A Pilot Study toward the Development of ERD and SSVEP based Hybrid Brain Computer Interface

This thesis is submitted in partial fulfilment of the requirements for the degree of

Master of Science in Biomedical Engineering

By

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13th August 2015

Declaration

‘This thesis is the result of the author’s original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.’

Signed: Date:

Acknowledgements

I would like to say thank-you to all those who have supported me throughout this project.

A special thank-you to my supervisor Dr. Heba Lakany for all her help and input.

To my friends and family; thank-you for your unwavering faith in me and all your kind words of support, especially over the last few months of this project, you gave me the confidence to keep up with my work.

Finally, a silly little thank-you to all the readers I do not know for taking your time to read this work.

Abstract

Brain-computer interfaces (BCI) are devices that allow for the brain to communicate information to a computer. In situations where a victim of brain trauma or disease has suffered damage causing paralysis or impaired movement, BCIs may be the answer in providing assistance to neurological function. Development of BCIs continues to increase, but literature suggests the next step is the hybrid brain computer interface (hBCI). The simplified concept behind the hBCI is by having two BCIs, in which both signals can be detected simultaneously, creates the situation that if one BCI is to fail to show user intent the other may succeed. Using a non-invasive method such as surface electroencephalogram (sEEG), able to detect signals from brain activity, this pilot study will look into the development of a hBCI combining the modalities of event-related de-synchronisation (ERS) and steady-state visual evoked potentials (SSVEP). The aim of this project is to show the hBCI proposed works, to find where improvements can be made and to identify the synergies of SSVEP and ERD modalities.

A duel task experiment was performed on 4 healthy subject, ages 22-35, in which they must look at a flickering LED and move their wrist in the direction corresponding to that LED. Four LEDs are setup about a point, providing intuitive directions for wrist movement, and only one will flicker at any time.

Results show that the SSVEP and ERD hBCI can work, but there may be limitations. The main limitation suggested by the results have also been found in other literature and is known as ‘dual-task interference’. The cause of dual-task interference hasn’t been well documented and only suggested or speculated so far.

Future experiments should validate the cause of this dual-task interference in hBCIs.

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Table 1. Explanation of sample code of the used.

List of Abbreviations

BCI	=	Brain Computer Interface
ECoG	=	Electrocorticography
ERD	=	Event-Related De-synchronisation
ERS	=	Event-Related Synchronisation
fMRI	=	Functional Magnetic Resonance Imaging
hBCI	=	Hybrid Brain Computer Interface
(s)EEG	=	(Surface) Electroencephalography
LED	=	Light Emitting Diode
MEG	=	Magnetoencephalography
MRI	=	Magnetic Resonance Imagining
NIRS	=	Near-Infrared Spectroscopy
SCP	=	Slow Cortical Potential
SE-hBCI	=	SSVEP and ERS Hybrid Brain Computer Interface
SSVEP	=	Steady-State Visual Evoked Potential
VEP	=	Visual Evoked Potentials

1. Introduction

Humans need to be able to communication and interact with others and their environment. The only way to do this is through movement. Actions such as speaking, sign language, touching and all manner of other gestures humans use each require some movement of their body.

The most debilitating diseases and disorders are those which hinder or stop movement, and thus the ability to communicate or interact. There are many causes of such debility; injuries, genetic factors and infections that result in nerve damage or impede anatomical function. Examples of some of the more serious conditions are multiple limb amputations and permanent paralysis. Examples of the most debilitating of them all are locked-in syndrome and amyotrophic laterals sclerosis.

Locked-in syndrome is a state of paralysis and can be the result of a stroke or head injury. The mind is fully conscious but the body is unable to respond to any of the brains voluntary commands, except eye movements and blinking (Smith and Delargy, 2005). Whilst amyotrophic lateral sclerosis is a disease that gradually degrades the functionality of motor neurons, eventually leading to a similar fate or death (Mancuso and Navarro, 2015).

Prevalence of amyotrophic lateral sclerosis in the U.S. population is reported to be 3.9 per 100,000 persons from October 2010 to October 2011 (Mehta et al., 2014). Prevalence of locked in syndrome in the EU is not currently an available statistic, however, in 2013 a study found 0.7 per 10,000 patients in Dutch long-term care organisations (Kohnen et al., 2013).

However, with the introduction of brain-computer interfaces (BCI), an alternative method of communication and interaction has become possible for some of these conditions.

As the name may suggest; a BCI is a device that is based on a brain signal detection method, and its main function is to act as an alternative interface by which the brain activity is recorded, analysed by a computer. The computer then transforms and classifies the recorded brain signal into a specific understandable command that allows for interaction with the subject's environment. One could consider BCIs as a form of translators for some of the brain activity.

Even more recently hybrid brain-computer interfaces (hBCI) have been developed. These hBCIs are a type of BCI that has combined either two individual brain signal detection systems or one brain and another physiological signal detection systems. Evidence from hybrid systems that have been created suggests that there has be an increase in BCI literacy, classification accuracy, reliability, information transfer rates, overall performance and reduction in false-positive outcomes when compared to non-hybrid BCIs. These terms are discussed in the Literature Review section. Although, what is improved and by how much depends on the combination of signals and the analysis methods used.

BCI studies investigating event-related de-synchronisation (ERD), in sufferers of amyotrophic lateral sclerosis or locked-in syndrome, have shown it is feasible, although the ERD signal is somewhat decreased (Kasahara et al., 2012). ERD suggests that a movement is being attempted or imagined. The last muscles to lose function are usually those responsible for eye movement and sphincter control (Smith and Delargy, 2005, Mancuso and Navarro, 2015). With the eye movements remaining functional, apart from in the most severe cases, this allows the usability of BCIs that use steady-state visual evoked potentials (SSVEP). SSVEP shows that the subject is looking as a visual stimulus flickering at a certain frequency.

It is important to develop the technology for BCIs that can make use of the advantages resulting from combining individual BCI modalities. This allows for future BCIs to increase their assistive and augmentative capacity and capability.

The aim of this project is to perform a pilot study on creating a hBCI that combines detection of steady-state visual evoked potential (SSVEP) and event-related de-synchronisation (ERD) during a motor task.

