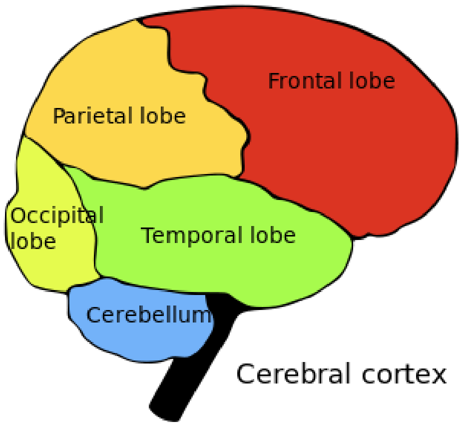


Figure 2-2: Lobes of the cerebral cortex (Irving et al. 2007).

2.4 EEG

Electroencephalography, most commonly referred to as EEG, is a technology based on substantial research and evidence (Tatum et al. 2008). EEG measures neural brain activity, which usually corresponds to the brain's two lowest functional levels (Dietmar et al. 2010). It is a technology that has been in use, in both clinical and research settings, for decades (Tatum et al. 2008). Moreover, it is a lightweight, inexpensive technology that is easy to apply (Tatum et al. 2008). EEG has high temporal resolution, which is useful for detecting changes within certain time intervals (Tatum et al. 2008).

Using a galvanometer, the initial discovery of the brain's electrical activity is attributed to Richard Caton (1842-1926). His published works exhibited experiments using dogs, apes and other animals. Caton found, when measuring currents from the external surface of the skull of animals, that "electric currents of the grey matter appear to have a relation to its functions" and that "[when] any part of the grey matter is in a state of functional activity, its electric current usually exhibits negative variation" (Caton 1875). Vladimir Pravdich-Neminsky (1879-1952), a Ukrainian physiologist, undertook further research of mammalian brains and the concept of evoked potential (refer to section 2.6.3.4.1). The pioneering work from these researchers, in particular Caton, provided Hans Berger (1873-1941) with the foundation to expand on EEG knowledge and apply its first usage with human subjects.

Berger, a German physiologist and psychiatrist, invented the electroencephalogram, the first human EEG recording. He discovered various brain rhythms associated with different human activities. One rhythm in particular, the alpha wave rhythm, has been coined Berger's wave in tribute to his discovery (McFarland & Wolpaw 2011).

2.4.1 Usage – past, present, future

EEG technology has had both clinical and research usages. For example, in the diagnosis of epilepsy, coma, encephalopathies, brain death, tumors, stroke, and focal brain disorders (Tatum et al. 2008). Additionally, seizure prediction has been a focus of long-term EEG recordings (Tatum et al. 2008). One more recent usage of EEG is with neurofeedback research, which aims to recondition and retrain brain rhythms (Hammond 2006) using BCI technology. Future anticipated usages of EEG include military communication between soldiers, robotic control and further in-home applications of BCIs.

2.4.2 Brain rhythms

EEG signals can be divided into wave or rhythmic patterns relating to particular signal frequencies most prevalent during particular human activity.

Table 2-3 below shows the relationship between frequency bands, brain anatomical location and human activity. In general the brain wave patterns are categorized as delta, theta, alpha, beta, gamma, and mu bands (Hammond 2006). These EEG bands are measured in Hertz (Hz); that is in cycles per second.

It is important to note that humans have various components of each EEG band present in the brain (Hammond 2006). The degree to which these bands exist depends on the user's 'state' of mind. For example, if the user's mind is wandering then more theta waves will be present as opposed to an anxious person who may display more beta brain waves (Hammond 2006).

Table 2-3: Rhythmic activity of the human brain (Hammond 2006; Tatum et al. 2008; Pfurtscheller & da Silva 1999; Kirmizi-Alsan et al. 2006).

Wave Type	**Frequency (Hz)**	**Anatomical Location**	**Activity**
Delta	Up to 3.5	Frontal lobe in adults; waves with high amplitudes	Adult slow wave sleep; some continuous attention tasks
Theta	4 to below 8	Not located in positions related to activity	Drowsiness; idling; active repression of an action or response
Alpha	8 to 12	Posterior head regions; higher amplitude on dominant side	Relaxed; reflection; closing eyes; inhibition control
Beta	>13 to 30	Both sides of brain (symmetrical), evident at front; low amplitude waves	Alert; working; active; busy; anxious thinking; active concentration
Gamma	30 to 100+	Somatosensory cortex	Perception that combines two different senses; short term memory matching of recognized objects, sound, tactile sensations`
Mu	8 to 13	Sensorimotor cortex	Shows rest state motor neurons

2.4.3 Wave patterns

When depicting the various EEG bands, there are some important distinguishing features between them (see Figure 2-4 below). Delta waves are depicted by high altitudes and slow changing patterns (Hammond 2006). Normally, these delta waves are experienced during sleep. Beta waves are depicted as fast and small. These are associated with high alertness and outward-focused concentration (Hammond 2006). Berger named the first wave he saw the **alpha** wave. The alpha waves are larger and slower than beta waves and are associated with a relaxed brain state. Theta wave frequencies lie in between alpha and delta waves and are associated with a very relaxed, almost drowsy state (Hammond 2006). Mu waves cross over with other frequencies but are generally associated with the sensorimotor cortex, which specifically pertains to physical movement and sensation (Dornhege et al. 2007). Gamma waves have a high frequency pattern and are often associated with combined neuronal populations working together to perform a particular cognitive or motor task.

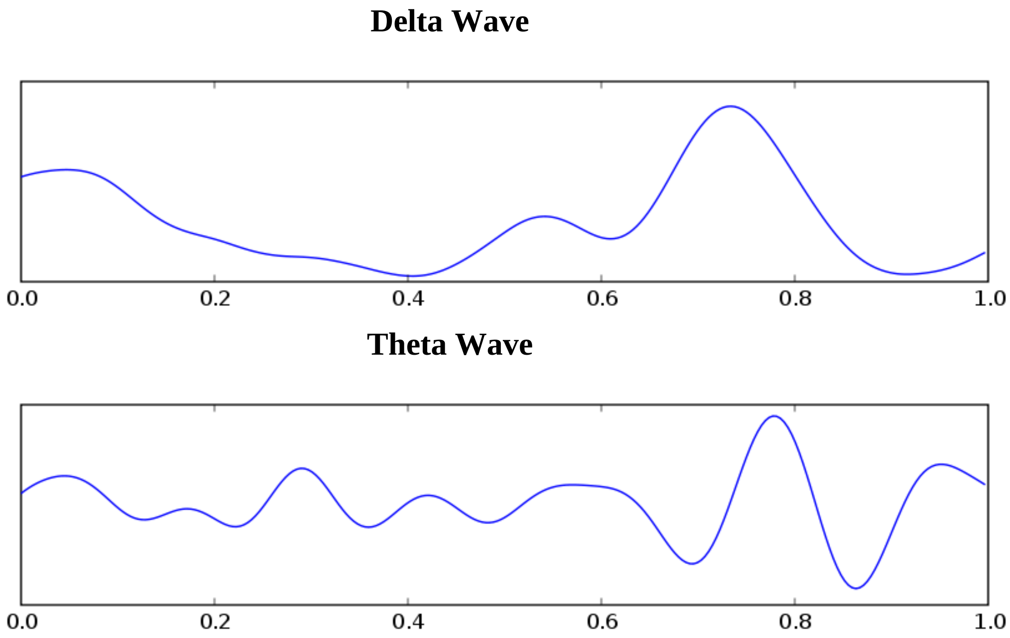


Figure 2-3 Wave patterns of EEG bands (Gamboa 2005).

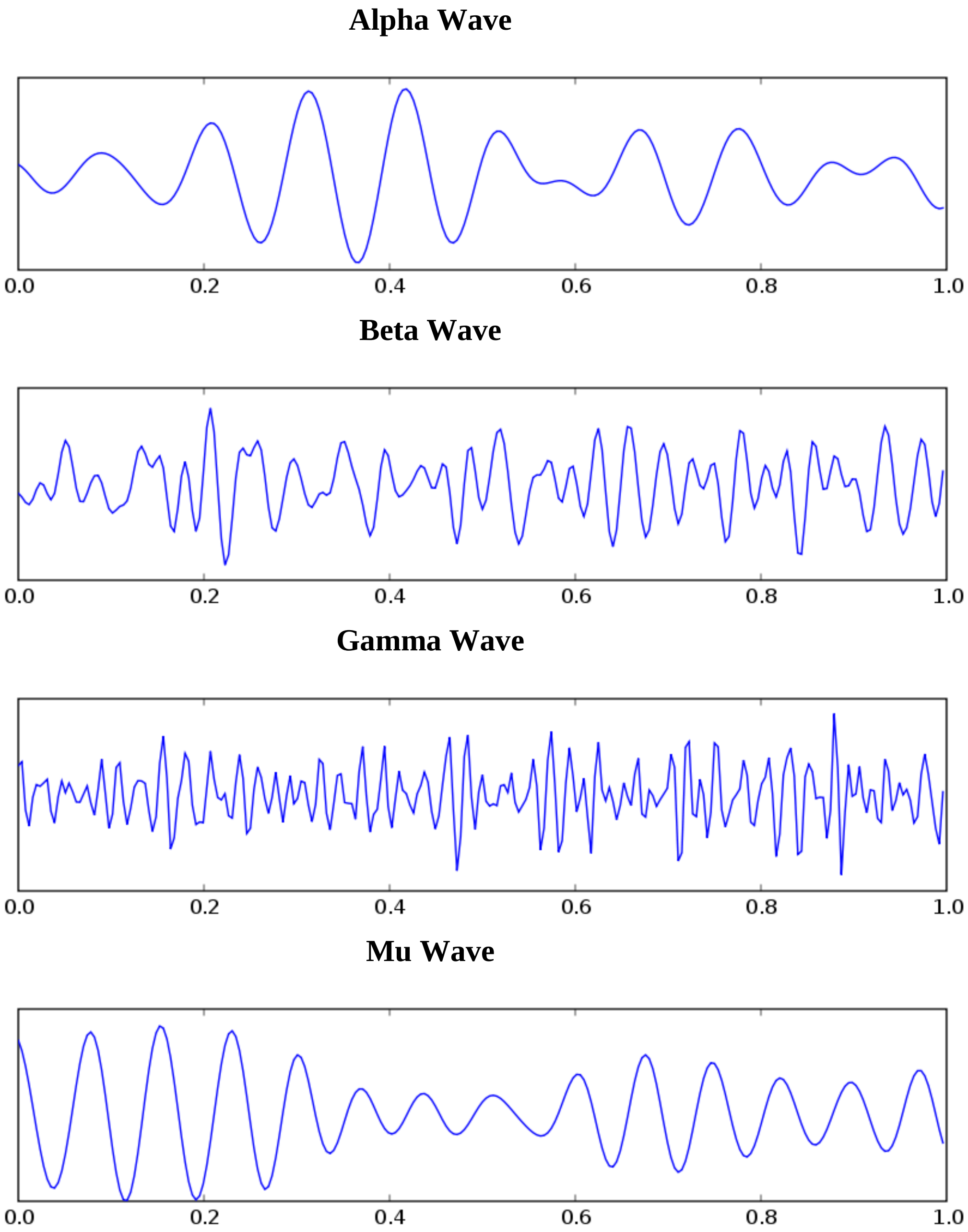


Figure 2-4 Wave patterns of EEG bands (Gamboa 2005).

With consideration to Figure 2-4 above, it is important to note that the normal EEG varies by age, abnormalities and state.

2.4.4 Limitations and artifacts

One of the disadvantages of EEG is that it is difficult to interpret the array of mixed signals that are measured (Dietrich et al. 2010). Moreover, EEG is known to have limited spatial (topographical) resolution and frequency range (McFarland & Wolpaw 2011; Tatum et al. 2008).

Due to the nature of EEG, it is susceptible to a range of biological and environmental artifacts. Biologically, EEG artifacts can be influenced by eye, heart, tongue and muscle related activity. Eye blinking (see Figure 2-5) and eye vertical movement, are particularly, known to have a significant effect on EEG recordings (Dornhege et al. 2007; Tatum et al. 2008). Environmentally, electrodes settling, poor EEG electrode grounding, and presence of IV drips can cause interference with EEG signals (Tatum et al. 2008). Other artifacts within this category, called system artefacts, include interference from power supply, impedence disturbance, cable faults, and electrical noise (Sanei & Chambers 2009). A number of independent component analysis techniques have been developed to remove EEG artifacts (Dornhege et al. 2007).

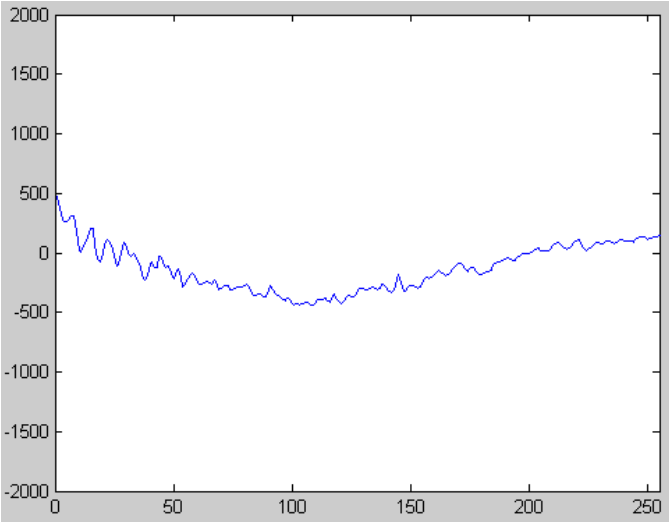


Figure 2-5: Artifact noise resulting from eye blinking.

2.4.5 EEG measurement

Sanei & Chambers (2009) state that an "EEG signal is a measurement of currents that flow during synaptic excitations of the dendrites of many pyramidal neurons in the cerebral cortex" (p. 7). As has been discussed in detail above (refer to section 2.3), currents flow within dendrites belonging to neurons. These currents produce an electrical field that is captured by EEG systems (Sanei & Chambers 2009).

2.4.6 EEG recording methods

As indicated earlier (refer to section 2.2 above), brain signals can be recorded using EEG, MEG, or fMRI technologies (Sanei & Chambers 2009). These technologies represent changes in function and physiology. Each technology has its respective advantages and limitations. More generally, fMRI and MEG are restricted to laboratory use and quite expensive. fMRI technology can be useful to investigate specific research questions in terms of the "location of sources of brain activity and alteration of brain activity in diseases" (Kubler & Muller 2007). Nevertheless, fMRI's time resolution is very low as compared with EEG where the complete bandwidth is seen. EEG is a very portable and cheap technology. However, EEG has the disadvantage of having a low spatial resolution, which corresponds in part to the number electrodes used for recording (Sanei & Chambers 2009) as well as the high impedence effect of the skull (Sanei & Chambers 2009).

Initially, EEG recordings were made using galvanometers and at one point the string galvanometer was the standard photographic recording device (Sanei & Chambers 2009). Later on EEG recordings were made with electrodes connected to amplifiers, then filters and finally a needle style register (Sanei & Chambers 2009). The latter allowed for multichannel recordings to be plotted on graph paper. More recently, it was realized that in order for EEG signal analysis to occur, the analogue signal would need to be converted to digital form for use with computerized systems (Sanei & Chambers 2009). Sanei & Chambers (2009) state that this conversion is undertaken by multichannel analogue-to-digital converters (ADCs).

EEG signals are measured in micro (μ) volts and are usually sampled with a minimum frequency of 200 samples per second as their effective bandwidth is about 100 Hz (Sanei & Chambers 2009). Signals are amplified before being converted to digital form in order to retain the signals' information (Sanei & Chambers 2009). A filter is used, before or after conversion, to minimize the effect of noise so that appropriate signal processing can occur. For example, a highpass filter is used to eliminate very low frequency components as found in breathing. A lowpass filter is used to mitigate high-frequency noise. Finally, in many situations a notch filter is used eliminate the 50 Hz frequency of the power supply (Sanei & Chambers 2009).

2.4.7 EEG Electrodes

Various electrodes are used to record brain signals as per section 2.4.5 above. The types of electrodes used include disposable electrodes (no gel or pre-gelled), reusable disc electrodes (gold, silver, stainless steel, or tin), headbands, electrode caps, saline-based electrodes and needle electrodes (Sanei & Chambers 2009).

2.4.7.1 Electrode Positioning

The 10/20 system is an international standard for describing the positioning of scalp electrodes in EEG testing (Niedermeyer & da Silva 2004). This standard was recommended by the International Federation of Societies for Electrocephalography and Clinical Neurophysiology (Sanei & Chambers 2009). The standard facilitates reproduction and comparison of studies conducted with various subjects over time. Each electrode position is labelled according to its underlying lobe and hemisphere location (see Figure 2-6 below). For example, the letters F, T, C, P and O are the first letters of the lobe names frontal, temporal, central, parietal and occipital. Odd numbering is used for electrodes on the left hemisphere and conversely, even numbers are used on the right (Niedermeyer & da Silva 2004).

Two anatomical landmarks are used as reference points for electrode positioning (Niedermeyer & da Silva 2004). These include the position between the forehead and nose (nasion) and the position at the lowest part of the skull on the back of the head (inion).

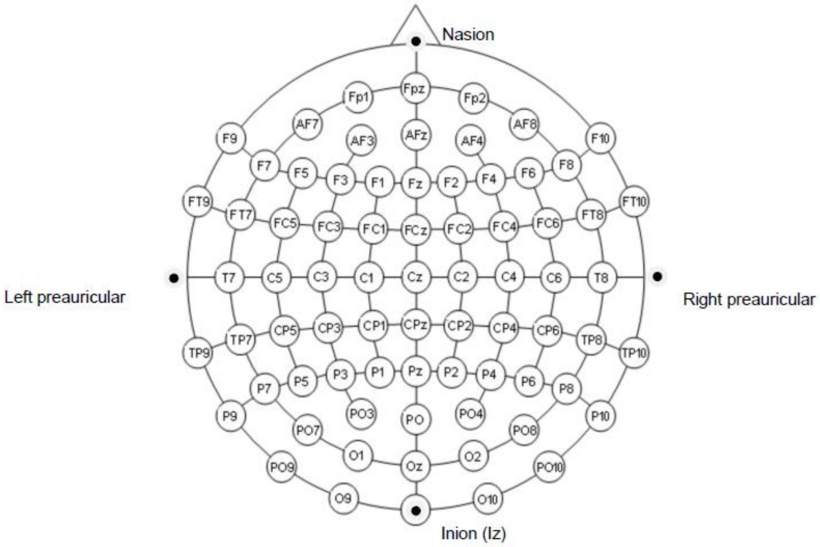


Figure 2-6: 10/20 electrode positioning system (g.tec medical engineering n.d.).

2.4.8 EEG considerations

Recording, measuring and interpreting EEG signals is a complex process. This process not only considers biological and environmental factors relating to the healthy individual but also abnormal patterns occurring for a range of reasons. Sanei & Chambers (2009) classify abnormal patterns into three categories as follows: “widespread intermittent slow wave abnormalities”, “bilateral persistent EEG”, and “focal persistent EEG” (pp 20-21). These relate to artifacts such as eye closure, impaired conscious reactions, or some type of cerebral disturbance, respectively (Sanei & Chambers 2009).

Another consideration is that of ageing. As people age their number of neurons reduce – large neurons diminish and small neurons increase in number (Sanei & Chambers 2009). This pathology is often attributed to a reduction in blood flow in the cerebrum (Sanei & Chambers 2009). These physical changes will inevitably affect the type of brain signals experienced compared with normal recordings from younger individuals.

A third consideration is mental disorders. These disorders include conditions such as dementia, epilepsy and psychiatric disorders (Sanei & Chambers 2009). Such disorders often involve a physical change in the structure of the brain.

Other considerations include external effects such as drug use, watching television or listening to music. These effects have been shown to affect the normal EEG signal pattern (Sanei & Chambers 2009).