The objectives of this pilot study are:

- To show that ERD and SSVEP based BCI can be used together.
- To identify any challenges with using ERD and SSVEP.
- To identify synergies in using two BCI modalities.

1.1 Background

BCIs are devices that require, by definition, detection of brain signal. Not only are there multiple methods of recording and detecting brain signals and activity e.g. electroencephalography (EEG), magnetoencephalography (MEG), electrocorticography (ECoG), magnetic resonance imagining (MRI), functional magnetic resonance imaging (fMRI), near-infrared spectroscopy (NIRS), but there are also multiple signals that can be detected in the brain e.g. slow cortical potential (SCP), visual evoked potentials (VEP and SSVEP), event-related potentials (P300 and ERD/ERS) (Leuthardt et al., 2009, Daly and Wolpaw, 2008).

Invasive methods of recording for BCIs would provide the clearest results, but there is obvious high risk to the health of those who would use them. However, this question is very difficult to answer ethically. Due to the ethical concerns and requirements these methods tend to be less popular.

Non-invasive methods have challenges to meet regarding, for example, signal to noise ratio but pose almost no or little risk to the user. These would have the most benefit for the risk involved and generate much less ethical concern. As such they tend to be the more popular type to research in current times. They also have a much

larger potential toward the gaming market for the general population, as seen with the Emotiv™ BCI (Boutani and Ohsuga, 2013).

There are many different types of BCI each with its own set of advantages and limitations when compared to one another. The same can be said of using one of the many detectable signals in the brain. Combining different BCIs modalities together, or with a device that records a non-brain based signal, this creates a hBCI. To be considered a hBCI at least one of the devices must record a signal from the brain (Pfurtscheller et al., 2010a). Depending on the combination, it is possible to get a unique set of the overall advantages and disadvantages. The desire at this stage is that the combination results in maximised advantages whilst minimising the limitations.

A couple of issues with designing and developing a hybrid BCI system, costs aside, are an increase of the device's complexity and the demand on the subject. The greater complexity leads to more time to spend on the set-up, to validate the hybrid and to sort out the following analysis.

In this thesis the focus is on using non-invasive EEG recording to simultaneously detect SSVEP and ERD, and does not go into further detail with the other types or other combinations.

1.1.1 Brain

The brain is a very complex organ. One of its main tasks is to process input of sensory information and control motor output. Thinking of the brain simply, it can be said that various areas within have developed to deal with certain tasks be it motor or sensory based (Frahm, 1993). Various areas are illustrated in figure 1 (Bear et al., 2007).

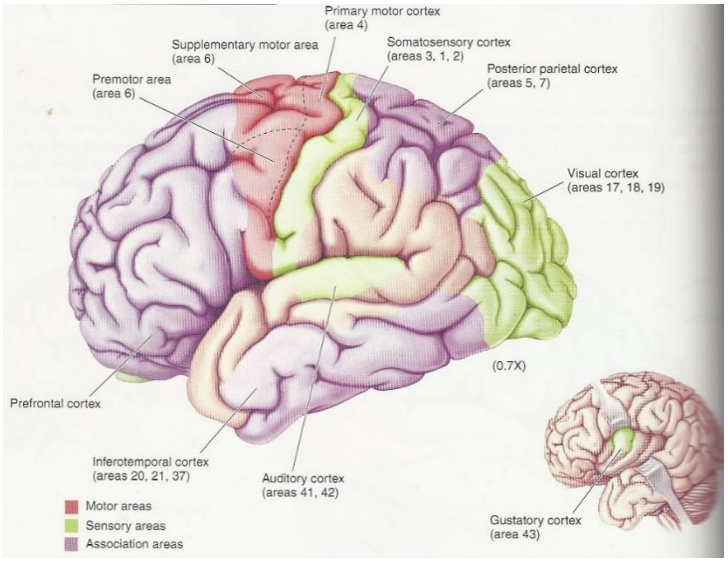

Figure 1 illustrates the numerous areas of the brain (Bear et al., 2007).

The brain is heavily interconnected within itself and it has been shown that multiple areas are responsible for a specific outcome (Kelly et al., 2010, Frahm, 1993). The concept of a specific part of the brain being responsible for a specific function is most likely correct, however, with what we consider as a simple action tends to be made up of multitudes of much smaller interactions within the body. An example for this would be the act of saying a simple word such as ‘the’; the musculature controlling the jaw, tongue and lips must be activated in a very specific sequence to get the right sounds out at the right time throughout the pronunciation of the word. Not only must the brain process that information but it must also interrupt the autonomic control over breathing to get the required amount of breath through the vocal chords that must be contracted at that precise moment. There is more than what is mentioned that a normal brain would have to process, however, that was an example of just how complex a function can be which the average person would consider very simple task. The main areas of interest for this project are the motor cortex, shown to be responsible for voluntary motor function of the body (Pineiro et al., 2001), and the

occipital lobe, shown to be responsible for visual processing (Bender et al., 1957). These are the areas that ERD and SSVEP can be recorded from, respectively (Allison et al., 2012).

1.1.2 EEG

Surface Electroencephalography (sEEG) is a method that uses electrodes to record the brain's activity by measuring electrical signals across the scalp over time. This signal is amplified, filtered and analysed. Analysis can then be performed on the data by a computer. There are many methods of analysing EEG and some of these are discussed in the analysis section.

Measurements made by the electrodes represent the changes in the electric fields generated by neuronal activity. When an action potential travels along a neurone the current produces an electromagnetic field (Francis et al., 2003), this is illustrated in figure 2 (Baillet, 2010).

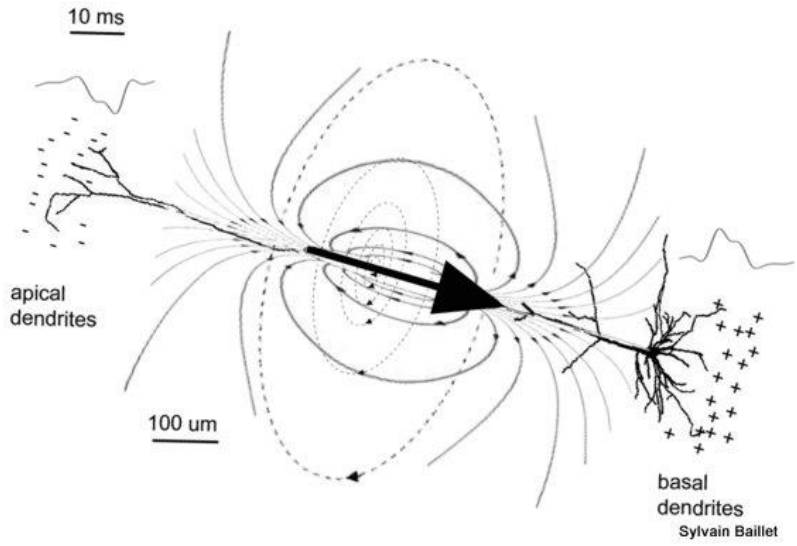

Figure 2 illustrates the electric fields generated by an action potential (Baillet, 2010)

The more neurons that are active, simultaneously, the stronger the electromagnetic field produced (McFadden, J. 2002). As someone performs a specific action, or experiences a specific sensory stimulation, a larger number of neurons become active within certain areas causing a larger change in the pattern of electric fields. This partially refers back to the complexity of performing an action mentioned earlier, for example, a large number of neurons are required to activate a group of muscles to perform a single action. Neurons that have control over different parts of a single limb are anatomically quite close to each other, as shown by the motor cortex homunculi shown in figure 3 (Dewey, 2007).

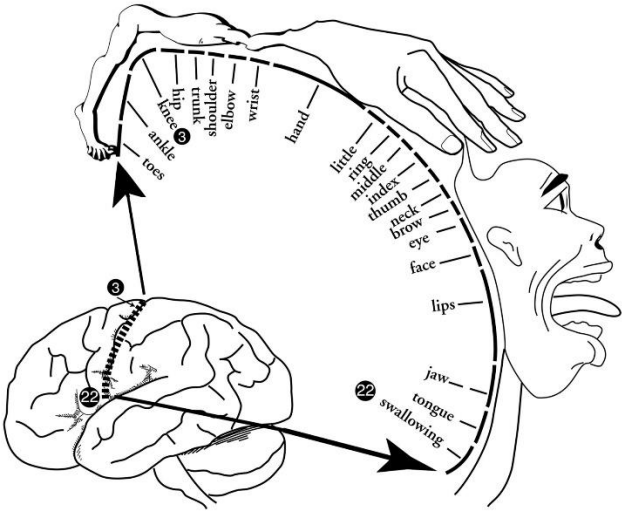

Figure 3 illustrates the motor cortex homunculi showing how different areas of the cortex are responsible for processing information from across different limbs (Dewey, 2007).

The concepts of electromagnetic field generation in neurons follow those of electromagnetic fields created by current flowing through a wire. Some of the principles and observations made for wires can be applied to neuronal activity. One of the more important principles would be that the further the distance from a current,

the weaker the electrical fields are. This gives rise to the problem that small activations or activation deep in the brain may not be detected at the surface. There is also the possibility that noise generated from regular brain activity may drown out the desired signal.

When attempting to detect a specific signal, caused by performing an action, it is impossible for someone to only activate the area(s) involved with that action. Many autonomic functions and voluntary decisions are made at the same time to maintain an alert and interactive status. All this activity results in undesirable signals in the recorded data, these unwanted signals are considered as noise. During the recording, of EEG, short periods of relatively large amounts of noise are caused by actions such as swallowing, coughing, head movement, jaw clenching, blinking and eye movement. Subjects of EEG experiments, when told to sit still, may, for example, feel the need to perform some or all of these actions to relieve an irritating sensation and feel more comfortable. Any signal detected at the same time as these events must be discarded in the final use of the data in order to avoid analysing the noise instead of the desired signal.

Ideally the change in electric field is so large that the recorded signal can be easily selected from amongst the noise. Having the electrodes in the closest position to the area of activity provides the best signal acquisition. However, placing electrodes at any position over the brain would make comparisons to other works difficult. This problem has been dealt with by creating various patterns of electrode positioning. The most common being the standardised international 10-20 electrode placement, illustrated in figure 4 (image from TCT Research Limited, 2012).

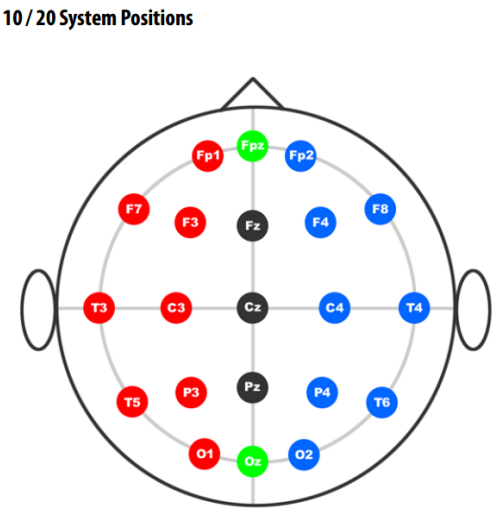

Figure 4 illustrates the 10/20 system positions (image from TCT Research Limited, 2012).

With this system the furthest distance an electrode could be from the optimal positioning, across the scalp, would be 10% of the scalps total length. The 10-10 electrode placement reduces this to 5% by placing electrodes in-between those of the 10-20 set-up, illustrated in figure 5 (image from TCT Research Limited, 2012).

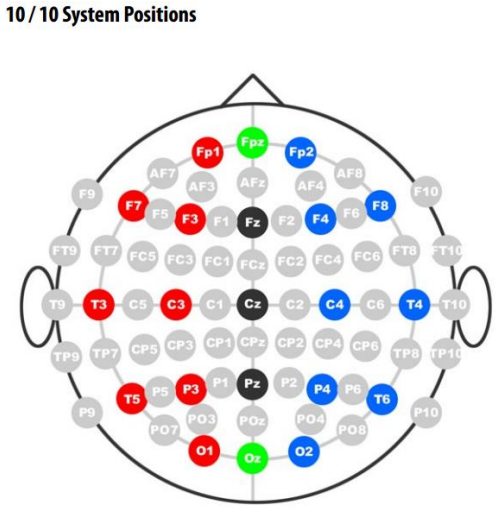

Figure 5 illustrates the 10/10 system positions (image from TCT Research Limited, 2012).