2.5 BCIs

Brain computer interfaces (BCIs) can be categorized into three areas of research. These areas include invasive BCIs, partially-invasive BCIs and non-invasive BCIs. Invasive BCI research involves the implantation of electrodes directly into the grey matter of the human brain. These devices have a higher spatial resolution than their counterparts (Dornhege et al. 2007). However, little evidence exists to determine the long-term effects of electrode implantation in the brain (McFarland & Wolpaw 2011). Moreover, additional considerations relating to corrosion and integrity of electrode materials have to be made.

Partially-invasive BCIs are not embedded within the brain matter but rest underneath the skull. Once again they have a better resolution than non-invasive BCIs. Partially-invasive BCIs use electrocorticography (ECoG) technology, which measures electrical activity underneath skull (Dornhege et al. 2007).

Non-invasive BCIs are the most popular form of BCI technology. Electrodes are placed on the outer edge of the skull. Due to its positioning, non-invasive BCIs are subject to environmental and biological artifacts and have a lower spatial resolution than other BCI technologies (as discussed in section 2.4.4 above). Non-invasive BCIs have been commonly used with EEG technologies. New research is being conducted into the benefits of other technologies such as Functional Magnetic Resonance Imaging (fMRI), Magnetoencephalography (MEG), Positron Emission Tomography (PET), and Functional Near Infrared (fNIR) (Allison 2009; Pantazis & Leahy 2006). Nevertheless, as described earlier (refer to section 2.4), EEG remains to be a well established method for clinical and research use.

2.5.1 BCI standards and legislation

The Australian Standards of particular relevance to this research include:

- AS/NZS 3200.1.0:1998 Medical electrical equipment. Part 1.0: general requirements for safety – Parent Standard
- AS/NZS 3200.2.26:2005 Medical electrical equipment: Particular requirements for safety – Electroencephalographs

AS/NZS 3200.1.0:1998 details the general safety requirements for medical electrical equipment. Whilst it is considered that the commercial BCI is more likely to be used in the home environment, adherence to safety requirements in this Standard provides a suitable baseline to ensure the safety of the user. One particularly relevant guideline of this Standard is the protection against electrical shock hazards.

AS/NZS 3200.2.26:2005 emphasises that EEG equipment must have body floating (BF) and/or cardiac floating (CF) applied parts. An applied part is that part of the equipment that comes in contact with the user. As the type names suggest, these applied parts are considered to be floating and should be separated from earth.

From an international perspective, relevant standards include:

- IEC 60601-1-1 Ed. 2.0 (Bilingual 2000) Medical electrical equipment - Part 1-1: General requirements for safety - Collateral standard: Safety requirements for medical electrical systems
- IEC 60601-2-26 Ed. 2.0 (Bilingual 2002) Medical electrical equipment - Part 2-26: Particular requirements for the safety of electroencephalographs
- I.S. EN 60601-2-26:2003 Medical Electrical Equipment - Part 2-26: Particular Requirements For The Safety Of Electroencephalographs
- BS EN 60601-2-26:2003 Medical electrical equipment. Particular requirements for safety. Particular requirements for the safety of electroencephalographs
- I.S. EN 60601-2-26:2003 Medical Electrical Equipment - Part 2-26: Particular Requirements For The Safety Of Electroencephalographs
- JIS T 1203:1998 Electroencephalographs

When Australian Standards are viewed in conjunction with international standards, it is seen that electrical safety is not considered to be dependent on voltage, but on leakage currents (AS/NZS 3200.1.0:1998; IEC 60601-1). One approach used to implement safety in medical electrical equipment is through circuit separation. Some commercial BCI devices, such as the Emotiv, already meet this standard by design (refer to section 2.5.6 below).

In Australia, relevant legislation pertaining to BCIs is covered by the Workplace, Health & Safety Act 1995 and the Electrical Safety Regulation 2002.

2.5.2 Classification of equipment

With reference to international classifications, the commercial BCI can be regarded as a class III medical device “in which protection against electric shock relies on supply at safe extra-low voltage (SELV) and in which voltages higher than those of SELV are not generated” (Al-Nashash 1997, p. 18). Some BCI devices can further be categorized as BF types of medical equipment, which encompass floating isolated applied parts. For example, the Emotiv EPOC

> “uses a very low-power wireless chipset which operates in the 2.4GHz band (Bluetooth and WiFi also work in this band). [It uses] less power than Bluetooth earpieces, and the headset antenna is located on the outer surface of a 2-stack screened PCB about 20 mm from the skin surface, in the right front pod. [It is estimated that] the skin exposure level is approximately 1000 times less than a Bluetooth earpiece which is usually mounted against the skin. [The EPOC has undergone] emission testing against US FCC Part 15 Standards and [complies] with all emission limits with a substantial safety margin.” (Emotiv 2010, p.1).

Others devices may be categorised as type B devices. These are indicated as having adequate protection against electric shock but may need to be modified to BF standard to meet current Australian Standards for medical equipment safety.

2.5.3 BCI components

The basic BCI is comprised of four components. These include signal acquisition, feature extraction, translation algorithm and an operating environment (Wolpaw et al. 2002).

2.5.4 BCI systems

Current trends in BCI development have focused on 3 main BCI systems including sensorimotor rhythms, P300 evoked potential, and cortical neuronal activity (McFarland & Wolpaw 2011). Sensorimotor rhythms produce signal amplitudes in relation to imagined movement or change of movement. With respect to EEG waves discussed above, sensorimotor rhythms pertain to mu (μ) waves.

P300 systems respond to spikes elicited by user response to the presentation of a stimulus (Dornhege et al. 2007). These systems have been successfully used with communication applications such as recognition of the next letter to type when it is flashed on screen. To date, the P300 response has been effectively implemented with visual and auditory stimuli (Alwasti et al. 2010).

Cortical neuronal systems involved recording of implanted electrodes. They are able to "detect action potentials of single neurons" (McFarland & Wolpaw 2011, p.62). In practice, the user can learn to control the firing rate of neurons to elicit an action such as cursor control.

2.5.5 Approaches to BCI design

Typically, there have been three approaches to BCI design in the past. Early devices required the user to adapt to the system and often took months of training to develop reliable usage. This approach is termed operant conditioning (McFarland & Wolpaw 2011). A second approach, called machine learning (Dornhege et al. 2007) places the onus of 'learning' on the machine. The machine is required to adapt to the user. A third approach to BCI design is termed optimized co-adaptation. In this latter approach, both the machine and user adapt and learn for more efficient operation and reduce demands placed on the user (McFarland & Wolpaw 2011).

2.5.6 Commercially available BCIs

A number of commercially available BCIs have been recently developed for the mainstream gaming community. Currently, the devices in existence include the OCZ Neural Impulse Actuator, the NeuroSky Mindset, the Star Wars Force Trainer, MindFlex, Emotive Systems, and ENOBIO. Zhang et al. (2010) conclude that current commercial BCIs can only provide a low signal-to-noise ratio and are seen to be measuring the volume of noise. As such Zhang et al. (2010) states that current commercial technology is not sensitive enough to provide fine control such as is required to control a robotic device.

2.5.7 Limitations of EEG-based BCIs

Mak & Wolpaw (2009) outline a number of limitations of EEG-based BCIs. It can be seen that placing electrodes on the outer skull will have impact on the strength and spatial resolution of EEG signals. As such, non-invasive BCIs may have weak signals and limited frequency range (Mak & Wolpaw 2009). Current BCI systems to date require intensive user attention and can lead to fatigue. Moreover, many non-invasive BCI technologies are inconsistent in performance. Many laboratory-based BCIs require the user to use a large series of commands, which is user intensive (Mak & Wolpaw 2009). With respect to invasive BCIs, there is no long-term research support for the viability and safety of managing implanted devices in the brain (McFarland & Wolpaw 2011).

EEG-based BCIs are subject to biological and environmental artifacts that impact upon brain signal recordings. As BCI systems have been predominantly research focused there is need for standardization of BCI systems to minimize complexity and address ongoing needs for technical support (Mak & Wolpaw 2009). Additionally, most-laboratory based BCIs are unappealing and lack aesthetic value for the general user. It is important to note that BCIs also need the robustness to function in complex and unstable environments like people's homes, in order to be viable (Mak & Wolpaw 2009; Sellars et al. 2007).

Many BCI systems have used wet electrodes in the past, which require preparation and time-consuming application. Current research is investigating the value of using dry, capacitance-based electrodes (Mak & Wolpaw 2009). This approach would also ease the burden of use for carers who would inevitably be involved in the process of applying electrodes, troubleshooting EEG signal quality and operating BCI software (Mak & Wolpaw 2009).

Current in-home implementation has been limited to simple communication and environmental control applications targeting people with severe disabilities (Mak &

Wolpaw 2009). There is much scope for improvement in bringing the BCI out of the laboratory into the home and increasing the commercial interest of the general population.

Dietrich et al. (2010) poses that electromagnetic artifacts and skin/sensor related resistive and capacitive nonlinear variations are also important BCI challenges.

2.6 Signal processing

Brain signals carry information represented as time-varying quantities (Leis 2002). As such signal processing, with respect to BCIs, is concerned with extracting relevant features from these signals and translating these features into logical controls for use in an application (Alwasiti et al. 2010). Signal processing draws from the fields of mathematical analysis and algorithms (Leis 2002). To date, many algorithms have been developed to process EEG signals such as multiway processing, frequency-domain analysis, time-domain analysis and spatial-domain analysis (Sanei & Chambers 2009). Signal processing of BCI signals can be use to model neural activities, localise brain signals, and monitor particular conditions such as epilepsy, to name a few (Sanei & Chambers 2009).

2.6.1 EEG signal modelling

Hodgkin and Huxley have provided a foundational model from which current signal models have been generated, as seen in Figure 2-7 below. Their squid axon model demonstrates a functional understanding of the electrical excitation of the brain’s nerve axon. This model has been adapted by the Simulator for Neural Networks and Action Potentials (SNNAP) to reflect current practice in physiology (Sanei & Chambers 2009).

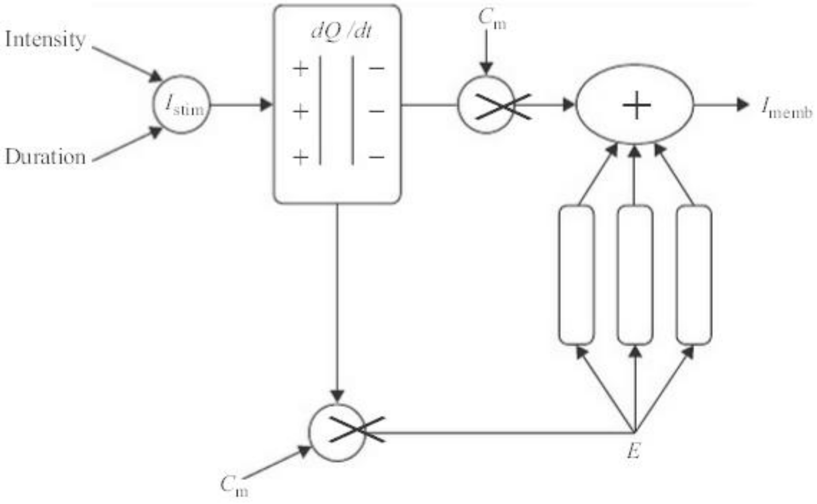


Figure 2-7: Hodgkin and Huxley excitation model (Sanei & Chambers 2009).

One simple model that has been devised is the Morris-Lecar model (Sanei & Chambers 2009), which represents a reduced biophysical model down to a single action potential. As signal modelling is quite a complex area of research, it is beyond the scope of this research.

2.6.2 Nonlinearity of the EEG signals

It is important to reiterate that EEG signals are produced by an array of localized neurons at the site of the measuring electrode. The human brain is subject to various "biological and physiological phenomena" (Sanei & Chambers 2009, p. 50) so that its system is best described as nonlinear. Concepts drawn from chaos theory and dynamic analysis have proven helpful to analyse and model the brain system (Sanei & Chambers 2009). However, no single person or group have successfully provided a complete model of the complex brain system.

2.6.3 EEG Components

There are several EEG components that are used in BCIs (Alwasiti et al. 2010). These EEG components can be divided into four separate categories, namely neuronal potentials, slow cortical potential (SCP), oscillatory EEG activity, and event related potentials (ERP).

2.6.3.1 Neuronal potentials

Neuronal potentials provide two dimensional control of a BCI in terms of the neuron's location and its rate of firing. Voltage readings are taken from a single neuron (Alwasiti et al. 2010). This category is connected with invasive BCI options due to its reliance on having a high spatial resolution.

2.6.3.2 Slow cortical potential (SCP)

SCPs are related to the synchronization between dendrite potentials. Higher synchronisation represents a negative SCP and conversely a lower synchronisation represents a positive SCP (Alwasiti et al. 2010). It has been demonstrated that humans are able to regulate their individual SCPs (Hinterberger et al. 2007). However, trials in BCI communication have shown this component to be relatively difficult to master with respect to accuracy (Hinterberger et al. 2007).

2.6.3.3 Oscillatory EEG activity

Of particular relevance to BCI systems is the oscillatory EEG activity as seen in "the mu-rhythm (10 to 12 Hz) and the central beta rhythm (14 to 18 Hz)" (Alwasiti et al. 2010, p. 821). These oscillations are associated with the sensorimotor cortex and have been termed sensorimotor rhythms (SMR). SMR have been shown to provide a high degree of accuracy (up to 81%) for subjects (Hinterberger et al. 2007). Nevertheless, this category requires training on the part of the user.

2.6.3.4 Event-related potentials (ERP)

Event-related potentials (ERP) pertain to brain signal response as a direct result of perception or thinking patterns. ERPs are able to reflect signals associated with higher order processes such as attention, memory, anticipation, and change in mental state

(Dornhege et al. 2007). Once an event has occurred, these potentials ensue after a fixed time.

2.6.3.4.1 Evoked potentials

Evoked-potentials are electrical recordings using EEG in response to the presentation of a stimulus (Dornhege et al. 2007). These potentials are considered to be exogenous ERP. The user controls the BCI by changing their focus between various stimuli.

2.6.3.4.2 P300 Events

The P300 is considered to be an endogenous event. A positive signal is displayed 300 ms after the onset of an event (Alwasiti et al. 2010), as per Figure 2-8. Research has shown this component to demonstrate the most efficiency for the user and requires no training (Hinterberger et al. 2007). An event can exist in the form of any particular stimulus, however, visual and auditory stimuli have been shown to be effective in trials (Hinterberger et al. 2007; Sellars & Donchin 2006).

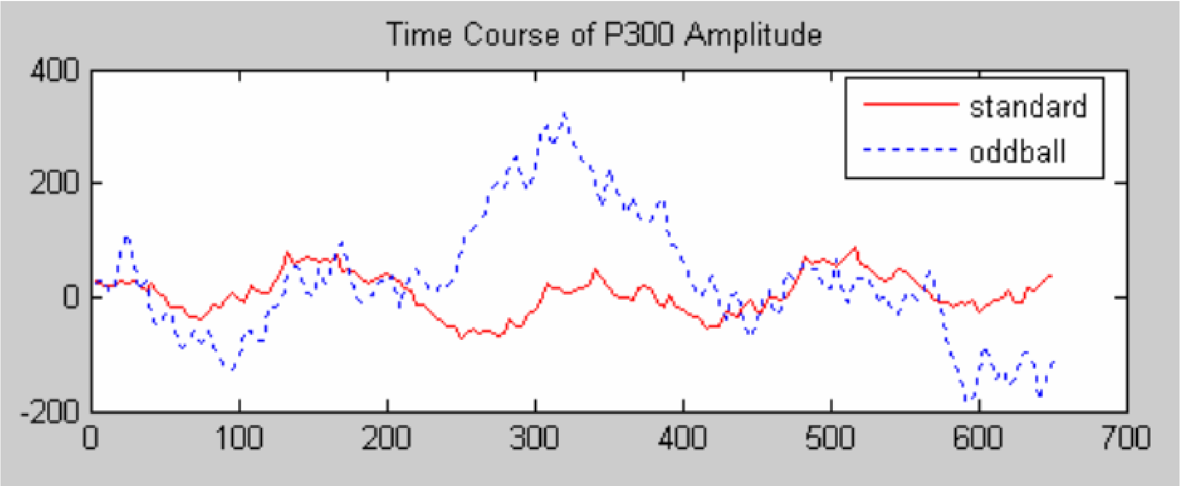


Figure 2-8: P300 response depicted by rise in amplitude approximately 300 ms post stimulus (Goel & Brown 2006).

2.6.4 Source localization

The human brain is comprised of different anatomical landmarks that exhibit electric current or magnetic field when activated (Sanei & Chambers 2009). If further understanding of brain function is to be gained, the study of brain signal source localisation can assist. In fact, this area of learning has been under investigation over the past two decades (Sanei & Chambers 2009). As has been discussed (refer to section 2.4.4), EEG provides a low spatial resolution. As such the relative number of sources remains undetermined, further compounding the difficulties faced with EEG source localisation. Some algorithms have been developed for source localisation including the ICA method, MUSIC algorithm, LORETA algorithm, FOCUSS algorithm, standardised LORETA, and partially constrained BSS method, to name a few (Sanei & Chambers 2009). Source localisation has the potential to significantly improve the functioning of BCIs. However, due to its complexity, it is beyond the scope of this research.

2.7 Human factors

One of the key components of a BCI is that it operates by user intent. However, matching user intent to a required action is a challenging endeavour. Not only are there inherent brain pattern differences between users (Dornhege et al. 2007), research also shows that the same users brain pattern varies considerable (Dornhege et al. 2007). Factors such as alterness, time of day, learning effect, quality of sensor connection and others can affect the BCI signal. Further research into calibration methods and machine learning algorithms may help to bridge the gap towards greater signal consistency.

2.8 Existing Software for BCI Testing and Analysis

Some software tools and applications have been developed for the testing and analysis of EEG signals for real-time BCIs. These have been summarised in terms of license, programming language used, and operating system requirements in

Table 2-4 below.

Table 2-4: Software tools available for EEG analysis (Schlögl et al. 2007).

Package	License	Language	Requirements
BCI2000	?	C++	Windows
Bioelectromagnetism	GPL	Matlab	Matlab
BioSig	GPL	Octave, Matlab, Simulink, C/C++, Qt, Java, Python	Various
EEGLAB	GPL	Matlab	Matlab(5+)
EMEGS	GPL	Matlab	Matlab(6+)
FieldTrip	GPL	Matlab	Matlab
LORETA	?	Unknown	Windows
OpenEEG	GPL	Various	Various

2.8.1 BCI2000

BCI2000 is a cross-platform compatible software application developed for BCI research and development (BCI2000 2011). BCI2000 aims cater for any BCI system and most BCI methods and disseminate the project to different laboratories. Thereby, BCI2000 endeavors to reduce time, cost and effort spent testing novel BCI methods. BCI2000 is comprised of four modules for BCI modeling including: “signal acquisition, signal processing, user feedback and operating protocol” (Mellinger & Schalk 2007).

2.9 Ethical Considerations

The field of BCI research is not without its concerns. With the advent of BCI technology and its benefits, a number of ethical considerations are raised and should be addressed. One issue is how to obtain consent from people who do not have clear channels of communication. It is important that the rights of people to refuse assistance are respected. Similarly, the severely physically disabled person may relish the idea of being able to communicate but has never had the opportunity or has lost this ability, for example, people with ALS.

Appropriate risk versus benefit analysis should be conducted with the implementation of BCI technology. For example, does the BCI cause unnecessary strain, stress and user fatigue even though a user may be able to use the device to communicate. Moreover, does the device add to the burden of care or enhance the work of carers. It is important to note that BCI technology is a shared responsibility of teams including health professionals, engineers, family, carers and users.