1.1.3 SSVEP

Steady-state visual evoked potentials (SSVEP) are a popular signal to measure for BCIs because of its higher user literacy, minimal training period and information transfer rates (Pfurtscheller et al., 2010a). It is detected by recording EEG activity in the occipital lobe which corresponds to a constant flickering visual stimulus. The frequency at which the visual stimulus flickers is matched by an equal frequency of synchronised activity in the occipital lobe (Wu et al., 2008). To acquire strong SSVEP signals requires the user to stare at a flashing LED of frequencies about 15Hz (Luo and Sullivan, 2010), or lower (Lin et al., 2012), as this has been shown to provide the highest amplitudes.

Frequencies around the range of 15-25 Hz are associated with inducing an epileptic fit (Fisher et al., 2005) and should be avoided. Sufferers of photosensitive epilepsy should not be using SSVEP based BCIs. This leads to a decrease in potential user population. Also, those with damage to the occipital lobe or blindness would not be able to use SSVEP based devices. Various visual impairments reduce the strength of the signal recorded (Lin et al., 2012). SSVEP based BCIs would be ideal for people without any sort of visual impairment but even those with minor visual impairments, such as those with corrected vision by use of glasses, should still be able to benefit from the device.

There are still more considerations to be made with using SSVEP signals. Although not a major problem, there is a limit to usable frequencies, ranging from 3.5 to 75 Hz (Luo and Sullivan, 2010), and the minimal difference detectable between different frequencies is 0.2Hz (Srinivasan et al., 2006). This potentially allows for up to 357 different usable frequencies. However, harmonics of selected frequencies must also be taken into consideration (Zhu et al., 2010). For higher frequencies; prime number frequencies would be the best choice. For lower frequencies; 4Hz and 6Hz could also

be considered equivalent to prime values because, as mentioned earlier, the minimal value measureable is 3.5Hz, so 2Hz and 3Hz would not be used.

The different frequency bands of natural brain activity generate a lot of noise, and it is important to know what to expect from the frequencies selected. The different bands (rhythms) are known as:

- Delta (1-4Hz), related to high emotional or sleep states in young children.
- Theta (4-7Hz), related to high emotional or sleep states in children and adults.
- Alpha (8-12Hz), related to relaxed state.
- Beta (12-30Hz), related to awake or de-synchronised states.
- Gamma (25-100Hz), related to activity in the somato-sensory cortex.

Information of these bands has been gathered from Setare et al., 2013.

1.1.4 ERD

Event-related de-synchronisation (ERD) is the other brain signal to be measured. De-synchronisation in the motor cortex corresponds to an imagination or intention of movement. The signals generated have been related to the de-synchronisation or suppression of μ waves which are between 8-13Hz (Pfurtscheller et al., 2006), sharing a similar band to alpha waves but are found more specifically over the motor cortex (Pfurtscheller et al., 2006). μ waves represent the inactivity of the motor cortex, and so de-synchronisation of this frequency band suggest activity. Harmonics of these values have also been used (Allison et al., 2010, Brunner et al., 2010).

The specific pattern of activation across the motor cortex can be linked to a specific movement of a certain limb (Pastor et al., 2003, Pfurtscheller, 2001, Blankertz et al., 2004). By comparing patterns of activation of multiple locations, or a single location

over time, key features can be identified from the significant differences in the patterns (Jia et al., 2004). These features can then be used to identify which action has been performed from the EEG.

However, there are also quite a few problems associated with ERD measurement. One of the problems is shared with the SSVEP BCI, in that there is a difference in brains between members of the population. Therefore, the signal might not always be generated from the same location every time. Also, another problem is the large frequency bands. The frequencies that are generated, or suppressed, can have a large variation from person to person (Mohr and Nagel, 2010).

ERD originates from within the brain whereas SSVEP requires sensory information from outside the body to be produced, so any break in the process leading up to neuronal stimulation would prevent SSVEPs. ERD has more problems with BCI literacy (Pfurtscheller, 2001, Pfurtscheller et al., 2010a) and training (Setare et al., 2013), compared to SSVEP, which could be a result of not being able to predict the outcome of the ERD as is possible with the SSVEP. There is also the issue average person finds it much more difficult to imagine a motor task than to look at a flashing light (Brunner et al., 2011, Allison et al., 2010) which could contribute to the limitations of ERD BCIs.

2. Literature Review

From this point onward, in this thesis, the hBCI using SSVEP with ERD will be referred to as a ‘SE-hBCI’.

When comparing papers discussing similar or the same research, for example using the SE-hBCI, results generated may differ significantly(Pfurtscheller et al., 2010a). The differences between papers are not always clear and sometimes some information is left out. It is important to review the literature in an attempt to identify

some of these differences, but it is also important to identify the similarities and points authors agree or argue on. Thus a literature review provides a good rounded point of view into the chosen topic of interest.

2.1 Review of SSVEP and ERD hBCI from Literature

This section will look into the past and most recent uses of the SSVEP and ERD hBCI, providing a better understanding of the overall system, its requirements and limitations. There will be a focus towards providing reasoning into the decisions made for this project.

Many papers have shown that the hybrid of SSVEP and ERD is able to work and work well (Allison et al., 2012, Brunner et al., 2010, Pfurtscheller et al., 2010a, Li-Wei et al., 2014). Papers that studied the single modalities SSVEP and ERD before combining them into a hBCI provide a good comparison between the hBCI and a BCI. The hBCI and BCI are mainly compared to each other with use of values gained for:

- Classification accuracy, the probability of which the intent of the subject can be correctly categorised, for example, correctly answering the question; is the subject intending to move right or left?
- Reliability, the extent to which results of an experiment will yield the same results.
- Information transfer rates, the number of bits of data transferred per second. More is better.
- Reduction in false-positive, or false-negative, outcomes. Using the example question of; is the subject intending to move left or right?, a false-positive would be chance or number of times the BCI reads left or right when there is

no intention from the subject, and a false-negative is when the BCI reads nothing when the subject is intending to move left or right.

In the process of showing the hBCI works a lot of papers decide not to measure the false readings (Allison et al., 2010, Brunner et al., 2011, Li-Wei et al., 2014), because at this stage the more important outcome is to show its functionality. This pilot study takes on this same thought, the objective is to show that the hybrid is able to work and is an area of research that should be continued. Pfurtscheller et al., 2010, are one of the few that have measured false-positive rates, achieving 1.46 per min in their experiment, and showed that using one of the modalities as a switch greatly reduced the rate of false-positive, without the switch they yielded 5 per min. This shows one of the many possible functionalities of using the hBCI.

The highest accuracies achieved with the hBCI are 97% and 95.6%, achieved by Li-Wei et al., 2014 and Brunner et al., 2011, respectively. These values are over 10% higher than what most other research teams have achieved, which are in the region of 70-85%. This information suggest that although high accuracies are possible it is less likely that results will achieve similar values, making the reliability of these high accuracies questionable and further validation by repetition of the experiments should be done.

Brunner et al., 2011, are one of the few research teams that compared their hBCI accuracy to the accuracies of the individual SSVEP and ERD modalities, generated from experiments they performed. Their results show that if averaging the accuracy of the individual BCIs together, yielding 89%, and comparing it to the hBCI, yielding 96.5%, the hBCI obviously has a higher accuracy. If the hBCI is compared to the individual modalities the SSVEP BCI produces a higher accuracy, 98.1%, whilst the ERD BCI is much lower, 79.9%. This shows that there is a large benefit to ERD in the hybrid, however, the SSVEP becomes slightly more limited. Other research teams

that compared the individual BCI to the hBCI showed similar results; that the SSVEP BCI outperformed the hBCI. Allison et al., 2012, also showed that, 4 of their 6, subject's results suggested that the ERD modality had been limited. Allison et al., 2012, go on to discuss the cause of this may be 'dual task interference', an occurrence by which one of the tasks has an influence over the other modalities recording.

If a subject using a BCI or hBCI produces results that show accuracies of less than 60-70% the subject is considered BCI illiterate (Pfurtscheller et al., 2010a). Different studies use either 60% or 70% as their threshold. Logic suggests that use of hBCI can increase the user literacy, because if one BCI is to fail to show user intent the other may succeed. Results from Allison et al., 2010, suggest this to be the case, with 2 of their BCI illiterate subject, under 70% accuracy, achieving over 70% with the hBCI.

Allison et al., 2010, and Brunner et al., 2011, gave participants questionnaires to try to correlate any failing or problems with the feelings of the subjects. Brunner at al., 2011, following and improving upon questionnaire used by Allison et al., 2010, was able to achieve better answers, by using words instead of numbers to rate their experience, in their questionnaire and gain a better idea of possible ideas for improvement from them. The results of the questionnaire suggested that the simultaneous tasks of motor imagery and visual were more difficult than the separate tasks. Therefore, in this pilot study the tasks must be made simple and as intuitive as possible to avoid any difficulty. To help reduce the effect the experiment has on the subject a comfortable intensity of LED will be used.

The most common LED flicker frequencies used appear to be 8Hz and 13Hz (Allison et al., 2010, Brunner et al., 2011, Pfurtscheller et al., 2010b), which are at the ends of the bands for expected ERD, mentioned in the background. Therefore the frequencies chosen in this pilot study should avoid going too much in the band of μ rhythms. The papers mentioned also check for the harmonics of the flicker frequencies, and so the

chosen frequencies must avoid overlapping fundamentals and harmonics in order to avoid confusion or false positives in results.

The main considerations acquired from this review are:

- To ensure appropriate LED frequencies are selected. These must avoid overlap of fundamental and harmonic frequencies of each other. Frequencies chosen should also avoid the areas between 8-12 Hz, and its harmonic of 16-24 where possible.
- To ensure the motor task is as simple and easy to complete. This should be a very simple movement and very intuitive with the cue and the visual task.
- To be aware of the possibility of dual task interference when analysing the results.

3. Method

The objective of this study is to investigate the feasibility of developing a hybrid brain computer interface using SSVEP and MRP (movement related potentials). This section details the experimental set up, protocol and subjects involved in the experiment. Data produced from the experiment and methods of analysis of the data sets are also described

3.1 Experiment Setup

3.1.1 LED Setup

Four holes are made in a squared piece of cardboard (30x30cm), to hold the LEDs, equidistant from each other 10cm vertically and horizontally away from the centre as

shown in Figure 6. Four LEDs are set up in the cardboard and wiring behind is taped down, to the back of the board to minimize movement of the wires.

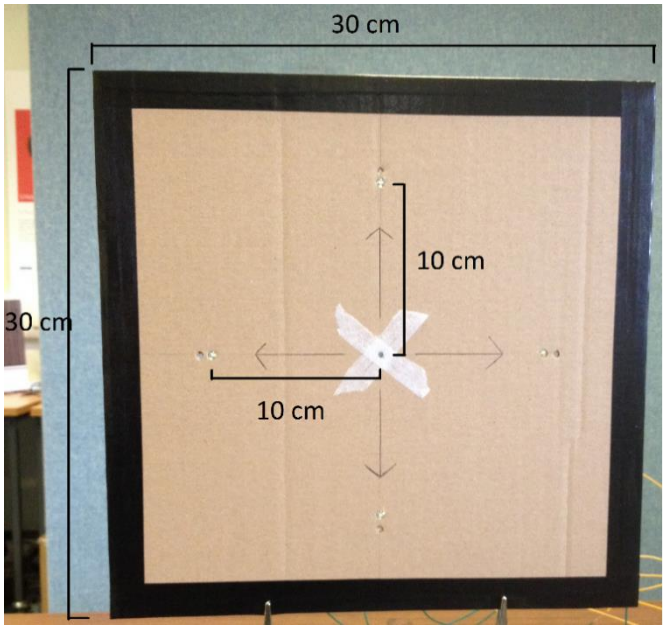

Figure 6. Illustrates the cardboard background with LEDs mounted. Measurements of the board are shown.