Whilst there are no known side-effects of non-invasive BCIs, there is no evidence for long term implantation of devices in invasive BCIs (Wolpaw et al. 2002). Moreover, some people may have allergies to the gel used on electrodes. At this time, there is no longitudinal data showing the long-term effects of using the brain as a sole form of control. For example, what effect does the BCi have on personality and personhood through long-term neurofeedback modification of brain signals. It is also possible that BCI technology can promote inactivity for healthy mainstream users and thus contribute to declining health standards.

Another consideration is therapeutic applications and understanding where clear boundaries exist between ethical and non-ethical practice.

As invasive technologies gain popularity, ethical considerations should be made as ‘experimentation’ moves from animal subjects to human subjects. In early stages of many technologies, experimentation is a part of the learning process as many factors are unknowns. However, by using people, who are already disadvantaged in some way, as test subjects poses ethical concerns for the general community.

It is not only the immediate benefits of BCI technology that need to be taken into consideration. Future possible applications need to be carefully anticipated and reviewed. For example, use of BCI technology to invade human privacy or even as an active device to control a subject in some way rather than allowing the user full control as is current practice.

The engineering considerations with respect to BCI also need to be made with respect to the Code of Ethics standards. This code provides guidance in the demonstration of integrity, competent practice, the exercising of leadership and the promotion of sustainability (Engineers Australia 2010). BCI technology applications must be guided by these principles for the well-being of the general community and environment.

2.10 Conclusion

This chapter has provided a thorough grounding the in study and implementation of BCI solutions. Ethical considerations should be adhered to with respect to future development in this area. Particular signal processing and machine learning algorithms are beyond the scope of this project.

Chapter 3 Designing a Robust and Reliable BCI Solution

> *"The whole of science is nothing more than a refinement of everyday thinking".*
> *- Albert Einstein*

3.1 Introduction

Previous chapters have described the brain-computer interface (BCI) model (refer to section 2.5 above) and discussed the context for it use. From these chapters the reader may have gained increased insight into the workings of the human brain, the types of brain signals that are produced, the various methods for acquiring brain signals, and the related signal processing methods used to extract and translate relevant signal features for use with an application. In this chapter the research methodology that was used to test and evaluate BCIs is discussed in detail.

With reference to the project aim (section 1.2), this research can be further broken down to ask two general questions:

1. Is it possible…?
2. And if so, how?

The first of the two questions explores the notion of the potential to produce a reliable BCI solution that is to be used in a home environment. This question evidently requires some form of testing and evaluation in order to 'prove' the feasibility of the project aim. Moreover, proof is ascertained through appropriate evaluation against a set of predetermined criteria. These criteria and the concept of what constitutes a reliable solution for this research is further discussed in section 3.4 below.

The second question necessitates a practical outlook using sound principles established by evidence-based practice and supplemented by observations made during BCI testing and evaluation. Importantly, if the first question proves to be false, the latter will explore what requirements, if any, are necessary to make the project possible.

The following sections discuss the selected research methodology and justification of the same. Relevant advantages and limitations of the project methodology are outlined. Furthermore, the structure of a robust and reliable solution is discussed as a reference point for project ‘success’. Moreover, an evaluation of commercial BCIs is made to describe selected devices chosen for this research. Suggestions for improving commercial BCIs are discussed with respect to project outcomes. Additionally, ethical considerations made during BCI testing and evaluation are presented.

3.2 Research methodology

One of the main objectives (refer to section 1.3) of this research is to determine the potential or feasibility of a BCI solution for the home environment. In this regard, a deductive methodology was chosen. A deductive research method sets out to prove a theory (Heffernan 2008; Burney 2008). With respect to BCIs, the hypothesis is that commercial BCIs **do** provide a reliable solution for disabled users in their home. The concept of what constitutes a reliable solution is further discussed in section 3.4 below.

The deductive approach takes a top-down perspective working from the general to the more specific (Burney 2008). Applied to this research project, the deductive approach is used to analyse commercially available BCIs systems, leading to evaluation and finally a framework for creation of a reliable BCI solution for in-home usage. This approach reflects growth in knowledge and understanding as the research progresses and is supported by Bloom’s taxonomy of learning (Overbaugh & Schultz n.d.), as depicted in Figure 3-1 below.

Figure 3-1: Bloom’s taxonomy of learning. (Source: Overbaugh & Schultz n.d.)

Further to the deductive research approach, a combination of qualitative and quantitative methods will be considered for comparative analysis of selected BCIs. Gabarino and Holland (2009) describe the importance of considering the relative advantages of both quantitative and qualitative approaches. Quantitative methods can help to describe relationships between data whilst qualitative methods outline “the quality of those relationships” (Gabarino and Holland 2009, p.11). Moreover, the claim is made “that qualitative and quantitative methods and data are often more powerful when combined” (Gabarino and Holland 2009, p.11) in an appropriate manner. Their combination helps to produce better measurement, analysis and/or action. In this project, some information used in evaluation has been obtained by experience whilst other data represent factual, objective results. It is considered that both data types have their place in developing a well-rounded framework for developing a robust and reliable BCI solution.

The following steps outline the process followed towards developing a framework for a reliable solution:

1. Select an appropriate research methodology (as discussed above).
2. Determine key criteria for a robust and reliable BCI solution (refer to Criteria for Evaluation on page 42 below).
3. Research existing commercially available brain computer interfaces.

4. Research existing in-home solutions associated with available BCIs.
5. Evaluate existing BCI devices and associated solutions.
6. Determine appropriate research subjects (if relevant).
7. Determine an appropriate testing and operating environment with respect to both hardware and software considerations.
8. Compare and analyse selected BCI devices with respect to Criteria for Evaluation. Consider advantages and disadvantages, ability to extend and integrate with a reliable application, and additional criteria as outlined in section 3.6 below.
9. Based on results from step 8, develop a framework from which a robust and reliable BCI solution can be built.

3.3 Research design

As discussed in section 2.5.3, the valid BCI system should acquire direct brain signals, provide feedback to the user, operate in real time and function as a result of user intent (Pfurtscheller et al 2010). Figure 3-2 depicts the over-arching BCI model used in this research project.

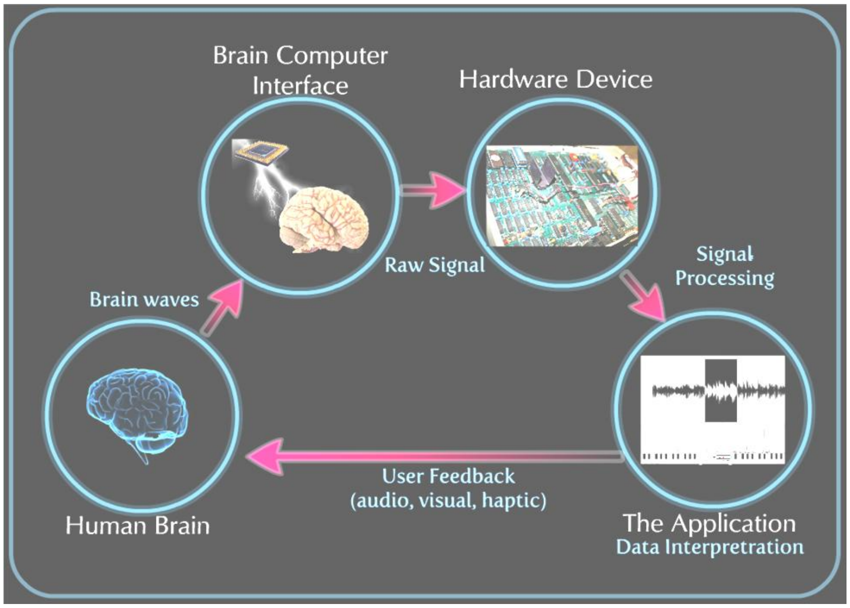


Figure 3-2: Brain-computer interface model

In this model the brain signal source is derived from a single user being the researcher. These signals are acquired through selected brain computer interfaces, as discussed in the "Evaluating commercial BCIs" section below. Raw brain signals (amplified brain signal) are then passed to an operating environment. In this research, the operating environment consisted of a PC running a Windows XP operating system. This system was selected as it is commonly accessible to general users. It is widely used by many users for standard daily operation and access to other relevant applications. Further details of the system specifications are located in Appendix B. A suitable BCI solution can be extended to function in other operating environments and embedded hardware devices.

Once the amplified signals were received by the operating environment, signal processing techniques were applied to extract relevant signal features and translate these for use in an application. The basic process for EEG signal processing is illustrated in Figure 3-3 below. Existing signal processing techniques were used including the P300 evoked potential and in-built algorithms provided by respective BCI SDKs.

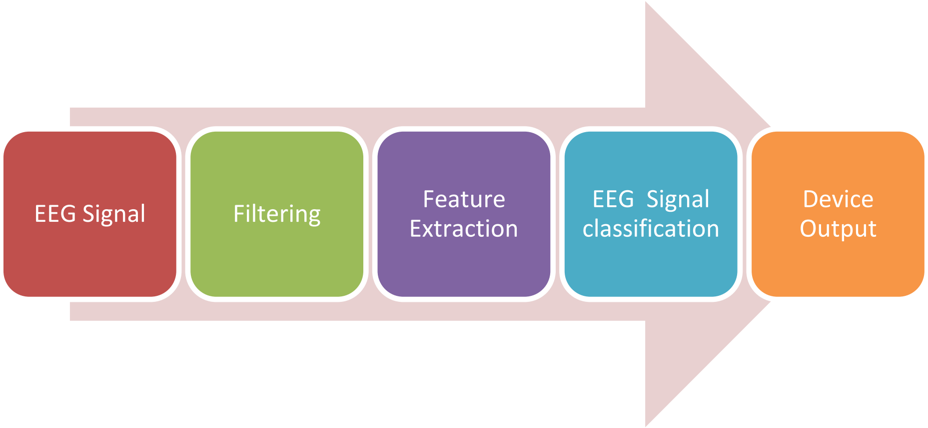


Figure 3-3: BCI signal processing sequence (Redrawn from: Norani & Khuan 2010).

In order to visualize and analyse received brain signals, various software options were explored. Selected software solutions are discussed in chapter 2.

This research focused on developing an application for imagined music. Imagined music is considered to be a new and developing area (Schaefer et al. 2008; Schaefer et al. 2009;

Grierson 2008) for BCIs. To date, in-home BCI solutions have focused on environmental control and communication tools (Sellar et al. 2007). Music has been coined ‘the international language’ (Ball 2005). Moreover, music can be used for pleasure, creation of atmosphere and importantly, self-expression. One way that people with physical disabilities may wish to express themselves is through the art of music. For example, Jason Becker and Ned Mann are musicians with ALS who are passionate about their craft (Hawkins 2009; Varga 2010). These two individuals still have the ability to use eye tracking and head tracking systems, respectively. However, there are many individuals who do not possess the physical capability to use these movement based devices. Using an EEG-based system to enable people to express themselves in music is considered to be both therapeutic and empowering.

Combining both auditory and visual feedback may contribute to a suitable BCI solution, particularly in using an imagined music program for composition. Sellers and Donchin (2006) have shown that auditory-P300 stimuli can be used successfully with people with ALS.

3.4 What is a robust and reliable solution

Reliability is an important requirement in attaining an appropriate BCI solution that can be used in the home. Reliability in this research is defined as the measure of repeatability and consistency that a BCI solution provides with respect to accurately capturing and translating user intent (Trochim 2006b). For example, when a user moves a mouse with their hand to the right it is expected that the mouse cursor on-screen imitate the intent of the user in a consistent manner. A solution would be considered unreliable if the mouse cursor moved in a different direction, moved too fast, did not move at all or a random application opened up onto the desktop screen. In the same way, if a user desires to move that same mouse cursor by soley using the signals from their mind, a reliable solution entails that the cursor can be moved consistently as intended by the user.

A robust BCI solution takes into consideration that the BCI device should operate with persistent characteristic behavior with respect to the user. In practical terms this means that a BCI solution should be resistant to internal and external artifacts that cause the application to operate in any alternate manner to that intended by the user. Moreover, the BCI solution should work consistently irrespective of individual user differences and idiosyncrasies. The latter requires additional research into signal processing methods and machine learning algorithms, which is beyond the scope of this foundational research. Nevertheless, one of the objectives of this research aims (refer to section 1.3) to develop a framework from which a reliable and robust functional application. This is anticipated to be obtained through the testing and evaluation process for selected BCIs.

3.5 Criteria for Evaluation

As discussed earlier, an important consideration made with this research project is what constitutes a robust and reliable solution. In order to evaluate a measure of success, it was deemed crucial to outline some defining elements or criteria as a baseline to compare results. This consideration is particularly relevant as devices are being used in a home environment that exposes BCIs to greater disruption, commonly through noise (Sellars et al. 2007). A reliable solution is necessary if the device is going to have any value for users.

The following criteria were selected as representative of a robust and reliable BCI solution for use in the home environment. An appropriate solution should therefore be:

1. Low cost
2. Reliable
3. User friendly
4. Easy to use
5. Plug and play
6. Non invasive
7. EEG-based

In Australia, 5.2% of working age people receive the Disability Support Pension (DSP) (ABS 2010). Due to the nature of their situation, many people on the DSP have outlay costs for various assistive technologies on top of living costs (Anglicare 2008). Many people rely on funding support in Australia and abroad, for example from the Medical Aids Subsidy Scheme (MASS 2010) and other relevant funding groups. At present there is no funding provision for BCIs as it is a relatively new technology. In consideration of these needs, an appropriate BCI solution was capped at AU$2000.

Reliability has been discussed in section 3.4 above. This is considered to be a key performance criterion and was given greater weighting as described section 3.7 below. An unreliable BCI solution is not suitable for in-home use.

One of the considerations that need to be made with respect to in-home devices is that they need to be user-friendly. This means that a solution should be simple in its setup and maintenance. Additionally, a user-friendly solution should be both portable and safe. Whilst laboratory-based BCIs can be hard-connected via multiple lines and bulky caps with various electrodes can be applied to the user (Dorhenge et al. 2007), this setup is difficult to replicate in the user home environment, needless to say undesirable. For example, the user or carer may not have the time, patience or aptitude for complex BCI setups. Moreover, hardwired connections raise additional issues of electrical safety. Additionally, the user may need to move about the room or home and requires a solution that can easily be removed from the user and replaced as needed.

Ease of use is related to user-friendliness but particularly pertains to operating the BCI solution. Ideally, this means that a solution is run entirely with the use of brain signals. If an on screen popup occurs, the user is required to key in particular words or the application loses active focus, this could be an issue, particularly for those with limited to no physical movement. Whilst carer support can be anticipated, ideally the user should be able to operate their application and operating environment independently. Moreover, carer support may not be provided at full monitoring (24 hours a day, 7 days per week). Further to this, clear and simple instructions for use need to be provided in using the BCI device and its associated applications.

Plug and play is an important criterion for a robust and reliable solution. Whilst basic troubleshooting can be anticipated on the occasion as with other peripheral devices (e.g. mouse), it cannot be assumed that the user or carer has the technical skill or aptitude to resolve inherent BCI issues. Moreover, a solution that requires a user to extend an existing device or system, albeit via hardware or software, is not deemed suitable. This latter consideration has contributed to the elimination of particular devices from this research as discussed in section 3.7 below.

Invasive solutions raise a number of ethical dilemmas with respect to implantation of devices in the brain, long term effectiveness and reliability of embedded devices, and limited research support to date. Both invasive (e.g. IR devices) and partially-invasive (e.g. ECoG devices) solutions were excluded from this research. Moreover, these solutions require surgical intervention, and are not readily available to most users, and can incur increased costs (Wolpaw et al. 2002).

Whilst there are several non-invasive methods for acquiring brain signals or imaging results, the EEG has long been established as a reliable technology. Moreover, technologies such as fMIR and MEG are expensive, laboratory-confined and not portable. These matters have been discussed in detail in section (refer to section 2.6 above).

3.6 Data for comparative analysis

In order to compare the effectiveness and suitability of selected BCIs the Criteria for Evaluation above was further broken down into observable elements for testing. These elements have been outlined in

Table 3-1 below.

Table 3-1: Data for comparative analysis of selected BCIs (Wolpaw et al. 2002).

General Criteria	Specific Criteria	Importance
Low Cost	Under $2000	5
Reliable	Consistency of performance	5
	Speed	4
	Accuracy	5
	Resistance to external artifacts	5
	Resistance to biological artifacts	5
User Friendly	Aesthetics(compactness, design, cosmesis)	2
	Safety	5
	Ease of preparation	4
	Time to setup	4
	Time to calibrate	3
	Time to become operational	4
	Maintenance	3
	Portability	5
Ease of Use	How easy it is to operate BCI	4
	Independent control	5
	Demand for user's attention	4
	Fatigue rating	4
Plug and Play	Convenience	4
	Carer rating	4
	Complexity	4
	Off-the-shelf software base user assistance	3
Non-Invasive	This is evaluated without consideration for technology used for signal acquisition.	5
EEG-Based	Strength of signal	4

	Number of channels	3
	Placement of electrodes	5
	Resolution	4
	Sampling rate	4

A weighted matrix was developed to compare the results. Each criterion was given a weighting of importance as described in

Table 3-2 below. Furthermore, each selected BCI was evaluated on how well they satisfied the weighted criterion, as per Table 3-3 below.

Table 3-2: Weighting of importance of criterion

Weighting	Interpretation
5	Extremely important
4	High importance
3	Medium importance
2	Low importance
1	Very low importance
0	Not important

Table 3-3: Weighting of BCI match to criteria

Weighting	Interpretation
5	Very high criterion match
4	Highly criterion match
3	Moderate criterion match
2	Low criterion match
1	Very low criterion match
0	Does not meet criterion

Selected criteria are explained herewith to provide further clarification of what is being measured. Consistency of performance refers to how well the BCI device in question correctly captures user intent to perform a desired action over subsequent trials. Speed pertains to a time response from the point in time where user intent is elicited to the point in time where the system responds with the required action. Accuracy relates to how closely user intent matches a desired response.

When considering ease of preparation, particular reference is made to the tasks required by the user or carer to perform before and during placement of the BCI device on the user's head. These tasks may include sensor preparation, sensor installation, BCI positioning on onto the user's scalp, and device pairing, to name a few. Time to setup, time to calibrate and time to become operational all refer to the notion that the less time the user has to spend on these tasks the better for more expedient access to desired applications. A good example for the latter criteria is the PC mouse, which when plugged in requires minimal time to install relevant drivers and then become fully operational for use by the user. Some users may require calibration of particular mouse features such as cursor size, speed or clicking configurations. If these features are saved as part of a user profile then they can be accessed with minimal effort and time on the part of the user. Similarly, if users can gain fast operational control with the BCI this is helpful to determining a robust solution.

Independent control refers to capturing direct user intent as opposed to capturing EEG produced by activity in the brain's usual pathways such as direction of gaze (dependent control). Wolpaw et al. (2002) suggest that having independent control is particularly important for individuals with severe neuromuscular disorders. An example of independent control is the P300 evoked potential discussed in the P300 Events section (2.6.3.4.2) above.

As users with physical disabilities are likely to use the BCI as their main form of connection to a preferred operating environment it is important to give due consideration to the demands placed on the user. These demands include the level of attention required by the user and in turn how quickly one fatigues with user of a particular device. Fatigue not only relates to cognitive performance but also physical endurance. For example, an uncomfortable BCI headset is not going to have a long lasting positive effect for the user.

Convenience refers to the plug-and-play nature of the device. This criterion relates to elements discussed within the user friendliness category. Additionally, it refers to how well the BCIs manages resources with respect to user time, user energy expenditure, and technical expertise required. A carer rating is included that relates to the time requirements of the carer and complex nature of BCI system involved in the setup, troubleshooting, monitoring, and maintenance of the BCI. Therefore whilst this criterion encompasses a number of criteria it has a specific focus for the carer.