The cardboard also is used as a plain background to prevent attention being drawn away from the LEDs. Black electrical tape is applied along the edges to strengthen the cardboard and as a frame to attempt to keep the subjects attention within the edges of the cardboard. The centre of the board is marked with a white 'X', made from Micropore™ tape, with an inked black dot in its centre. The white tape 'X' and black dot make the centre easily found for subjects to rest their eyes upon. This helps prevent too large a movement made with the eyes at the start and end of each trial, reducing eye movement artifacts in the EEG.

To avoid complications of the experimental setup, such as inability to valid the flicker frequencies that can arise from using a computer screen, LEDs with a microchip controlled circuit are used instead. The breadboard circuit allows for use of an oscilloscope to check the frequencies, at the pins, produced by the microchip.

An oscilloscope is used to validate the frequencies produced, for the LEDs, by the microchip.

3.1.2 Circuit

Figure 7 shows a circuit diagram of the circuit built into the breadboard.

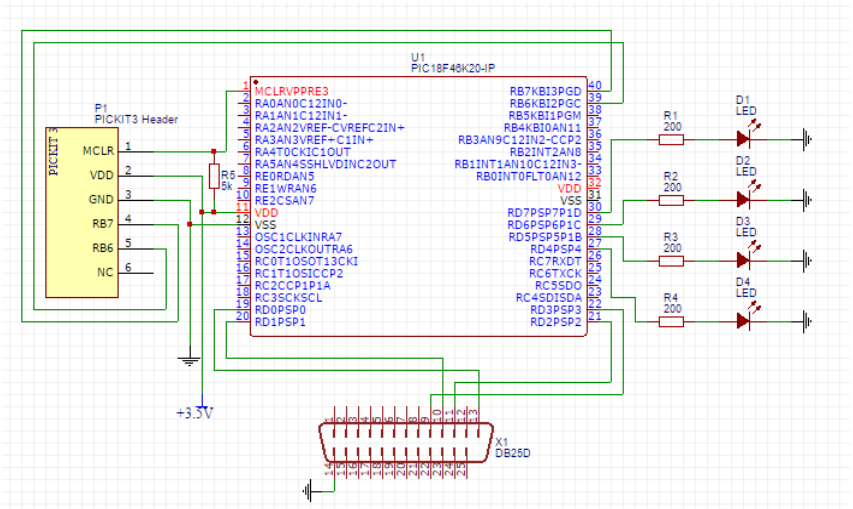

Figure 7. Illustrates the circuit diagram of the breadboard circuit created for the experiment.

3.1.3 Microchip

A PIC18F46K20 microchip is programmed to make the LEDs flicker at the desired frequencies and durations, as well as send a trigger signal to the computer software Curry 7™ at the start of each trial.

The trigger signal is sent via a DB-25 Female connector with 9 wire core cable to a DB-25 Male connector with 9 wire core cable that is connected to the Neuroscan™ EEG via the another DB-25 Female connector. Only 5 of the 9 wires in the cable are used, this is because 4 allow for an easy trigger signal coding with 1 extra for the ground connection.

MPLab X™ is the software program used in conjunction with an X8 compiler to code the programing for the microchip. The programming language used is C. Code for the microchip sets the LEDs flicker for a fixed duration approximately 3s or 4s, ±0.25s, with a rest period of 6s or 7s, ±0.25s. In total, there is a period of approximately 10s from the start of one LED flashing to the next, this is one complete trial. The

randomisation of stimulation period between 3 or 4 seconds for flicker duration helps prevent the subject from habituation, i.e. predicting when the LED stops flickering. The subject is not informed of the specific durations of the LED on or off periods.

Frequencies that the LEDs flicker at are 8Hz, 9Hz, 13Hz and 14Hz. These frequencies have a corresponding trigger of 64, 32, 16 and 8, respectively.

A random sequence, made up from 44 trials, is used to split up the experiment and allow the subject rest breaks throughout. A sequence has each LED turn on 11 times before it ends, totaling 44 trials in each sequence. The number of trials is chosen as the maximum number that can fit into the maximum predicted duration of the experiment, that being 1hr 30mins. More information on the timing of the experiment can be found in the 'Experiment Protocol' section.

To generate a random sequence a Random Sequence Generator (RSG) is used. Input values to this generator are; the smallest value is 1 with the largest being 44, this is set to format in 8 columns. Columns 1 to 4 are assigned frequencies with 3 second durations and columns 5 to 8 are assigned the same frequencies with 4 second durations. This results in 4 more 3 second durations. The random numbers generated into each column provide the order, from 1 to 44, of when each frequency with duration of 3 or 4 seconds is coded. An example of a generated sequence is visible in figure 8.

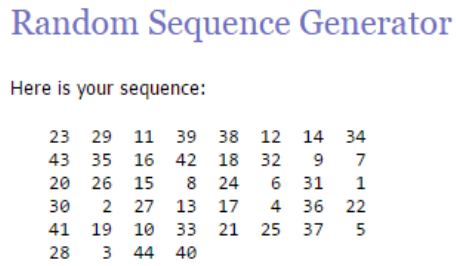

Figure 8. Cropped Screen-print of the www.random.org sequence generator. Above numbers were not used, this screen-print is just an example of how each sequence was created.

Table 1. Explanation of sample code of the used.

Code	Explanation

// Trigger for 2
TRISD = 0b00001111;
Delay1KTCYx(25);
	<- Here starts the trigger sequence for LED 2.

TRISD = 0b00001011; Delay1KTCYx(25);	<- The change of 0 to 1 will cause a 32 trigger signal to be sent to Curry 7.
TRISD = 0b00001111;	<- Here ends the trigger signal for LED 2.

// Frequency 9 Hz
for(i=0;i<54;i++)
	<- This code tells the chip to repeat the next bit of code 54 times before moving on.