EEG can be further broken down into strength of signal, number of channels used, sampling rate and resolution. The strength of the signal not only relates to the intensity of the signal perceived by the operating system but also the distance that the device can be used from the operating system. The number of channels can affect the degree of spatial resolution received by the system. More importantly, the placement of channels can allow the user to attain particular signals. For example, the P300 evoked potential is often seen in locations such as Fz, Cz, P3, Pz, P4, PO7, Oz, and PO8 (Feldman n.d.; King 2009). If the BCI device provides electrode placements at these locations, then the P300 response can be appropriately detected. Refer to Figure 2-6 for electrode placements.

3.7 Evaluating commercial BCIs

As indicated in section 2.5.6, Zhang et al. (2010) have identified a number of commercially available BCIs. These devices were evaluated with respect to predefined criteria outlined in section 3.5 above. As a result a number of devices were excluded from the project. Commercial BCIs were excluded due to replication of technology, limited expandability or over-reliance on the part of the user, and cost. For example, the NeuroSky MindSet was excluded as it uses the same chip, communication protocols and dry sensor technology as the MindWave (NeuroSky n.d.a). It was deemed that results obtained through the MindWave, being the cheaper option, could be replicated in the MindSet.

The OCZ Neural Impulse Actuator (NIA) captures biopiotentials produced by activity in the skin, muscles and nerves (REF). As such this reflects a mixed signal rather than an EEG based system. Moreover, the OCZ NIA is also listed as an end of life product and is no longer available (OCZ Technology 2010). Given its emphasis on electromyography

(EMG) data and that this device is no longer in production, the OCZ NIA was eliminated from this research.

The Star Wars Force Trainer and the MindFlex are both BCI devices used in toys. Both use the same chip found in the NeuroSky MindSet and MindWave devices. However, the former each use different firmware (Frontier Nerds 2010). Moreover, the Star Wars Force Trainer does not output "EEG power band values" (Frontier Nerds 2010). NeuroSky have encouraged interfacing of BCI devices with the arduino electronics prototyping platform (NeuroSky 2011). Nevertheless, this approach does not meet the criterion of a plug-and-play system. Moreover, the average user may not have the technical skill, aptitude or physical ability to create a functional solution using these devices. As such these were both excluded from the research.

One commercial device that may offer promising results for in-home users is the Enobio. The Enobio is able to use dry electrodes except for its passive Driven Right Leg (DRL) electrode (Starlab n.d.). Four channels are used for input and ASCII data as the Enobio's output. The reliability of this device is worth exploring in future research, however, this device was excluded as its current pricing as at June 2011 was quoted at 3750€, which is beyond the budget constraints of this project (as defined by criterion 1 in section 3.5 above).

Two devices were deemed appropriate for this research, namely the Emotiv Epoc and NeuroSky MindWave. The Emotiv Epoc is an EEG-based BCI that consists of 14-saline sensors, which require some initial preparation before use. The October 2011 pricing for this device was US$299.00, thus well below cost constraints for this research. The Emotiv uses a universal serial bus (USB) to create a wireless connection between the device and operating environment. Thus it meets the criteria of being a plug-and-play device. The specifications for the Emotiv device are outlined in Table 3-4 below.

With respect to filtering Emotiv have indicated that they have applied filtering in the firmware and hardware of the Epoc device to remove interference from mains frequency. Emotiv research manager, Geoff Mackellar (2010), reports that the "signals are collected through a C-R high-pass hardware [sic] filter (0.16Hz cutoff), preamplified and low-pass filtered at 83Hz cutoff. Data is also processed in the headset as follows: raw ADC collection rate is 2048 /sec / channel. This data is filtered using a 5th-order sinc filter to notch out 50Hz and 60Hz, low-pass filtered and down-sampled to 128/sec/channel to eliminate mains harmonics".

Table 3-4: Emotiv Epoc specifications. Source: Emotiv Wiki n.d.).

Number of channels	14 (plus CMS/DRL references)
Channel names (Int. 10-20 locations)	AF3, AF4, F3, F4, F7, F8, FC5, FC6, P7, P8, T7, T8, O1, O2
Sampling method	Sequential sampling, Single ADC
Sampling rate	~128Hz (2048Hz internal)
Resolution	16 bits (14 bits effective) 1 LSB = 1.95μV
Bandwidth	0.2 - 45Hz, digital notch filters at 40Hz and 60Hz
Dynamic range (input referred)	256mVpp
Coupling mode	AC coupled
Connectivity	Proprietary wireless, 2.4GHz band
Battery type	Li-poly
Battery life (typical)	12 hrs
Impedence measurement	Contact quality using patented system

The second selected device, the NeuroSky MindWave, is also an EEG-based device that users dry sensor technology. It possesses a single electrode and a reference point clip placed on the ear lobe. The NeuroSky MindWave specifications have been outlined in

Table 3-5 below. Further system requirements and device specifications for the Emotiv and NeuroSky can be found in Appendix B. This device, as at October 2011, cost US$99.95

also meeting cost constraints for the project. As a plug and play device, the MindWave offers promising compact and simple system for in-home users.

Table 3-5: NeuroSky MindWave specifications. Source: NeuroSky n.d.b.

Number of channels	1
Sampling rate	512 Hz sampling rate
Resolution	12 bits ADC
RF Data rate	250 kbit/s
Rate power/ max power	30 mW / 50 mW
RF Frequency range	2.420 - 2.471 GHz
RF Max power	6 dBm
EEG maximum signal input range	1 mV pk-pk
Hardware filter range	3 Hz – 100 Hz
UART Baudrate	57,600 Baud
Wireless packet loss (of bytes)	5%
RF Range	10 m
eSense calculation rate	1 Hz

Criteria such as reliability, user friendliness and ease of use were evaluated during testing and evalution of BCIs section for both devices. A detailed comparative analysis of these devices can be found in section 4.4 below.

3.8 Limitations of the research methodology

Whilst the research methodology described in section 3.2 above aims to provide a reliable framework for the testing, evaluation and design of a BCI solution, there exist a number of inherent limitations to the approach used.

Firstly, this research lacks inter-rater reliability. Inter-reliability is concerned with consistency of results between multiple observers (Trochim 2006a). As this research was based on the results obtained from a single user, further testing is recommended with additional subjects to increase the robustness of results obtained.

Secondly, measuring some data types can be difficult if the user is both observing for changes as well as using a BCI device. For example, the user may be attempting to elicit a meditative brain signal whilst simultaneously concentrating on data produced in plots. This type of setup can produce confounding results.

Thirdly, this research has excluded more expensive options, which may serve to provide a suitable BCI solution for in-home use. If funding was provided for BCI devices in the future, devices like the Enobio would be suitable options for consideration. These devices will need to be tested separately in future work.

Fourthly, no hardware device was produced as a control to test the validity of results. Hardware development may present a useful focus for future projects extending from this research.

3.9 Conclusion

This chapter has described a suitable research methodology to test and evaluate the robustness and reliability of existing commercial BCI devices. A comparative analysis is considered important to determine validity of solutions and room for future improvement. This research approach has some limitations with respect to inter-rater reliability, some data measurement types, exclusion of expensive systems and no control device.

Chapter 4 Testing and Evaluation of BCIs

"Experience is food for the brain." - *Bill Watterson*

4.1 Introduction

Now that a solid grounding in brain computer interfacing has been established and the research methodology has been discussed, this chapter explores results obtained from the testing of selected BCIs. The Emotiv Epoc and NeuroSky MindWave were tested and evaluated to determine their potential for use in a robust and reliable BCI solution. The definition of reliability has been discussed in section 3.4 above.

Results obtained during this research will consider both qualitative and quantitative data. For example, factors such as user experience will be combined with recorded measurements. The testing and evaluation of BCIs can be divided into the following areas.

1. Setup of the BCI
2. Raw data, SDKs and APIs
3. Comparative analysis of BCI devices
4. Visualisation and Analysis Tools
5. Development Tools

4.2 Initial setup of BCIs

4.2.1 The Emotiv Epoc

The initial setup of the Emotiv required preparation of 16 saline sensors (14 input channels and two reference sensors), initial charging of the installed headset Lithium battery via USB connection, and installation of the EPOC control panel program (Emotiv n.d.). Sensor preparation involved hydrating 16 felt pads kept within a hydrator pack. The hydration solution applied was a standard saline solution, such as used with contact lenses. Sensors were then assembled individually into the Emotiv headset arms and turned clockwise to lock into place (Emotiv n.d.).

The Emotiv Epoc uses a USB to establish a wireless connection between the headset and operating system. In this case, a personal computer (PC) using Windows XP Professional (Service Pack 3) was used as a testing environment for the Emotiv. The particulars of the PC and Emotiv specifications are outlined in Appendix B. Moreover, the reason for selecting this operating environment has been discussed in section 3.3 above.

Figure 4-1: Emotiv Epoc device and wireless USB connector.

4.2.2 The NeuroSky MindWave

The NeuroSky MindWave required the installation of a single AAA battery into its headset. Appropriate drivers were installed on the selected operating system (see section 3.3) and the MindWave wireless USB Adapter was connected to a free port (MindWave 2011). COM port 13 was assigned to the MindWave device during testing of the same. As NeuroSky MindWave uses dry sensor technology, no preparation of its single sensor was required. The MindWave also includes a reference clip that is placed on the user's earlobe.

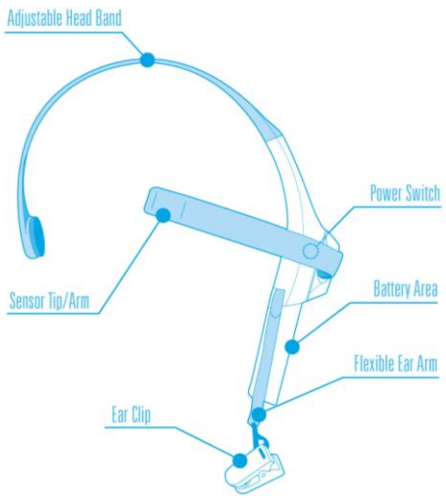


Figure 4-2: NeuroSky MindWave device

4.3 Extracting Raw BCI Data

Exploration into raw BCI data was addressed during this research as it provides the developer and researcher the ability to customize and target specific solutions to meet user needs. Raw BCI data is an amplified and filtered signal (usually for mains power interference) that can be further processed as required.

4.3.1 Emotiv API

Initially a developer edition headset was purchased to enable programming of the Emotiv Epoc device. However, it was found that raw data could only be displayed via a research edition software development kit (SDK). The respective company restricts access to the display of raw data in general and developer user products. As such the initial software was upgraded to enable access to the raw brain signals.

The documentation accompanying the Application Programming Interface (API) for the Emotiv Epoc was found to be sparse and fairly cryptic with respect to its usage. Nevertheless, thorough investigation revealed appropriate sample programs that were used to gain access to the Emotiv' raw data (see Appendix C).

The Emotiv API makes use of 3 header files (edk.h, EmoStateDLL.h, edkErrorCode.h) that are implemented in 2 Windows DLL files (edk.dll and edk_utils.dll) (Emotiv n.d.). The latter DDL files are not provided in this research due to proprietary restrictions. However, the header files have been included in Appendix C. Additionally, an edk.lib static library file is required (also not included).

One example test program used as a starting point for familiarisation with the Emotiv API allows the user to gain access to raw Emotiv data using a console.

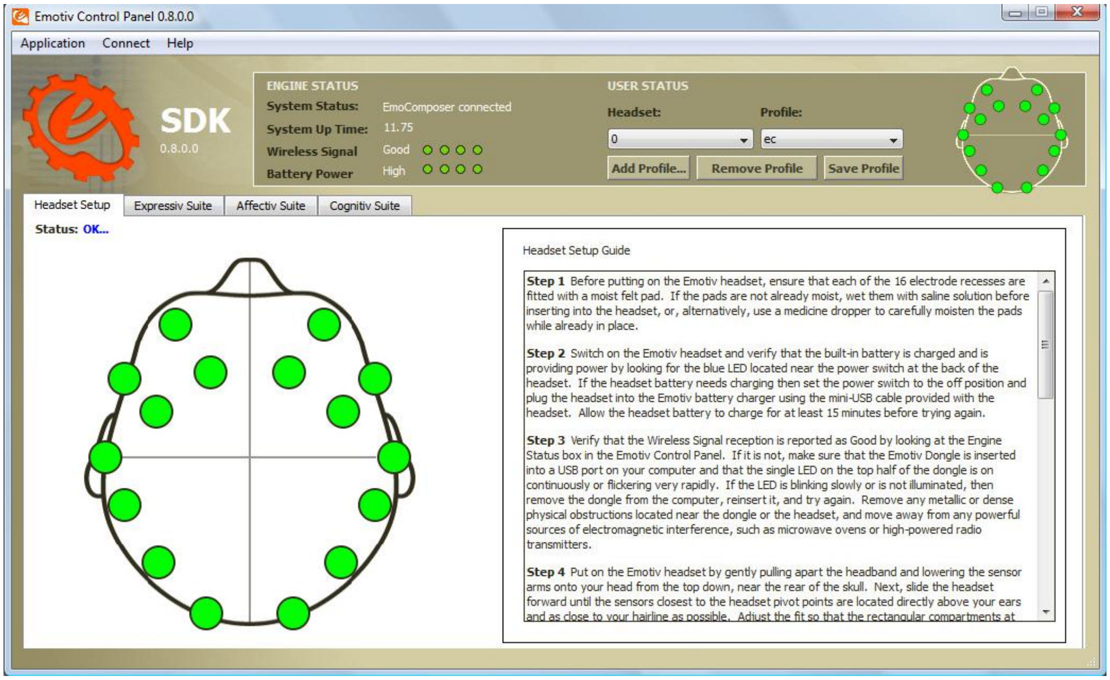
```
===================================================================
Example to show how to log the EmoState from EmoEngine/EmoComposer.
===================================================================
Press '1' to start and connect to the EmoEngine
Press '2' to connect to the EmoComposer
>> 1
Start receiving EmoState! Press any key to stop logging...

    17.546s : New EmoState from user 0 ...
```

Figure 4-3: Sample program output.

4.3.2 Emotiv SDK

Another approach used to obtain BCI data was through the in-built algorithms included as part of Emotiv's SDK. Emotiv categorise their proprietary algorithms into suites as follows: expressiv, affectiv, and cognitiv. The expressiv suite relates to facial movements and relies on EMG signals rather than EEG data. As such the expressiv suite was excluded in terms of acquiring user intent nevertheless it has value with respect to eliminating internal artefacts.

The cognitiv and affectiv components can be accessed via the Emotiv API or through the Emotiv Control Panel. The control panel also provides device and connection feedback to the user such as strength of wireless signal, battery power, connection status, user profile data, and quality of sensor connections. An example of the control panel setup is illustrated in Figure 4-4 below.



System Status: EmoComposer connected
System Up Time: 11.75
Wireless Signal: Good
Battery Power: High
Headset: 0
Profile: ec
Status: OK...

Headset Setup Guide

Step 1 Before putting on the Emotiv headset, ensure that each of the 16 electrode recesses are fitted with a moist felt pad. If the pads are not already moist, wet them with saline solution before inserting into the headset, or, alternatively, use a medicine dropper to carefully moisten the pads while already in place.

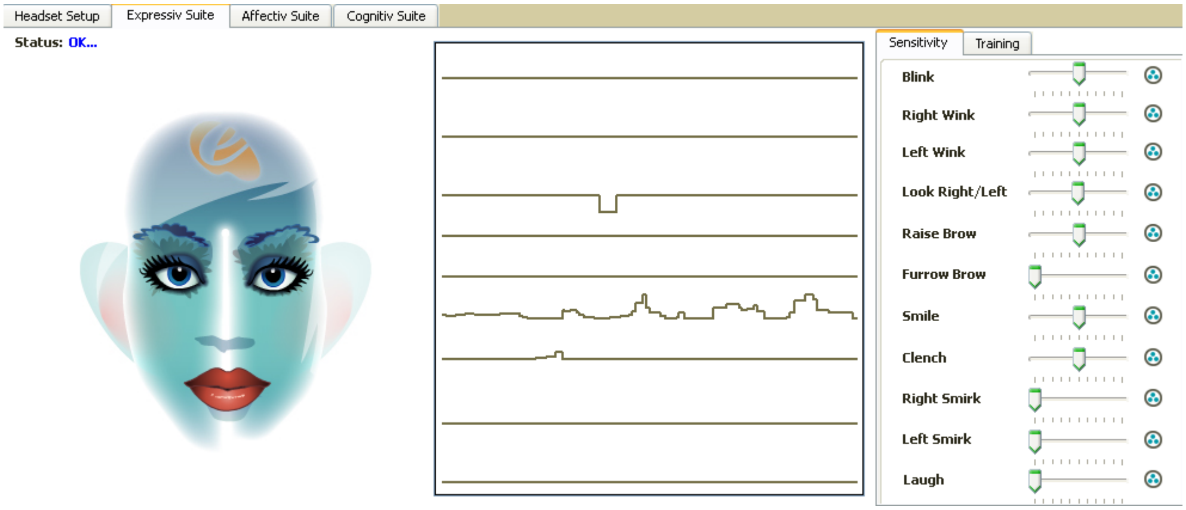
Step 2 Switch on the Emotiv headset and verify that the built-in battery is charged and is providing power by looking for the blue LED located near the power switch at the back of the headset. If the headset battery needs charging then set the power switch to the off position and plug the headset into the Emotiv battery charger using the mini-USB cable provided with the headset. Allow the headset battery to charge for at least 15 minutes before trying again.

Step 3 Verify that the Wireless Signal reception is reported as Good by looking at the Engine Status box in the Emotiv Control Panel. If it is not, make sure that the Emotiv Dongle is inserted into a USB port on your computer and that the single LED on the top half of the dongle is on continuously or flickering very rapidly. If the LED is blinking slowly or is not illuminated, then remove the dongle from the computer, reinsert it, and try again. Remove any metallic or dense physical obstructions located near the dongle or the headset, and move away from any powerful sources of electromagnetic interference, such as microwave ovens or high-powered radio transmitters.

Step 4 Put on the Emotiv headset by gently pulling apart the headband and lowering the sensor arms onto your head from the top down, near the rear of the skull. Next, slide the headset forward until the sensors closest to the headset pivot points are located directly above your ears and as close to your hairline as possible. Adjust the fit so that the rectangular compartments at

Figure 4-4: Emotiv Control Panel. Source: Emotiv n.d.

The Expressiv suite, as shown in Figure 4-5 below, provides an indication of the types of facial expressions that are being detected by the Emotiv Epoc system. These were included as part of routine testing of the device. However, further work may focus their use in obtaining pure EEG data by ignoring signals that cause interference. It is acknowledged that if an individual retains physical movement in the face that these components can be used to increase independent control. However, this is beyond the scope of this research project.



Status: OK...

Figure 4-5: Sample session of Expressiv Suite

The Affectiv Suite, without knowledge of proprietary algorithms, relies on EEG data (see Figure 4-6 below). Emotiv claim that the “Affectiv suite monitors player emotional states in real-time” (Emotiv 2010a). Through testing it has been identified that this description is not entirely accurate but rather more representative of the emotion required. For example, in activating the frustration component of the Affectiv suite, the user engaged in focused concentration on an object or mathematical arithmetic. This caused a rise in signal amplitude. Conversely, when the user relaxed, the signal amplitude lowered. Nevertheless, this approach this approach was not entirely consistent with respect to user intent, however, it did show the most response. A similar method was used with a Mind Your OSCs program discussed in section 4.5.5 below

System Status: Emotiv Engine is ready
System Up Time: 171.625
Wireless Signal: Good ○ ○ ○ ○
Battery Power: No Battery Meter Detected

Headset: 0
Profile: jw

Status: OK...

Show	Color	Detection Name
☑	red	Engagement/Boredom
☑	blue	Instantaneous Excitement
☐	orange	Long Term Excitement

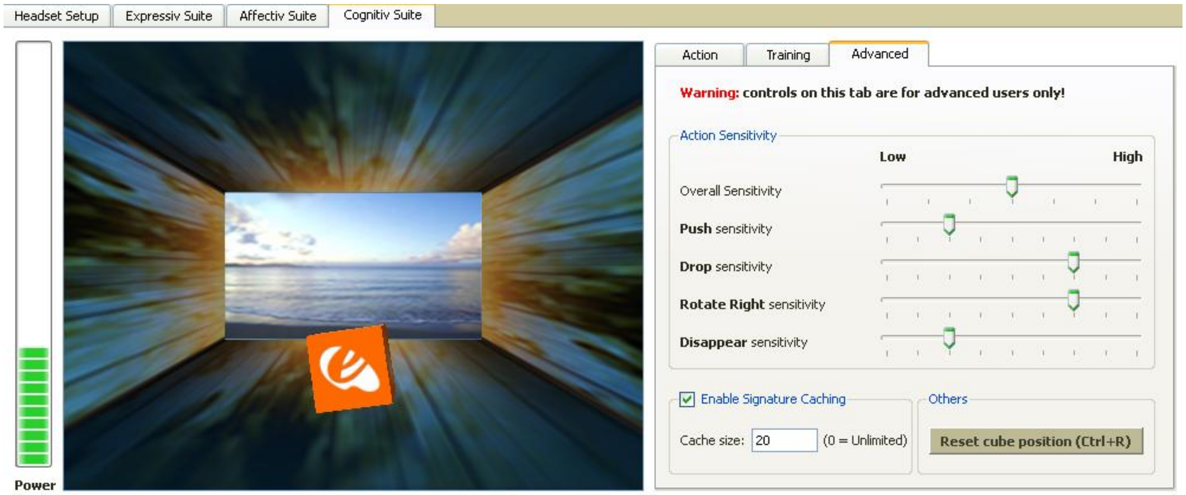
Display Length 30 Seconds

Show	Color	Detection Name
☐	red	Engagement/Boredom
☐	crimson	Instantaneous Excitement
☑	green	Long Term Excitement

Display Length 150 Seconds

Figure 4-6: Affectiv Suite. Source: Emotiv n.d.

The Cognitiv suite showed the most promise in reliably detecting and interpreting user intent as signals are able to be trained. A demonstration of the Cognitiv has been included in Appendix D. In this research, various actions were trained to control a 3D cube in space. For example, the cube was pushed, dropped, rotated to the right and made to disappear using signals from training sessions. A neutral recording option is available to increase the reliability of trained signals by comparing these against the brains neutral state. Actions produced by the ball did not always match user intent. In some instances, there was a delay in response. On a few occasions, the cube performed an alternatively trained action to that intended by the user. Moreover, at times the cube did not respond. Improvements in response were noted with additional training and by increasing the sensitivity of specific actions (see



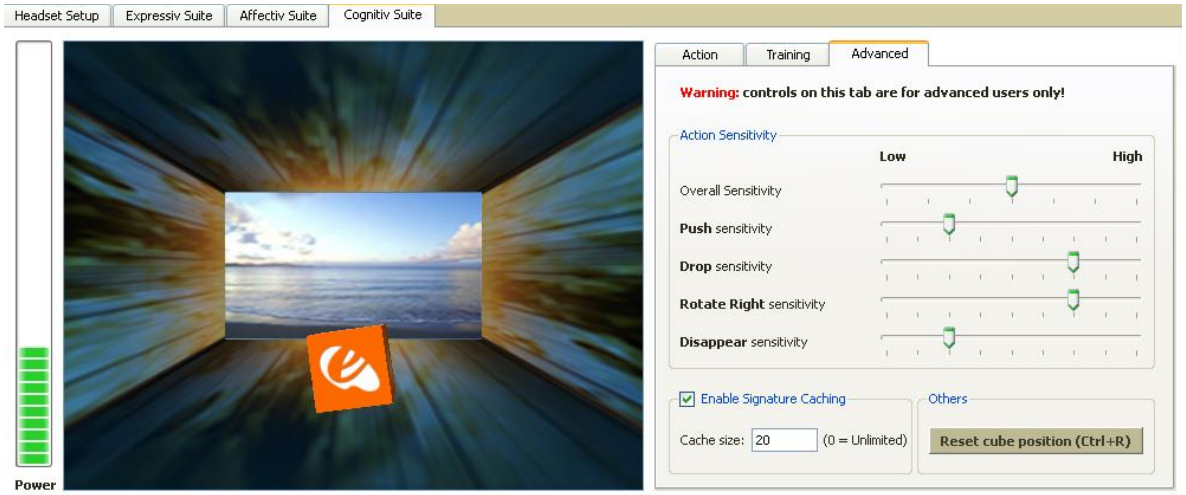
Warning: controls on this tab are for advanced users only!

☑ Enable Signature Caching

Cache size: 20 (0 = Unlimited)

Figure 4-7 below).

An interesting result occurred when the cube randomly performed actions such as rotate right or drop without the Emotiv Epoc headset being placed on the user’s head or any saline sensors installed.



Warning: controls on this tab are for advanced users only!

☑ Enable Signature Caching

Cache size: 20 (0 = Unlimited)

Figure 4-7: Sample obtained from Cognitiv suite.

4.3.3 NeuroSky API

Access to the raw brain signal can be obtained through the NeuroSky development kit. At the time of research this kit was available for free via the NeuroSky store, under the title MindSet Development Tools (MDT). Essentially, raw data can be obtained through several methods. These include the ThinkGear Connector (TGC), the ThinkGear Communications Driver (TGCD) and the ThinkGear Stream Parser (NeuroSky 2010a). The selection an appropriate method depends on the developer's operating environment and how the signal information is intended to be used.

The TGC executable runs in the background and provides an open socket on the local operating environment. Applications are able to connect with this socket in order to obtain data from the NeuroSky MindWave device. The TGC operates much like a daemon service (NeuroSky 2010a) and is suited to Windows and Max OS X operating system environments.

The TGCD also enables communication between the NeuroSky MindWave device and a PC/mobile device. The TGCD is a device driver that includes an API and "is available as a .dll (for x86 or ARMV4I platforms), as a .bundle (for Mac OS X platforms), or as a .java library (for J2ME/Symbian platforms)" (NeuroSky 2010a p. 8).

Finally, the ThinkGear Stream Parser is useful for development on platforms not addressed by the TGC or TGCD. The onus is on the developer to open the relevant serial I/O communication channel. NeuroSky (2010a) provide a Packet parsing library "for parsing and decoding the incoming data bytes" (p. 12).

NeuroSky applications rely on the thinkgear.dll and thinkgear.lib files in order to operate. These are available in the respective MindSet Development Tools kit and are not included in Appendices.

By modifying a sample MDT program raw data was passed to standard output using the following sequence:

```
connectionId = TG_GetNewConnectionId();
…
/* Set/open stream (raw bytes) log file for connection */
    errCode = TG_SetStreamLog( connectionId, "streamLog.txt" );
…
/* Set/open data (ThinkGear values) log file for connection */
    errCode = TG_SetDataLog( connectionId, "dataLog.txt" );
…
/* Attempt to connect the connection ID handle to serial port "COM13" */
    comPortName = "\\\\.\\COM13";
…
/* Read 100 ThinkGear Packets from the connection, 1 Packet at a time */
    packetsRead = 0;
    while( packetsRead < 100 ) {
…
/* Output raw data to screen */
    rawData = TG_GetValue(connectionId, TG_DATA_RAW);
    printf( "%d ", rawData );
…
TG_FreeConnection( connectionId );
```

Figure 4-8: Code sequence used to obtain raw data from NeuroSky MindWave

The program, as depicted in Figure 4-8 above, establishes a connection to the MindWave device using the TG_GetNewConnectionId() API command. Two files are used to capture incoming data including raw bytes and ThinkGear values. COM port 13 was used during testing and was appropriately assigned to variable comPortName. In order to obtain a suitable sample of packets, the program was modified to read 100 packets. Raw data was then displayed on the command line interface by printing values obtained through the TG_GetValue API command. The program was compiled using MinGW. Sample output from this program can be seen in Figure 4-9 below.

```
ThinkGear DLL version: 21
0 0 0 0 0 38 49 50 41 35 39 54 66 64 56 56 69 70 60 34 38 16 -18 -34 10 18 36 65
 90 92 60 20 0 2 27 57 75 74 64 67 68 56 60 84 106 108 86 65 69 90 100 84 64 36
-24 -122 -177 -141 -75 -19 42 85 104 100 100 113 118 122 113 82 41 7 -7 1 20 33
18 -10 -22 -4 16 9 -30 -82 -74 22 118 133 106 89 82 71 66 59 60 65 60 66 66 38
Press the ENTER key...
```

Figure 4-9: Sample raw data output from MindWave device

These values match the first of each line sequence recorded in the dataLog.txt file as seen in Figure 4-10 below (as per the circled highlighted section).

```
1319443335.796: [D4]  01
1319443336.187: [D4]  01
1319443336.593: [D4]  01
1319443337.000: [D4]  01
1319443337.015: [D0]  88 71
1319443337.031: [80]      38, 0026, -2.777126
1319443337.031: [80]      49, 0031, -2.712610
1319443337.031: [80]      50, 0032, -2.706745
1319443337.031: [80]      41, 0029, -2.759531
1319443337.031: [80]      35, 0023, -2.794721
1319443337.031: [80]      39, 0027, -2.771261
…
```

Figure 4-10: Corresponding output (to Figure 4-9 results) from dataLog.txt file.

```
1319443335.796:  AA AA 03 D4 01 01 29
1319443336.187:  AA AA 03 D4 01 01 29
1319443336.593:  AA AA 03 D4 01 01 29
1319443337.000:  AA AA 03 D4 01 01 29
1319443337.015:  AA AA 04 D0 02 88 71 34
1319443337.031:  80 D2 95 4D 8D 80 02 00 1C 61 AA AA 04 80 02 00 26 57
1319443337.031:  AA AA 04 80 02 00 31 4C
1319443337.031:  AA AA 04 80 02 00
1319443337.031:  32 4B
1319443337.031:  AA AA
1319443337.031:  04 80 02 00 29 54
1319443337.031:  AA AA 04 80 02 00 23 5A
1319443337.031:  AA AA 04 80 02 00 27 56
…
```

Figure 4-11: Corresponding output (to Figure 4-9 results) from streamLog.txt file.

In interpreting the data captured within the streamLog.txt file, NeuroSky's (2010b) MindSet Communication Protocol (MCP) provides useful guidance. The raw wave data is actually a signed 16-bit integer (2 bytes) that stores values ranging from -32768 to 32767. The first of the two bytes is "the high-order bits of the twos-compliment value, while the second byte represents the low-order bits" (NeuroSky 2010b, p. 7).

A typical Packet structure is comprised of a header, a payload and a checksum component. The header component is further subdivided into two sync values (SYNC) and one packet length value (PLENGTH), as shown in Table 4-1 below.

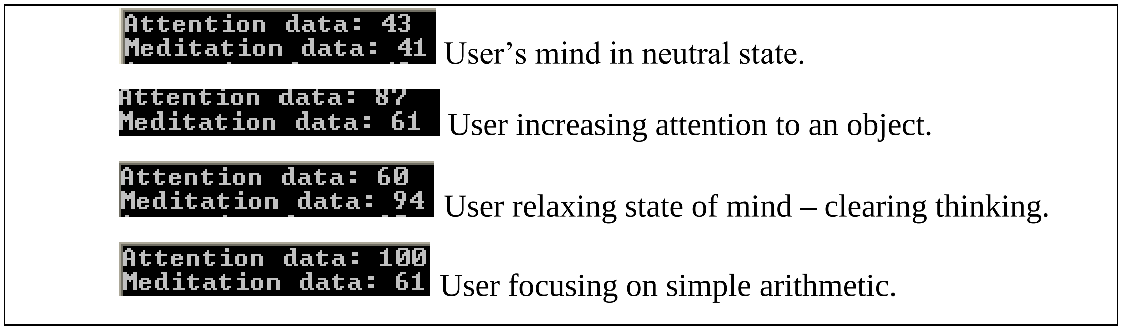
Table 4-1: Packet structure used by NeuroSky MindWave

Header			Payload	Checksum
[SYNC]	[SYNC]	[PLENGTH]	[PAYLOAD...]	[CHKSUM]

For example, the double value 0xAA (decimal 170) in Figure 4-11 on the second `1319443337.031` line is used to synchronise the start of a new packet. PLENGTH then reveals the length (number of bytes) of the data payload, which is 04. The value 0x80 then indicates a raw wave value. The two values highlighted in green (00 31) represent the signed 16-bit hexadecimal code for the number 49. Finally, 4C represents the checksum value to determine the validity packet for parsing. It can be seen that the first half of the line `1319443337.031:  80 D2 95 4D 8D 80 02 00 1C 61 AA AA 04 80 02 00 26 57` (highlighted) has been ignored as it was not correctly synchronised.

4.3.4 NeuroSky SDK

The NeuroSky MindWave SDK provides access to proprietary algorithms, called eSense™ meters. These meters fall into two categories namely attention and meditation. These algorithms attempt to identify increased focus to task as opposed to a relaxed state of mind. The value returned with respect to a meter measurement lies on a scale from 1 to 100. Using this scale, a value between 1 and 20 represents a strongly lowered level, a value between 20 and 40 is a reduced level, a value between 40 and 60 is considered neutral, a value between 60 and 80 is considered slightly elevated, and a value between 80 and 100 represents an elevated level (NeuroSky 2010b). For example, the sample taken in Figure 4-12 below above illustrates the transition from an initial neutral state to an increased state of attention state followed by an increased state of meditation and finally and finally an increased state of attention.



```
Attention data: 43
Meditation data: 41
```

User’s mind in neutral state.

```
Attention data: 87
Meditation data: 61
```

User increasing attention to an object.

```
Attention data: 60
Meditation data: 94
```

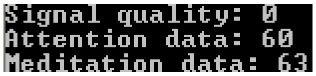
User relaxing state of mind – clearing thinking.

```
Attention data: 100
Meditation data: 61
```

User focusing on simple arithmetic.

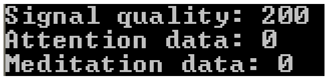
Figure 4-12: Sample eSense meter output in response to user thought patterns.

Another important in-built algorithm is that of signal quality. A value of 0 represents a good quality connection. In contrast, a non zero value (up to a value of 200) represents noise contamination. Figure 4-13 shows a sample representing a good connection between the headset and wireless USB device. Conversely, Figure 4-22 shows a value of 200 for signal quality in response to the headset reference sensor being disconnected. When the user’s eyebrows are raised this produces a signal quality of 26.



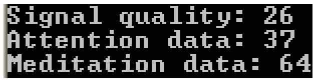
```
Signal quality: 0
Attention data: 60
Meditation data: 63
```

Figure 4-13: Headset with good quality connection.



```
Signal quality: 200
Attention data: 0
Meditation data: 0
```

Figure 4-14: Headset with disconnected reference sensor.



```
Signal quality: 26
Attention data: 37
Meditation data: 64
```

Figure 4-15: Signal quality in response to raising eyebrows.

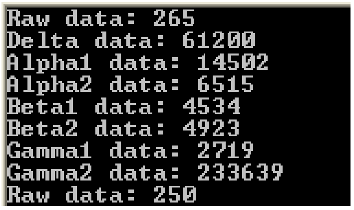
The NeuroSky MindWave also has access to a range of brain wave pattenrs such as delta, alpha1, alpha2, beta1, beta2, gamma1 and gamma2.

These patterns were accessed using the following code sequence.

```
/* Output raw data to screen */
attention = TG_GetValue(connectionId, TG_DATA_ATTENTION);
meditation = TG_GetValue(connectionId, TG_DATA_MEDITATION);
rawData = TG_GetValue(connectionId, TG_DATA_RAW);
delta = TG_GetValue(connectionId, TG_DATA_DELTA);
alpha1 = TG_GetValue(connectionId, TG_DATA_ALPHA1);
alpha2 = TG_GetValue(connectionId, TG_DATA_ALPHA2);
beta1 = TG_GetValue(connectionId, TG_DATA_BETA1);
beta2 = TG_GetValue(connectionId, TG_DATA_BETA2);
gamma1 = TG_GetValue(connectionId, TG_DATA_GAMMA1);
gamma2 = TG_GetValue(connectionId, TG_DATA_GAMMA2);
```

Figure 4-16: Accessing individual brain wave patterns.

A sample output of brain wave patterns is provided in Figure 4-17 below.



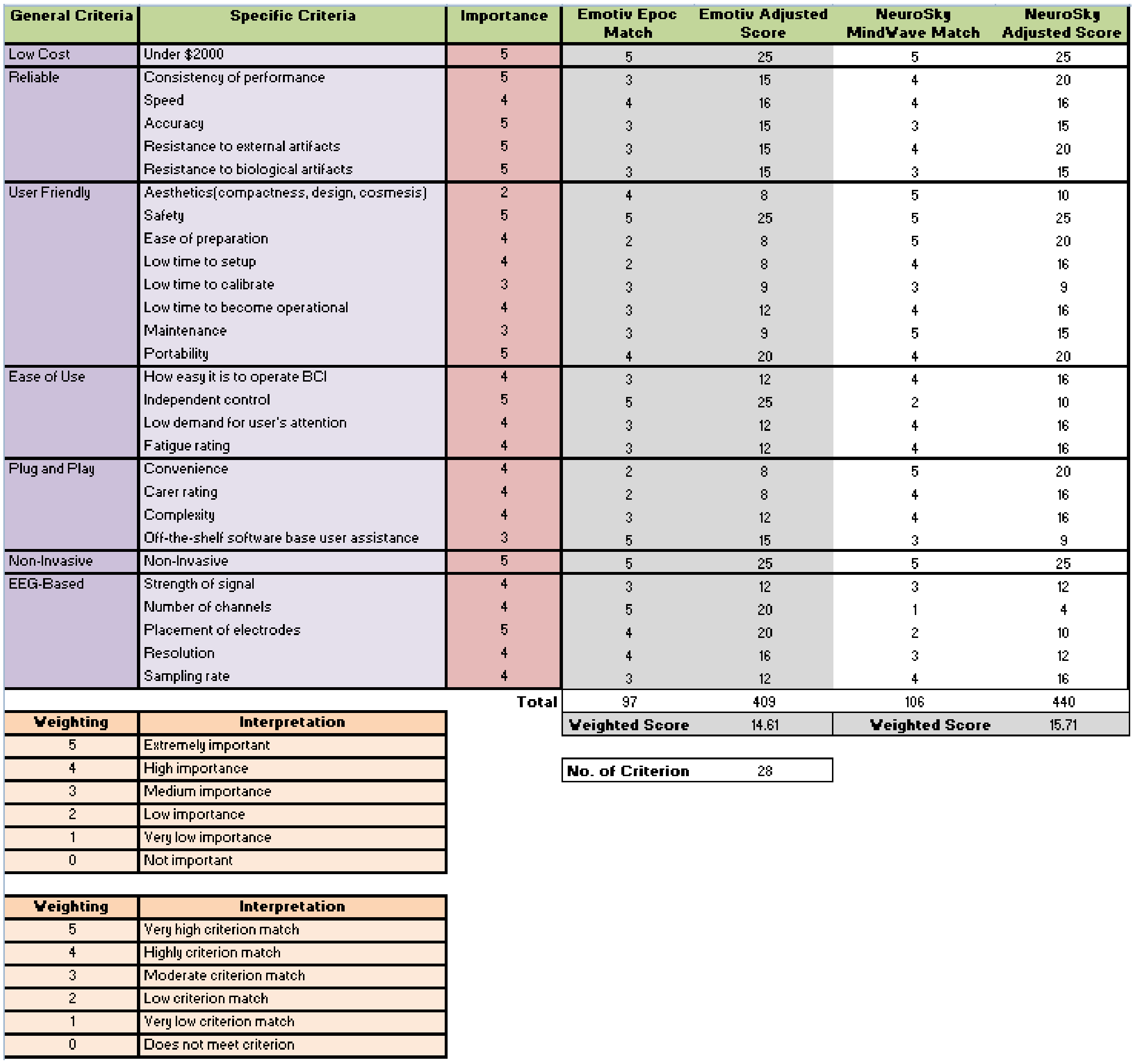
```
Raw data: 265
Delta data: 61200
Alpha1 data: 14502
Alpha2 data: 6515
Beta1 data: 4534
Beta2 data: 4923
Gamma1 data: 2719
Gamma2 data: 233639
Raw data: 250
```

Figure 4-17: Sample values for brain wave patterns.