{ LATDbits.LATD6 = ~LATDbits.LATD6;	<- This code causes pin 6, connected to LED 2, to toggle on or off creating the 50% cycle.
Delay100TCYx(135); }	<- The delay here causes the microchip to wait approximately 5.4ms.
PORTD = 0;	<- This bit of code ensures all pins are off

for(i=0;i<10;i++)
{
Delay1KTCYx(175);
}
	<- This bit of code make the microchip wait approximately 7 seconds

Toggling a pin, as mentioned in the code sample in table 1, every 5.4ms means it is being toggled at approximately 18Hz. The toggle means that the LED flash on for half that frequency, this generates the 9Hz required of LED 2. The trigger signal, timing delays and pin toggles are uniquely set to each of the 8 possible outcomes. The final sequence is made from these bits of code one after the other.

A PICkit™ 3 In-Circuit Debugger is used to upload the program from a laptop computer to the microchip. The PICkit™ 3 is also used as the power supply for the circuit, via the laptop which is connected by its charger to the mains. The PICkit™ 3 is set to supply 3.5V to the circuit.

The PICkit™ 3 is connected to the laptop via a USB cable; one end is the standard USB that can be connected to the laptop and the other is a mini-B plug which is connected to the PICkit™ 3.

A laptop does not need to be used. Any computer with a USB port and able to run MPLab X™ would be sufficient. The laptop is used as it is easily portable allowing for a more flexible set-up.

3.1.4 Curry 7™, Amplifier and Neuroscan

Electrodes are connected to an amplifier which is connected to the Neuroscan™ EEG which then relays the information to the computer and the software Curry 7™. Set up for the electrodes is planned out in acquisition configuration shown in figure 9.

Curry 7™™ allows for EEG acquisition, processing and analysis. Curry 7™ is used to set the recording channels, sampling frequency to 2 kHz, filters band pass between 1 to 49 Hz and a notch filter at 50Hz, and validate that the impedances of electrodes are below 5kΩ. Referencing is set to compute average reference (CAR).

Curry 7™ is also used to validate the trigger signals sent from the microchip.

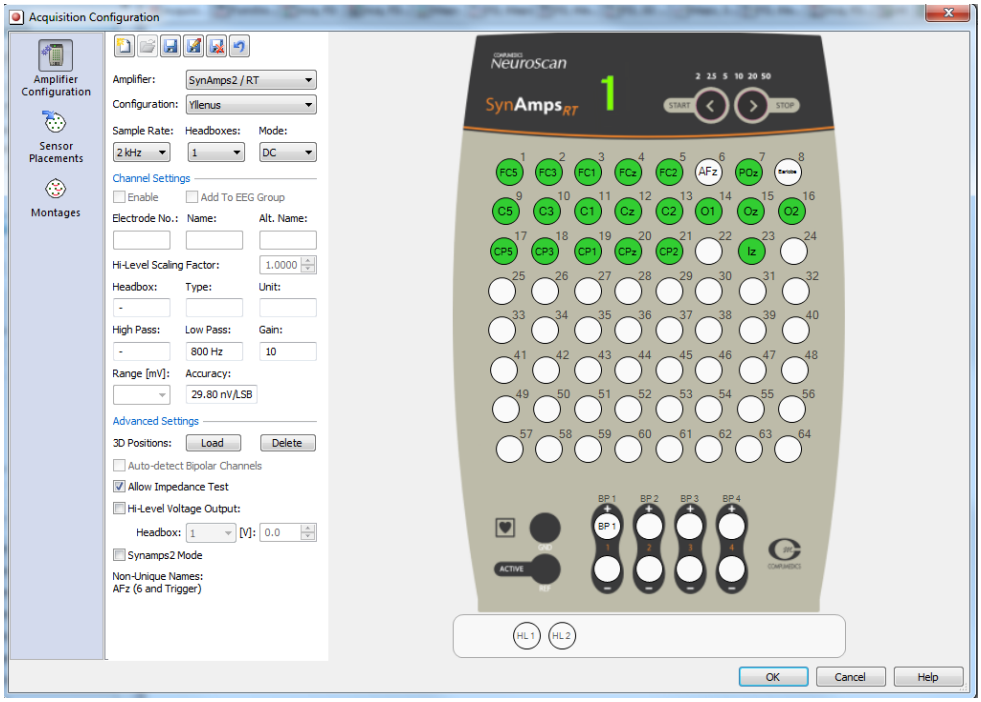

Figure 9. Shows a print-screen of the acquisition configuration as seen in the Curry 7™ software. Channels are set into a topographic layout partly matching the layout of electrodes on the EASYCAP, making it easy for the researcher to remember.

3.1.5 Subjects

Volunteers are asked to complete a screen questionnaire which is used to determine if they are able to participate or not, to read through a participant information sheet providing them with information on the experiment and the tasks at hand, and finally to provide their consent by completing a consent form. Information from these documents can be found in the appendix.

Four adults, 22-35 years of age, with unimpaired vision that pass the screening questionnaire are selected.

Subjects are seated on a wheelchair, with the breaks in use and holding a manipulandum with the right hand as shown in figure 10.

The wheelchair is placed approximately 1 m away from the LEDs set-up. This allows for the subjects eyes to be approximately 75 cm away from the LEDs whilst maintaining a comfortable seated position. The position of the wheelchair is marked on the floor with Micropore™ tape, this allows for positioning to be the same each time the experiment must be set up again.