4.4 Comparative analysis of selected BCIs

In order to establish and compare the robustness of BCI solutions a weighted matrix was established in accordance with section 3.6 above (refer to Table 4-2 below). The Emotiv Epoc obtained a weighted score of 14.61 as compared to the NeuroSky MindWave at 15.71. These values corresponded to a 70% and a 75% rating to an ideal solution, respectively. Some of the key disadvantages of the Emotiv Epoc are its time consuming preparation and maintenance requirements. Nevertheless, the Emotiv Epoc offers an expandable solution that be used to detect a range of EEG signals due to its number and placement of channels. In contrast, the NeuroSky MindWave only offers a single channel, which limits the spatial resolution of its data and the ability to detect particular EEG patterns such as the P300 evoked potential.

Table 4-2: Comparing the Emotiv Epoc and NeuroSky MindWave BCIs.



General Criteria	Specific Criteria	Importance	Emotiv Epoc Match	Emotiv Adjusted Score	NeuroSky MindWave Match	NeuroSky Adjusted Score
Low Cost	Under $2000	5	5	25	5	25
Reliable	Consistency of performance	5	3	15	4	20
	Speed	4	4	16	4	16
	Accuracy	5	3	15	3	15
	Resistance to external artifacts	5	3	15	4	20
	Resistance to biological artifacts	5	3	15	3	15
User Friendly	Aesthetics(compactness, design, cosmesis)	2	4	8	5	10
	Safety	5	5	25	5	25
	Ease of preparation	4	2	8	5	20
	Low time to setup	4	2	8	4	16
	Low time to calibrate	3	3	9	3	9
	Low time to become operational	4	3	12	4	16
	Maintenance	3	3	9	5	15
	Portability	5	4	20	4	20
Ease of Use	How easy it is to operate BCI	4	3	12	4	16
	Independent control	5	5	25	2	10
	Low demand for user's attention	4	3	12	4	16
	Fatigue rating	4	3	12	4	16
Plug and Play	Convenience	4	2	8	5	20
	Carer rating	4	2	8	4	16
	Complexity	4	3	12	4	16
	Off-the-shelf software base user assistance	3	5	15	3	9
Non-Invasive	Non-Invasive	5	5	25	5	25
EEG-Based	Strength of signal	4	3	12	3	12
	Number of channels	4	5	20	1	4
	Placement of electrodes	5	4	20	2	10
	Resolution	4	4	16	3	12
	Sampling rate	4	3	12	4	16
		Total	97	409	106	440
			Weighted Score	14.61	**Weighted Score**	15.71

No. of Criterion	28

Weighting	Interpretation
5	Extremely important
4	High importance
3	Medium importance
2	Low importance
1	Very low importance
0	Not important

Weighting	Interpretation
5	Very high criterion match
4	Highly criterion match
3	Moderate criterion match
2	Low criterion match
1	Very low criterion match
0	Does not meet criterion

The NeuroSky MindWave offers the ideal solution in terms of ease of preparation, setup and maintenance. One of its highlights is the use of a dry sensor, which does not require the time-consuming saline preparation of the Emotiv Epoc. Moreover, it was found during testing that the Emotiv required extra application of saline solution to preserve connectivity. Moreover, length and style of hair had an impact on the quality of connection. In contrast, the NeuroSky MindWave was conveniently placed on the forehead.

Both devices scored moderately in the areas of accuracy, resistance to biological artifacts, calibration time, and signal strength. These first two results suggest that further signal processing algorithms are required to improve device accuracy in determining user intent and eliminate undesirable EEG data. Signal strength was rated moderately as the devices did not register signals beyond an approximate 2 m range from the corresponding wireless USB adapter. Moreover, signal strength was sometimes impacted by head positioning or obstruction by objects.

The Emotiv Epoc scored a low carer rating in comparison to the NeuroSky MindWave. Through testing it was noted that a carer of a person with a moderate to severe physical disability would be required to setup the BCI device, be available for troubleshooting, maintain connectivity, and adjust the BCI for user comfort. These tasks were particularly more time-consuming and technically challenging with respect to the Epoc as opposed to the MindWave. One disadvantage shared by both devices is that after approximately 1.5 to 2 hours of continuous usage, the BCI devices created increased physical pressure against the skull and/or temporal musculature. This caused considerable discomfort to the user and the BCI devices had to be removed to obtain relief. The latter observation raises particular concern for individuals who cannot adjust the BCI themselves or communicate discomfort to significant others.

4.5 Development Tools

4.5.1 Compilers

Respective DLL and LIB files of the Emotiv Epoc and NeuroSky MindWave systems were tested with a range of compilers including MinGW, Cygwin, Msys and Microsoft Visual Studio 2010 Express. MinGW was sufficient to compile basic programs such as Appendices C and E, using console commands such as:

```
> gcc thinkgear.c thinkgear.dll thinkgear.lib -o neurosky
```

Or

```
> g++ main.cpp edk.lib edk.dll edk_utils.dll -o emotiv
```

to link static and dynamic library files appropriately into a corresponding executable.

The Epoc and MindWave DLL also work effectively with Microsoft Visual Studio 2010 Express. The DLL files appear to have been compiled using Microsoft Visual Studio and so this compiler may present as a more reliable option. An important consideration found when using various compilers is the need to configure the relevant environment (e.g. CodeBlocks or QT – refer to section 4.5.4) to import header files and library files. For example, in attempting to expand the Mind Your OSCs (described in section 4.5.5 below) application to integrate the NeuroSky MindWave it was important to configure the QT .pro file to link to relevant library files as follows:

```
LIBS += C:\msys\1.0\home\jem\lib\edk.lib \
        C:\msys\1.0\home\jem\lib\edk.dll \
        C:\msys\1.0\home\jem\lib\edk_utils.dll \
        -lwsock32 \
        C:\msys\1.0\home\jem\lib\thinkgear.lib \
        C:\msys\1.0\home\jem\lib\thinkgear.dll
```

Figure 4-18: Library file configuration for QT application.

The following is a screenshot of the application developed in QT to expand the Mind Your OSCs application.

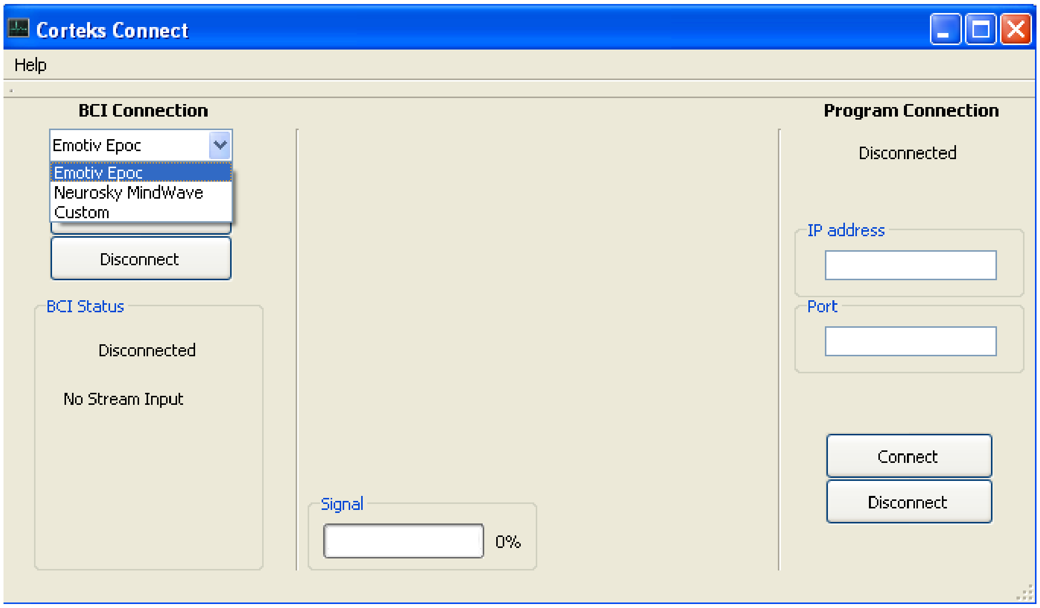


Figure 4-19: Program developed to integrate NeuroSky MindWave (incomplete).

4.5.2 MATLAB

The following section discusses the integration of BCI devices with the MATLAB environment for visualisation and analysis.

4.5.2.1 Emotiv Epoc

Initial research into importing C programming routines into MATLAB to display raw signals explored the concept of creating mex files. A mex file is a MATLAB facility that permits the running of C programs within the MATLAB environment (Spielman 2010). It replaces the main function with a mexFunction and uses special routines to construct data types specific to the MATLAB environment. However, this approach proved overly complicated as a simpler solution was found that made direct calls to the Emotiv edk.dll file. Two programs written by Franscesco Tenore (2010) for MATLAB greatly aided the real-time visualization and analysis of the Emotiv Epoc. The first program named eeglogger.m (see Appendix F) displays all available functions in the Emotiv's edk library. It makes calls to Emotiv's DLL via API calls consistent with the MATLAB programming interface. This program captures 10 seconds of data and outputs data obtained from gyro sensors in-built into the Emotiv Epoc headset. This program has the potential for modification in order to display real time data from “cognitiv” and “affectiv” data streams.

The second program focuses on obtaining “affectiv” data from the Emotiv Epoc for display in MATLAB’s command window and is aptly named affectiv.m. This program was modified with the following code (Figure 4-20) in order to plot and display real time affectiv data from the Emotiv Epoc.

```
medData = zeros(1,256);    %initialise buffer for meditation data
exitData = zeros(1,256);   %initialise buffer for excitement data
frustData = zeros(1,256);   %initialise buffer for frustration data

if emoState == 0
      j = j + 1;
      meditation = calllib('edk','ES_AffectivGetMeditationScore',eState)
      medData(j) = meditation;
      excitement =
calllib('edk','ES_AffectivGetExcitementShortTermScore',eState)
      exitData(j) = excitement;
      frustration =
calllib('edk','ES_AffectivGetFrustrationScore',eState)
      frustData(j) = frustration;
      ExpressIsActiv = calllib('edk','ES_ExpressivIsBlink',eState)

      if (j == 256)
         plotAFF(medData, exitData, frustData)
         j=0;
      end
end
```

Figure 4-20: Code to output Affectiv components.

The plotting function used is defined in plotAFF.m and is described as follows:

```
function plotAFF(data, data1, data2)
%This function is used to plot the received Affectiv data
x = 0:255;

plot(x,data, x,data1, x,data2)
axis([0 255 -0.01 1])
drawnow;
```

Figure 4-21: Plotting function for Affectiv data.

Effectively this code facilitated the real-time display of selected components from Emotiv's Affectiv suite. Active control of these signals proved difficult and further signal analysis and processing is required to obtain reliable system response to user intent.

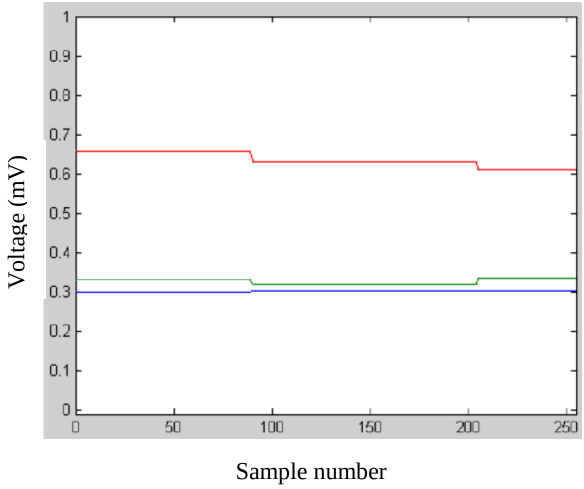


Figure 4-22: Affectiv data from Emotiv Epoc in MATLAB.

Both programs described above require that the Emotiv edk.dll file be present in the same working folder in order to access relevant data. This DLL file is obtained through purchase of Emotiv's Research, Education or Enterprise Plus SDKs.

4.5.2.2 NeuroSky MindWave

The NeuroSky MindWave provides a simpler API that can be used to output data in the MATLAB environment. Calls are made to a thinkgear.DLL file in order to display raw signals. Figure 4-23 provides an illustration of artefact noise produced by raising the eyebrows. This program can be further evaluated in Appendices.

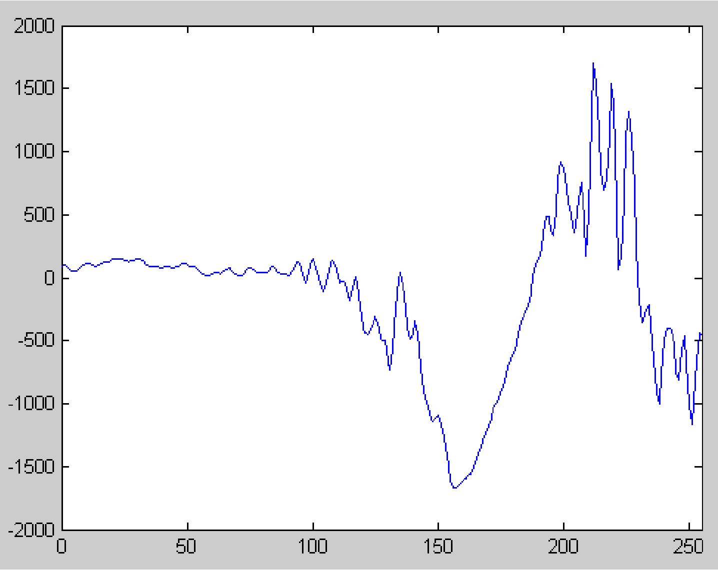


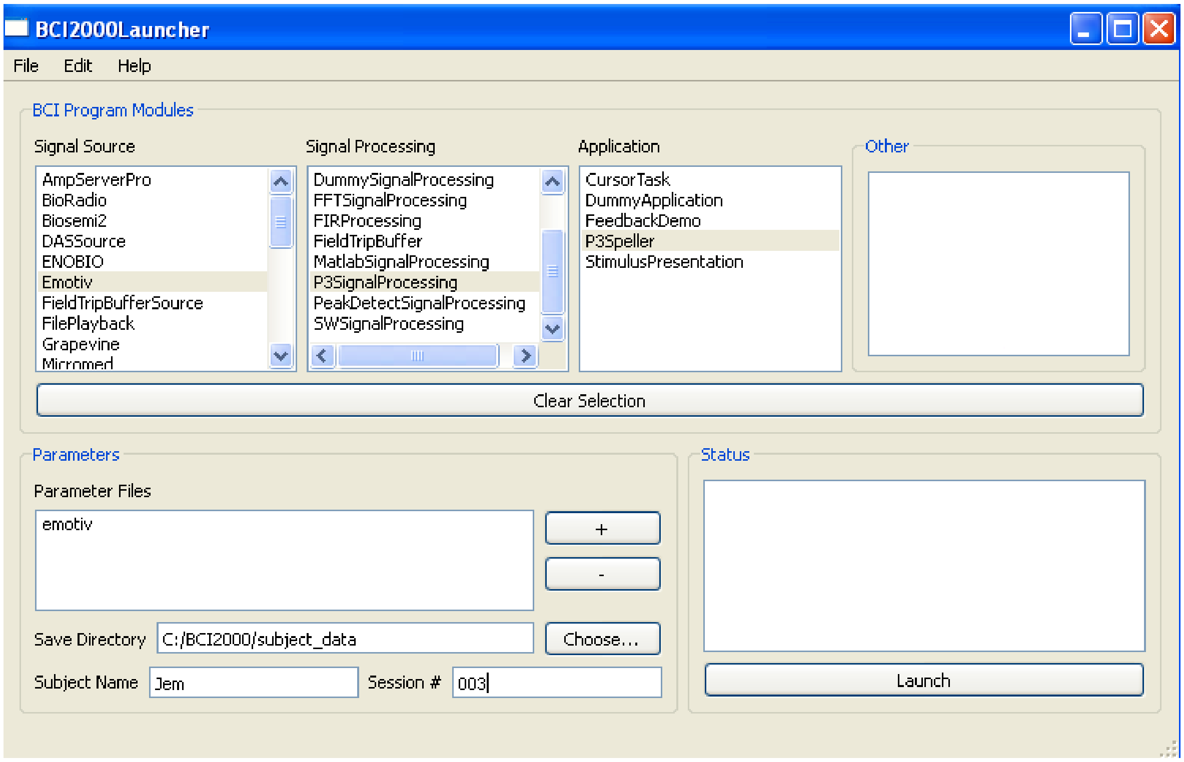
Figure 4-23: Artifact noise produced by raising eyebrows using MindWave in MATLAB.

4.5.3 BCI2000

BCI2000 provides a useful system to conduct BCI research. The BCI2000 source package was compiled with Microsoft Visual Studio 2010 Express using an included batch file. CMake was used to generate make files for compilation into executables. The following section details experimentation made using the BCI2000 system in conjunction with MATLAB.

4.5.3.1 *Emotiv Epoc*

The Emotiv Epoc was first started by using the BCI2000 Launcher. If compilation of BCI2000 source code has proven effective, Emotiv will be present as a Signal Source option. In order to test the P300 evoked potential, P3SignalProcessing was selected as the Signal Processing method. The P3Speller was selected as a suitable application that would correspond most closely to an imagined music implementation (see Figure 4-24).



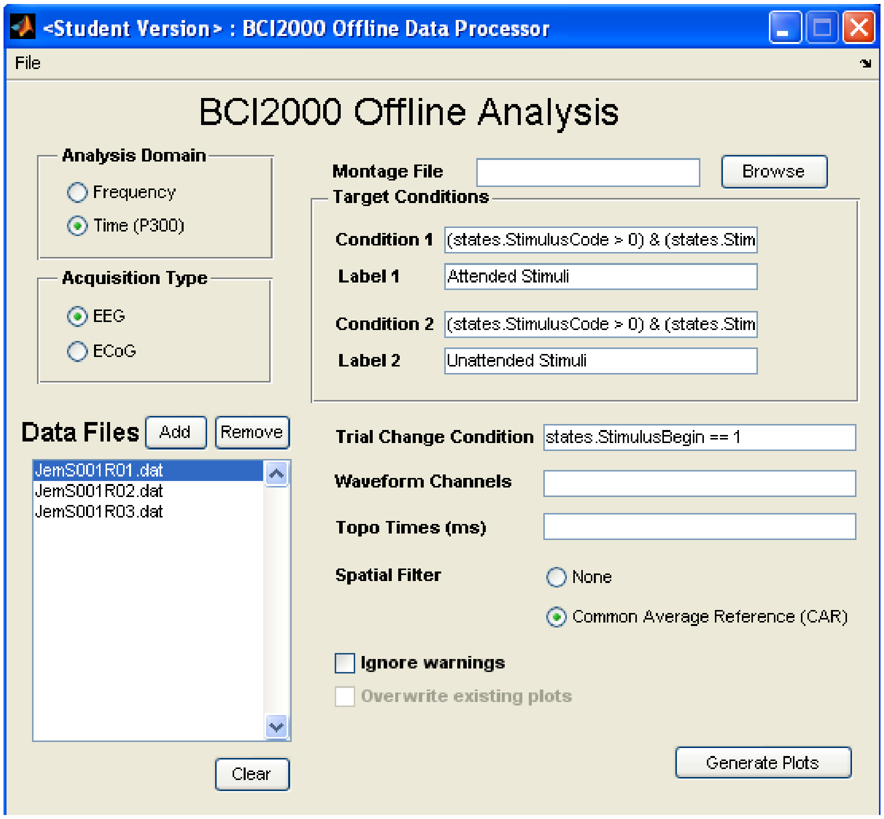
Signal Source: Emotiv
Signal Processing: P3SignalProcessing
Application: P3Speller
Parameter Files: emotiv
Save Directory: C:/BCI2000/subject_data
Subject Name: Jem
Session #: 003

Figure 4-24: Setting up the Epoc with BCI2000.

Once user details had been established, the Epoc was initialised using a parameter file as per Appendix G. The program was then launched.

The program required that the user attend to a desired letter as part of a matrix of rapidly changing letters. The idea is that a P300 evoked potential results as a reponse to recognition of the desired letter. Testing revealed occasional success with this method in spelling particular words such as “TEST”.

Once several data files of measurements were collected, these were used in Offline Analysis within the MATLAB environment as per Figure 4-25. A Common Average Reference spatial filter was applied to the data.



Analysis Domain
○ Frequency
● Time (P300)

Acquisition Type
● EEG
○ ECoG

Montage File

Target Conditions
Condition 1 (states.StimulusCode > 0) & (states.Stim
Label 1 Attended Stimuli
Condition 2 (states.StimulusCode > 0) & (states.Stim
Label 2 Unattended Stimuli

JemS001R01.dat
JemS001R02.dat
JemS001R03.dat

Trial Change Condition states.StimulusBegin == 1
Waveform Channels
Topo Times (ms)
Spatial Filter ○ None ● Common Average Reference (CAR)
☐ **Ignore warnings**
☐ **Overwrite existing plots**

Figure 4-25: Offline analysis of P300 signals.

Condition variables were filled with the following data:

Trial Change Condition: `states.StimulusBegin == 1`

Target Condition 1: `(states.StimulusCode > 0) & (states.StimulusType == 1)`

Target Condition Label 1: `Attended Stimuli`

Target Condition 2: `(states.StimulusCode > 0) & (states.StimulusType == 0)`

Target Condition Label 2: `Unattended Stimuli`

Subsequently plots were generated showing location of channels versus time delay after stimulus (see Figure 4-26). An r-squared value was produced by the plot to indicate predictability of response (red being high predictability). R-squared values between 250 ms and 550 ms were of particular interest (BCI2000 n.d.).

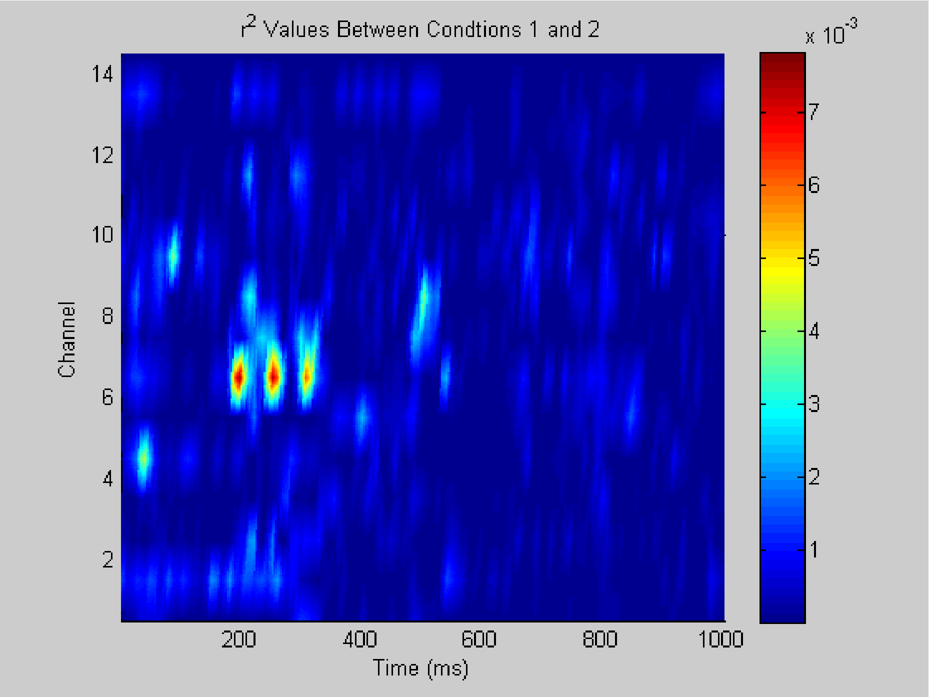


Figure 4-26: R-squared plot of predictability of response.

The four highest datapoints were selecting and reference details pertaining to channel location, time of datapoint and R-squared value were recorded as per Figure 4-27.

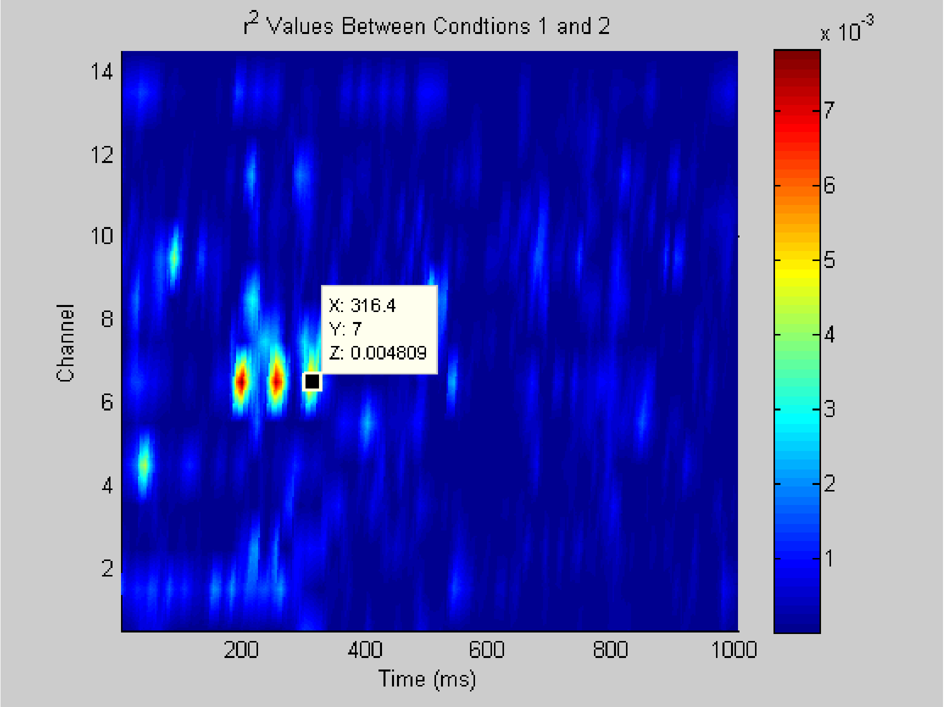
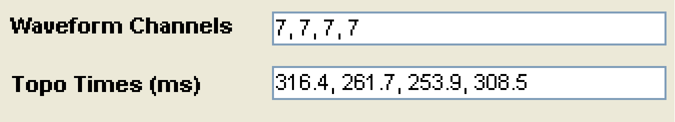


Figure 4-27: Recording of reference points.

The four recorded datapoints were then recorded in Waveform Channels field of the BCI2000 Offline Analysis tool as per Figure 4-28.



Waveform Channels	7, 7, 7, 7
Topo Times (ms)	316.4, 261.7, 253.9, 308.5

Figure 4-28: Using recorded values.

Further plots were then generated to produce “graphs that show the correlation between the selected times after the desired stimulus is given (the red line) and the brain’s responses to when the desired stimulus is not given (the blue line)” (BCI2000 n.d.).

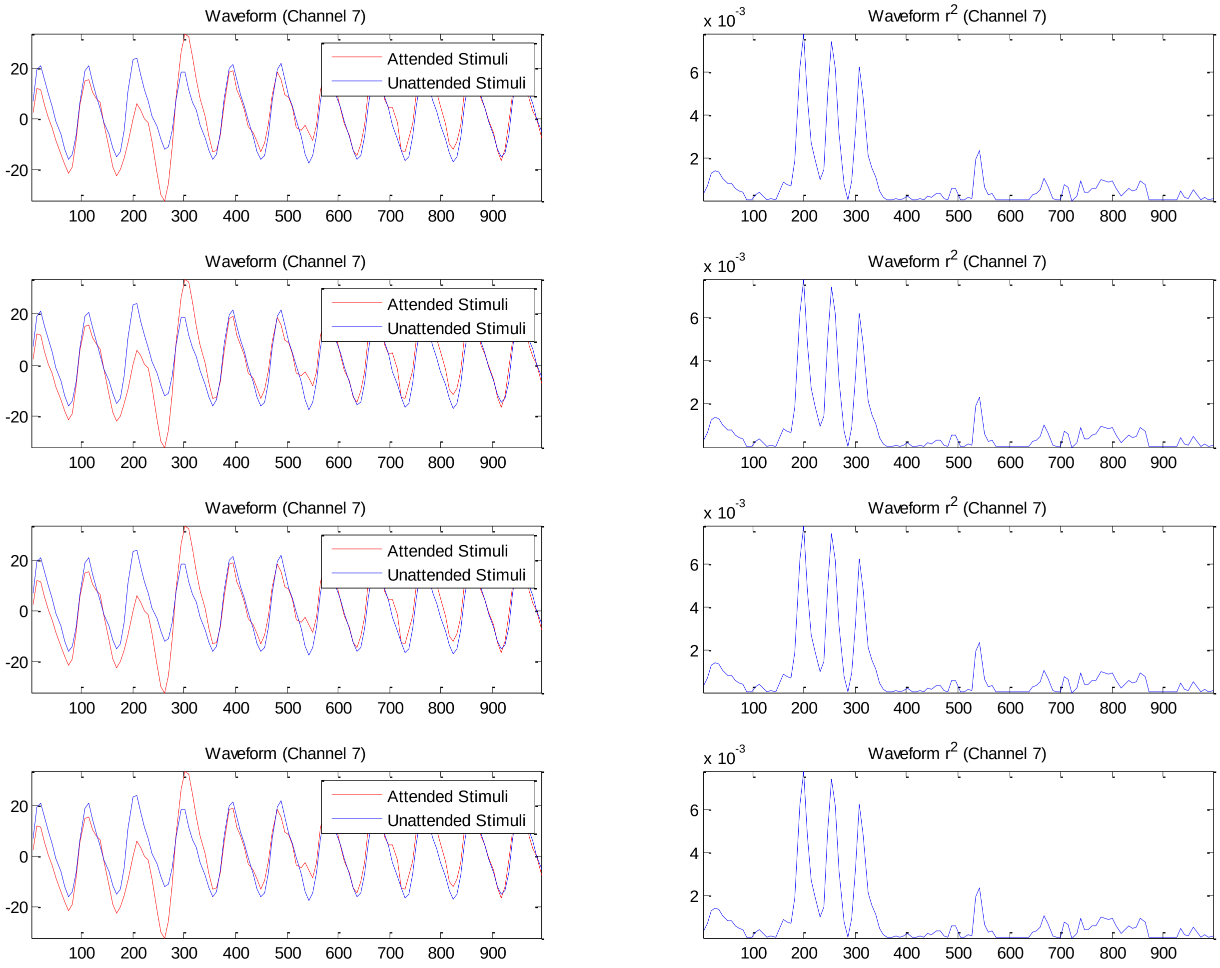


Figure 4-29: Corelation of desired stimulus and brain response.

4.5.3.2 NeuroSky MindWave

The NeuroSky MindWave was not effectively implemented with the P300 evoked potential. However, a similar process is used to startup the MindWave for further processing. A parameter file used for this device is found in Appendix G.

4.5.4 QT

QT is a development application used to generate graphical user interfaces. This application operates on a variety of platforms. QT was used in inital production of a functional application and was developed to include the NeuroSky MindWave not provided by the Mind Your OSCs application (refer to section 4.5.5).

Pure Data (refer to section 4.5.7) was found to be useful solution that could be later integrated with QT. Therefore research work was subsequently focused on the latter solution.

4.5.5 Mind Your OSCs

Mind Your OSCs is an open-source program developed by Rayne (2009) and is provided under the terms of the GNU General Public License as published by the Free Software Foundation. Mind Your OSCs helps to interface the Emotiv Epoc with other programs such as Pure Data (described in section 4.5.7 below).

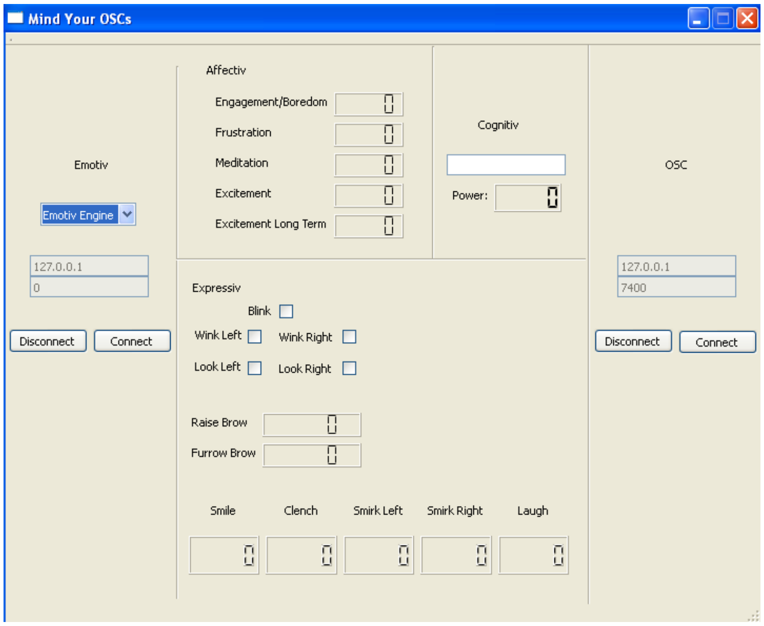


Figure 4-30: Mind Your OSCs interface.

As mentioned, this program was used in conjunction with Pure Data as demonstrated in Appendix H. Mind Your OSCs makes use of the open source oscpack developed by Ross

Bencina (2006) and is available from http://code.google.com/p/oscpack/. Oscpack provides a number of C++ classes to process (pack/unpack) Open Sound Control (OSC) packets (Bencina 2006). This tool has been designed to work within Windows and POSIX operating environments. See section 4.5.6 for further discussion on Open Sound Control.

4.5.6 Open Sound Control

Open Sound Control (OSC) is "a protocol for communication among computers, sound synthesizers, and other multimedia devices that is optimized for modern networking technology" (CNMATa n.d.). OSC provides real-time sound and media processing control and features the following:

- "Open-ended, dynamic, URL-style symbolic naming scheme
- Symbolic and high-resolution numeric argument data
- Pattern matching language to specify multiple recipients of a single message
- High resolution time tags
- "Bundles" of messages whose effects must occur simultaneously
- Query system to dynamically find out the capabilities of an OSC server and get documentation" (CNMATa n.d., p.1).

Due to is cross-platform compatibility, availability for extension, clear relationship with real-time sound control and ability to process naming schemes, OSC was considered a suitable option for developing an application for imagined music. Additionally, a number of programs have been developed that focus on mapping non-musical data to sound (CNMATb n.d.).

4.5.7 Pure data

Whilst exploring suitable options for an imagined music program, Pure Data was presented as a viable solution. Pure Data (Pd) "is a real-time graphical programming environment for audio, video, and graphical processing" originally developed by Miller Puckette (2011, p.1). This solution was attractive due to its combination of real-time processing and music features. By linking the Emotiv Epoc via the Mind Your OSCs program to Pure Data, testing was able to be conducted with various Emotiv suite components. Appendix D demonstrates the use of the frustration component of the Affectiv suite to manipulate sound output. Increased focused attention by the user caused a rise in sound pitch and subsequent mental relaxation resulted in a fall in sound pitch.

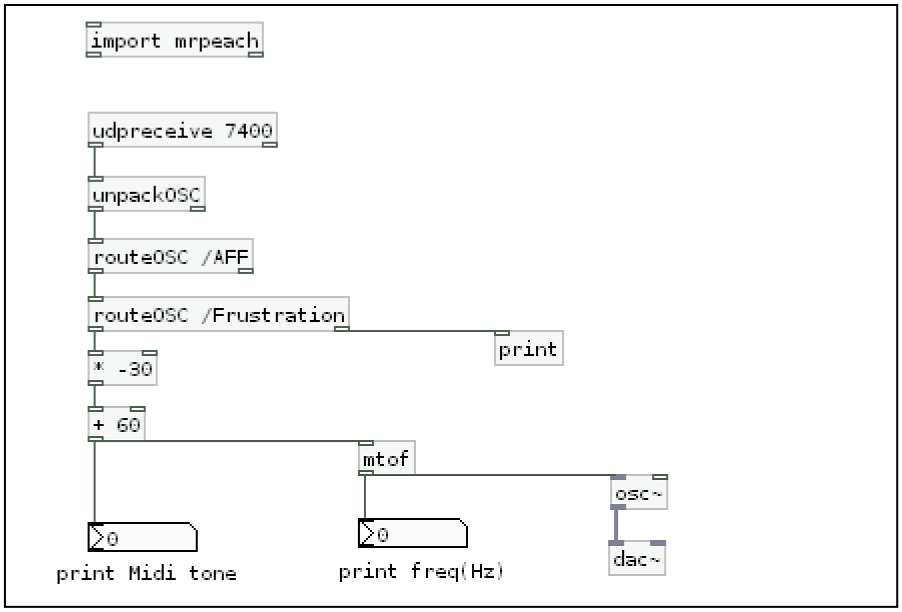


Figure 4-31: Pure Data program to extract frustration signal to control sound output.

Figure 4-31 demonstrates a basic program used to extract Emotiv data to manipulate sound output via the PC speakers. The import mrpeach command imports relevant library files such as udpreceive. Udpreceive creates a connection to the prescribed port, in this case 7400, in order to received OSC packets. UnpackOSC then converts the OSC package to a Pd-specific message. Afterwhich, routeOSC is used to direct the program to follow a particular path to obtain required data. In this example the path is AFF (Affectiv suite) → frustration (component). The mtof object is used to transpose a Midi tone to a particular frequency in Hertz. Following this, the osc~ object is used to generate a cosine wave for audio signal. Finally, the dac~ object provides real-time audio output.

4.6 Conclusion

This chapter shows that a potential solution can be developed using Pure Data for real time graphical and auditory processing of brain signals into imagined music. In-built SDK algorithms have room for improvement in developing accuracy of determining user intent. The P300 evoked potential provides one such option for performance improvement. As Pure Data is extendable, being an open source project, the P300 algorithm along with custom signal processing could be implemented as a Pure Data object. Further work on elimintating artifacts is required to improve the results obtained in this research.

Chapter 5 Developing the Functional Application

"An idea not coupled with action will never get any bigger than the brain cell it occupied."
- Arnold H.

5.1 The functional application – a framework for development

The following chapter discusses results obtained through the testing and evaluation of selected BCIs towards the development of a functional application for in-home use. It has been established that there are two main approaches in integrating the BCI device with a suitable application.

The first approach makes use of in-built SDK algorithms and links these to an appropriate application. In this approach the user creates a network connection between the BCI device and application through a control panel system or network protocol. The results have demonstrated that one useful approach is to link brain signals from the provided control panel or network protocol to OSC for further processing. This approach has proven successful by interfacing the control panel with Mind Your OSCs.

The second approach requires the developer to create their own signal processing algorithms and use API commands to establish a network connection, filter out biological and environmental artifacts, and appropriately determine user intent. This approach was tested on a simple level through the process of establishing suitable visualisation and analysis of signals. Due to its complexity, this approach, in part was beyond the scope of this research. With respect to using Pure Data, the developer may wish to develop Pd objects that provide signal filtering, feature extraction and feature translation of simplified testing with applications. As Pure Data is presented in a graphical form, this makes for efficient testing of algorithms as well as integration into other graphical forms such as OpenGL.

MATLAB was found to be an effective tool for visualisation and analysis of BCI data. By making direct calls to proprietary DLL files, this proved to be a much more efficient and flexible approach than developing mex files for MATLAB integration. MATLAB on its own, however, was not sufficient for full evaluation of BCI signals.

MATLAB was best implemented when combined with existing software tools such as BCI2000. This is due to the fact that BCI2000 has much in-built support for testing various BCI devices with different applications and signal processing methods. One such method, the P300 evoked potential, was used in this research. Limited success was obtained in writing preset words using a communication board with the Emotiv Epoc. However, occasional letters were accurately transcribed. These results may reflect interference generated by the user or the local environment. Thus an emphasis on filtering techniques is considered here for future applications. The NeuroSky MindWave was not able to function correctly with the P300 evoked potential. This may, in part, be linked to research that suggests that the P300 evoked potential is located around Cz and visual cortex (refer to Figure 2-6: 10/20 electrode positioning system (g.tec medical engineering n.d.). The MindWave however only provides one electrode placed on the forehead. This limitation presents issues of reduced spatial resolution and positioning requirements to extract suitable data.

The NeuroSky MindWave was found to be most effective in one dimensional control by adjusting the user’s level of attention. This approach still has valid applications for users with respect to determining user intent. For example, if a user wishes to increase the frequency of a note he or she can increase focus of mind. Conversely, if the frequency of the note should be lowered then user can relax the state of mind.

5.2 Improving BCIs

Through comparative analysis of selected BCI devices a number of improvements have been considered to increase the robustness and reliability of BCI solutions. The Emotiv Epoc offers the significant advantage of providing a number of channels to acquire brain signals. However, it has the disadvantages of increased setup time, maintenance requirements, and troubleshooting. This device offers the most promising potential to make use of a range of signal processing techniques such as the P300 evoked potential.

The NeuroSky MindWave provides the most efficiency, easy of use, and shorter setup and calibration times. This device is rated highly due to its compactness and simplicity of design. Moreover, the NeuroSky does not require any preparation of sensors, which is a limiting factor associated with the Emotiv Epoc. The disadvantages of the MindWave is that it only provides one sensor and thus limited BCI control for a range of signal processing techniques. The NeuroSky MindWave has a much simpler API than the Emotiv Epoc and is still relatively effective.

In order to improve future BCIs, research into the use of multiple dry sensors is encouraged. Combining the simplicity of the MindWave with the sophistication of the Emotiv could prove to be a challenging task. However, it is clear that better results are attainable for the part of the user and the carer. Further exploration into active sensors may help to provide increased signal information for processing.

On the software side of the BCI solution, it cannot be over-emphasized that signal processing and machine learning algorithms hold an important key to increasing the reliability of BCI solutions.

5.3 Factors for consideration

Whilst BCIs have offered promising outcomes for the user, there still exist a number of issues to address to increase its user profile and friendliness. These issues include user fatigue, speed, accuracy, independent control, and convenience.

Through testing and experimentation user fatigue became an apparent issue. The novelity of a new experience, combined with intense thought processing quickly brought on mental fatigue within 2 hours of use. Moreover, the pressure created by devices on the cranium proved unbearable after 1.5 to 2 hours. This pressure was almost impercible when BCIs were applied to the head, however, a cumulative pressure affect over time resulted in BCIs having to be removed for rest periods. This user discomfort in turn influenced the concentration and brain signals of the user. Future designs may need to look at more commonly used solutions such as a stylish hat.

Speed of processing is an important consideration both in terms of system processing as well as application processing. Ideally, when the user elicits an intention to act the system response should be prompt. Moreover, applications can be time consuming that require a user to attend to a series of events to simply produce a single letter or character. Creating more efficient applications so that BCI usage is comparable to mouse usage is a challenge for the BCI community.

Increasing accuracy of solutions is related to the quality of signal processing as well as the identification of user specific features that affect BCI performance.

Independent control is an important factor in this research as it is pertinent to people with moderate to profound physical impairment. Independent control does not rely on user gaze to elicit particular BCI signals but rather relates to endogenous stimuli requiring no training on the part of the user such as the P300 evoked potential. Further work in this area is recommended.

Through experimentation, the issue of convenience was raised. If the user had to move more than 2 m from the Wireless USB Adapter the signal connection was dropped between the BCI device and USB. Moreover, if the user had to remove the BCI and replace the same, this became a time consuming process, particularly with the Emotiv Epoc, to re-hydrate sensors as required, re-position sensors and determine quality electrode connection. The MindWave offers the better convenience rating.

5.4 Conclusion

This chapter suggests a framework for developing future BCI solutions. It is feasible to use existing commercially available BCI devices to develop in-home solutions. These solutions will need to consider issues of reliability, user fatigue, speed, accuracy, independent control, convenience, signal processing, and machine learning.

Chapter 6 Conclusions and Future Work

"But that the reasoning from these facts, the drawing from them correct conclusions, is a matter of great difficulty, may be inferred from the imperfect state in which the Science is now found after it has been so long and so intensely studied."

- Nassau William Senior

6.1 Summary and contributions of the research

This research has shown that two commercially available BCIs offer promising opportunities to the user with moderate to severe physical disability. These devices offer a 70% and 75% robustness rating with in-home application using the Emotiv Epoc and NeuroSky MindWave, respectively. Ratings were obtained through comparative analysis including both qualitative data, obtained through user experience, and quantitative data, which was measurable and factual.

Current solutions offer the in-home user the potential to obtain appropriate BCI control. However, in order to increase the robustness rating and reliability of each of the devices, further work needs to be established as discussed below.

Positive results have been generated from this research for future employment. Most importantly, this research has helped to establish a framework for building future functional applications for users at home. Additionally, comparative analysis of BCIs in this research may help future investigators quickly determine the benefits and limitations of existing commercial BCIs.

6.2 Limitations of research

This research demonstrated a range of useful results that can be further developed to produce functional applications for the in-home user. Nevertheless, a number of inherent limitations need to be considered in interpreting presented information and guiding future practice.

Firstly, this research has undertaken limited testing and development of signal processing techniques. Whilst the application of signal processing was originally intended at the outset, establishing a baseline for practice became a priority. Nevertheless, in order to increase the reliability of BCI solutions signal processing does need to be addressed with respect to extracting relevant features from EEG data obtained from commercially available BCIs.

Secondly, a complete functional application was not idealized due to various setbacks during the research process including lack of information with respect to appropriate compiler usage, limited or not readily accessible documentation on relevant API usage, developing knowledge into a new area of research, and variable consistency in detecting and applying user intent. Nevertheless, a framework for future applications has been established for ongoing research.

Thirdly, hardware design was implemented as a control or to further develop BCI solutions. Hardware design may be a useful focus in future BCI research.

Fourthly, the results obtained in this research could be improved through testing with multiple subjects. Nevertheless, an advantage of this research is that inter-user differences are eliminated and so results more closely reflect the actual performance of BCI devices in a range of tasks and trials.

Finally, this research only touched the surface on possible solutions available to improve issues of user fatigue, speed, accuracy, consistency, control, user friendliness and convenience, and signal processing algorithms for desired outputs.

6.3 Further Work

This research offers a framework for establishing future BCI applications. Future research should focus on the following:

- Improve inter-rater reliability by applying research testing and functional applications with appropriate subjects. The information obtained through such testing should help to guide further approaches to BCI research.

- Develop the concept of independent control. Independent control is not reliant on the usual neural pathways impacted by physical movement or positioning but rather makes use of evoked potentials to genuinely reflect user intent. Systems that promote the use of the P300 evoked potential, for example, can help to provide users with physical limitations the independent control required.

- One of the key features of BCI usage is accurate reflection of user intent. Due to the low spatial resolution of the BCI and the lower number of electrodes used in commercial BCIs as compared to laboratory based ones, signal processing work needs to focus on source localization, eliminating undesirable artifacts, more effective capture of SMR or P300 evoked potentials, and the contribution towards appropriate classification of extracted BCI features.

- One area that remains relatively untouched in this research is that of machine learning and optimized co-adaptation. Future research should focus on developing smarter systems based on neural networks in order to increase repeatability and consistency of BCI performance at home. Systems that can detect user differences or states can be optimised to work in conjunction with the user rather than the placing extra demand on user learning. The development of intelligent adaptation and learning algorithms will greatly aid this field of research.

- One observation made through this research is that of applying function abstraction modeling to enhance correlation with user intent. As discussed, the human brain has three main functional levels with brain physiological reactions at its base to complex, higher order thinking schema at its pinnacle. Abstraction layering may help to form connections between brain physiology and higher cognitive functions of the brain.

- Further research should focus on automating calibration and software operation tasks. A system has little value to a user if they are required to use physical interaction with an operating environment when they have an impairment. Moreover, the complexity of device troubleshooting can contribute to undue frustration for the user who may have limited technical skill or aptitude. Simple interface controls can help to guide the user.

- Feature extraction is a key component of signal processing. Further research into the relevant BCI features required for translation to use with functional applications is required.

- Reviewing and expanding on existing signal recording and processing techniques used in this research can prove beneficial to obtaining alternate visualization and analysis of signals.

- From a hardware perspective, more channels are better than less. However, work on reducing carer and user setup and preparation tasks is required. This may be undertaken through further investigation into dry sensor technology and active electrode sensors as opposed to passive.

- State based research may help to inform relevant user specific states useful BCI applications. Being able to detect when a user is intending to initiate action is just as important as not responding when the user does not have this intention. Such approaches can help to reduce user fatigue and attention requirements as well as allow users the flexibility of multi-tasking.

- Further applications for the home can focus on user anticipation, alertness/fatigue, familiarity/recognition, perceived error, stroke rehabilitation, robotic control and home automation.

- Further develop strategies to improve issues of user fatigue, speed, accuracy, consistency, control, user friendliness and convenience, and signal processing algorithms for desired outputs.

6.4 Conclusion

The field of BCI research is growing and developing at great speed. This research has shown that it is possible to develop a reliable, cost-effective and efficient in-home BCI application. Further work is required to increase the reliability of results.

This dissertation provided a thorough grounding into BCI research. BCIs were able to be tested using a range of software tools. In particular, MATLAB and BCI2000 proved useful for real time signal acquisition, visualisation and analysis of brain signals.

Comparative analysis between the Emotiv Epoc and NeuroSky MindWave showed that the MindWave is a better solution in terms of compactness, preparation time and ease of use. However, the Epoc is far superior with respect to obtaining a range of brain signals and responses such as the P300 evoked potential. This is due to its increased number and positioning of input channels. Both devices requires further work to reduce pressure placed on the cranium after prolonged usage.

By integrating signal features with Pure Data it was found that a viable imagined music solution could be developed. However, additional work on signal processing is required to substantiate reliable user intent.

With an emphasis on bringing BCI technology out of the laboratory and into the home, this project aims to investigate the potential of producing a reliable, cost-effective and efficient in-home BCI application for users in the general community.

Overall, this project has achieved its objectives and may help to provide a framework for commercial BCI investigation in the future.

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Appendix A

University of Southern Queensland

FACULTY OF ENGINEERING AND SURVEYING

ENG4111/4112 Research Project

PROJECT SPECIFICATION

FOR:	Jeremie ALEXIS
TOPIC:	Developing a functional application of an EEG based, commercially available brain computer interface
SUPERVISOR:	Dr. John Leis
ENROLMENT:	ENG4111 – S1, X, 2011; ENG4112 – S2, X, 2011
PROJECT AIM	This project seeks to determine and develop a viable, low cost brain computer interface solution for people with restricted movement.
PROGRAMME:	**Issue B, 14 August 2011**

1. Research background information relating to brain computer interface (BCI) design, electroencephalography (EEG) signal processing, human factors, and ethics.

2. Use MATLAB for real time acquisition, visualisation and analysis of brain signal inputs.

3. Conduct comparative analysis of selected brain computer interface systems.

4. Apply selected commercial brain computer interfaces in a functional application (e.g. environmental control, imagined music, or Functional Electrical Stimulation control for stroke rehabilitation).

<u>As time permits</u>

5. Work on improving issues of user fatigue, speed, accuracy, consistency, control, user friendliness and convenience and signal processing algorithms for desired outputs.

AGREED: __________________ (student) __________________
(supervisor)

Date: __/__/2011 Date: __/__/2011

Examiner/Co-examiner: __________________________________

Appendix B

B.1 Testing Environment – Operating System Specifications

AMD Athlon™ 64 X2 Dual Core Processor 4600+
2.41 GHz, 2.00 GB of RAM
Physical Address Extension

Microsoft Windows XP Professional
Version 2002
Service Pack 3

B.2 Emotiv Epoc System Requirements

2.4 GHz Intel Pentium 4 processor (or equivalent).
Microsoft Windows XP with Service Pack 2, Windows Vista or Windows 7.
1GB RAM.
50MB available disk space.
At least one USB 2.0 port

B.3 Emotiv Epoc Specifications

Number of channels	14 (plus CMS/DRL references)
Channel names (Int. 10-20 locations)	AF3, AF4, F3, F4, F7, F8, FC5, FC6, P7, P8, T7, T8, O1, O2
Sampling method	Sequential sampling, Single ADC
Sampling rate	~128Hz (2048Hz internal)
Resolution	16 bits (14 bits effective) 1 LSB = 1.95μV
Bandwidth	0.2 - 45Hz, digital notch filters at 40Hz and 60Hz

Dynamic range (input referred)	256mVpp
Coupling mode	AC coupled
Connectivity	Proprietary wireless, 2.4GHz band
Battery type	Li-poly
Battery life (typical)	12 hrs
Impedence measurement	Contact quality using patented system

B.4 NeuroSky MindWave System Requirements

	PC	Mac
Operating system	Windows XP/Vista/7	Mac OS X 10.5.8 or later
Processor	CoreDuo or equivalent	
Memory	1 GB or more	
Video	DirectX 9.0 or greater	Intel GMA900 or greater
Hard disk	1 GB free disk space	
USB	An available USB port	

B.5 NeuroSky MindWave Specifications

Weight	90 g
Sensor Arm Up	Height: 225 mm x Width: 155 mm x Depth: 92 mm
Sensor Arm Down	Height: 225 mm x Width: 155 mm x Depth: 165 mm
Rate Power / Max Power	30 mW / 50 mW
RF Max Power	6 dBm

RF frequency	2.420 – 2.471 GHz
RF data rate	250 kbits/s
RF range	10 m
Packet loss of bytes via wireless	5%
UART Baudrate	57,600 Baud
EEG maximum signal input range	1 mV pk-pk
Hardware filter range	3 Hz – 100 Hz
ADC resolution	12 bits
Sampling rate	512 Hz
eSense calculation rate	1 Hz

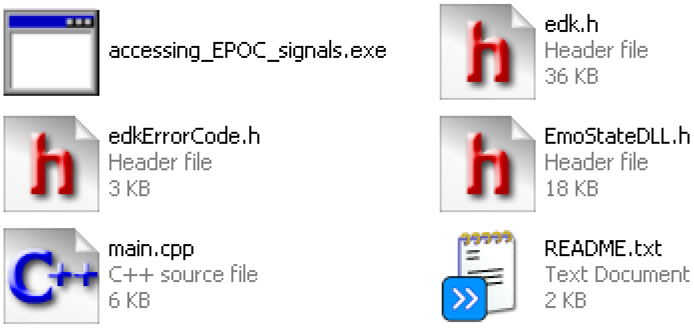
Source: NeuroSky 2011, MindWave user guide, viewed 18 July 2011, from <http://developer.neurosky.com/docs/lib/exe/fetch.php?media=mindwave_user_guide.pdf>.

Appendix C

This Appendix is included as an electronic resource. Please refer to attached resource CD.

Files included:

- edk.h
- edkErrorCode.h
- EmoStateDLL.h
- main.cpp
- accessing_EPOC_signals.exe
- README.txt



accessing_EPOC_signals.exe

edk.h
Header file
36 KB

edkErrorCode.h
Header file
3 KB

EmoStateDLL.h
Header file
18 KB

main.cpp
C++ source file
6 KB

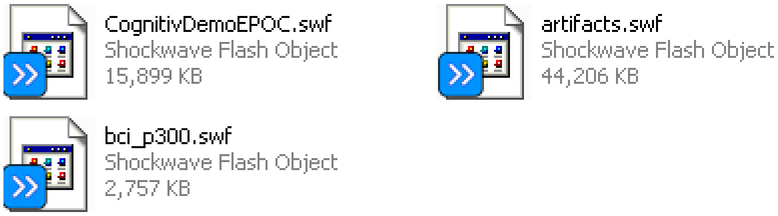
README.txt
Text Document
2 KB

Appendix D

This Appendix is included as an electronic resource. Please refer to attached resource CD.

Files included:

- CognitiveDemoEPOC.swf
- artifacts.swf
- bci_p300.swf



CognitivDemoEPOC.swf
Shockwave Flash Object
15,899 KB

artifacts.swf
Shockwave Flash Object
44,206 KB

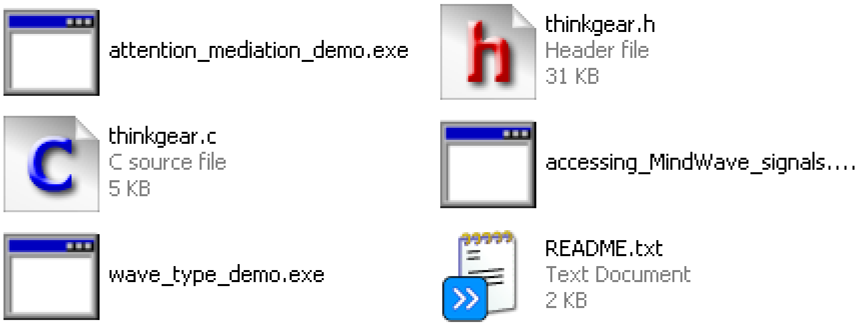
bci_p300.swf
Shockwave Flash Object
2,757 KB

Appendix E

This Appendix is included as an electronic resource. Please refer to attached resource CD.

Files included:

- thinkgear.c
- thinkgear.h
- attention_meditation_demo.exe
- accessing_MindWave_signals.exe
- wave_type_demo.ese
- README.txt



attention_mediation_demo.exe

thinkgear.h
Header file
31 KB

thinkgear.c
C source file
5 KB

accessing_MindWave_signals....

wave_type_demo.exe

README.txt
Text Document
2 KB

Appendix F

This Appendix is included as an electronic resource. Please refer to attached resource CD.

Files included:

- eeglogger.m
- thinkgear.h
- readRAW.m
- plotRAW.m
- README.txt

eeglogger.m
M File
10 KB

README.txt
Text Document
2 KB

thinkgear.h
Header file
32 KB

readRAW.m
M File
3 KB

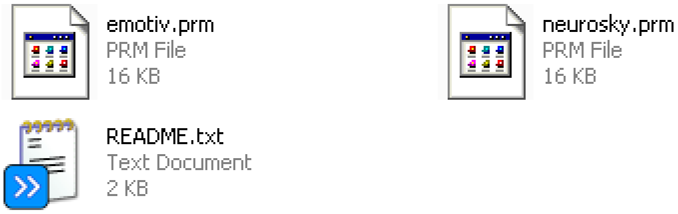
plotRAW.m
M File
1 KB

Appendix G

This Appendix is included as an electronic resource. Please refer to attached resource CD.

Files included:

- emotiv.prm
- neurosky.prm
- README.txt



emotiv.prm
PRM File
16 KB

neurosky.prm
PRM File
16 KB

README.txt
Text Document
2 KB

Appendix H

This Appendix is included as an electronic resource. Please refer to attached resource CD.

File included:

- PureData_demo.swf

PureData_demo.swf
Shockwave Flash Object
51,898 KB