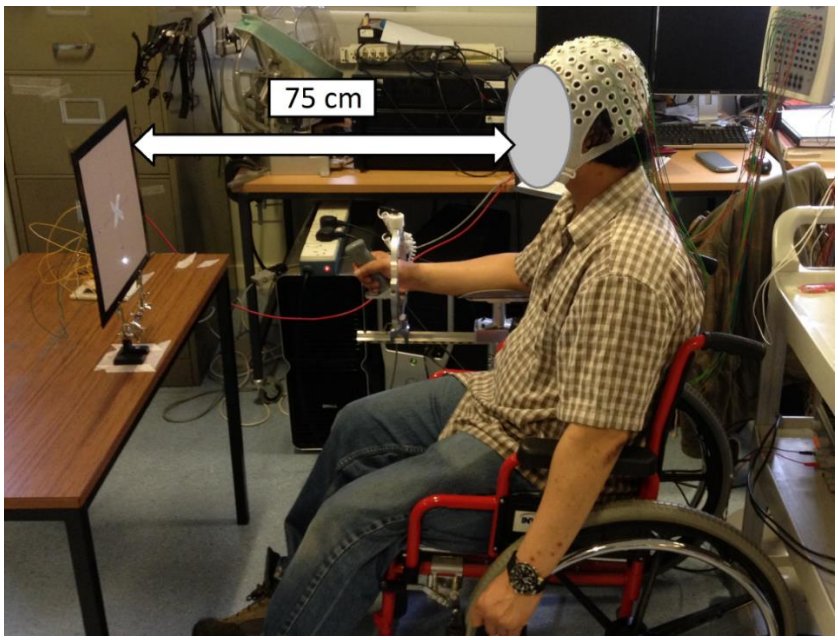

Figure 10. Photo of subject in the wheel chair in front of the cardboard that holds the LEDs. Subject sat, comfortably, with face approximately 75cm away from the board and right arm in the arm rest whilst grasping the manipulandum.

The manipulandum shown in figure 11 is a device that uses a potentiometers to measure changes in vertical and horizontal rotation. It is used to ensure that the subject has made the correct movement that is required of them when the cue is presented.

The manipulandum is connected to a CED 1401 machine. The potentiometer responsible for measuring changes in the vertical rotation is connected by a coaxial cable to channel 1 and the potentiometer responsible for measuring changes in the horizontal rotation is connected by a coaxial cable to channel 0. The CED 1401 is powered by the mains.

The CED 1401 is also connected to the computer via a cable that connects the CED host interface with the computer USB port and relays the changes in voltages as a result of the manipulandum being moved to a software program.

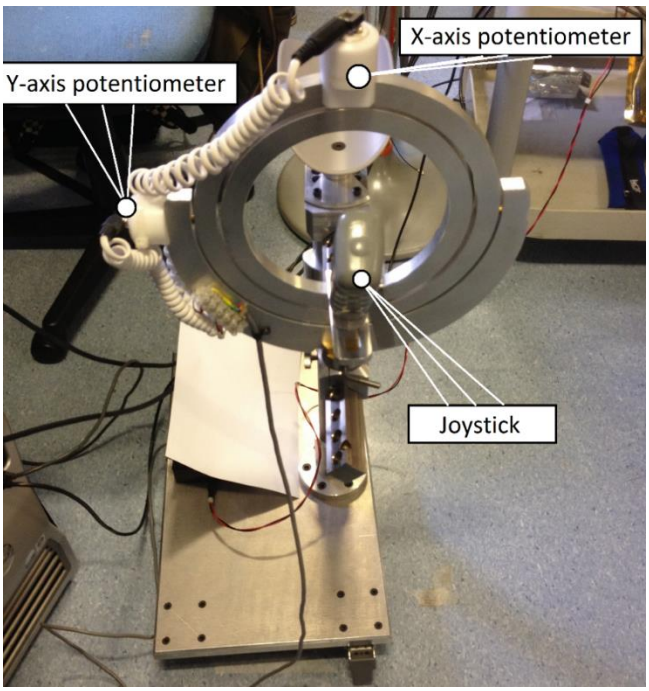

Figure 11. Annotated photo of the manipulandum. The potentiometers are visibly attached to the metal rings, which allow for rotation in all directions. A joystick is built into the centre ring, which is held and moved by the subject.

Spike 2™ 4.0.6 is the software program that is used to record the changes of the manipulandum. Changes in the vertical plane are plotted in the upper graph and horizontal changes are plotted in the lower graph. These graphs are used to validate the movements made by the subjects.

3.1.6 EEG electrode setup

Twenty-two electrodes in total are used to record the EEG signals. An EASY CAP with the international 10-20 set-up is used to maintain the same positions of the electrodes for each subject. The Cz positon of the cap is set as closely to the apex of the skull as the researcher can determine.

Fifteen electrodes are used to record the ERD signals at positions; FC1, FC2, FC3, FC5, FCz, C1, C2, C3, C5, Cz, CP1, CP2, CP3, CP5 and CPz.

Four electrodes are used to record the SSVEP signals are at positons; POz, O1, Oz, O2 and Iz. Figure 12 illustrates these positions.

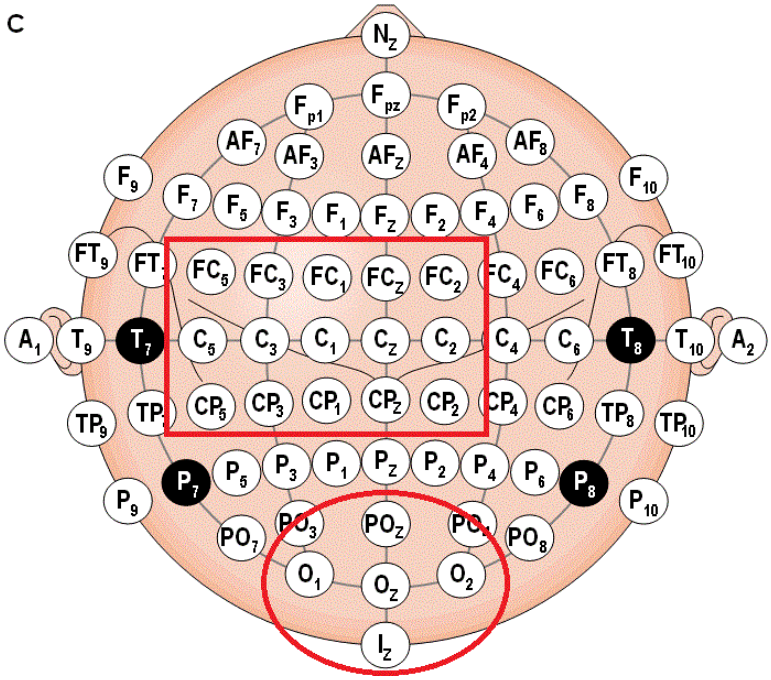

Figure 12. This image shows the 10-10 standard positioning of electrodes. Within the red square are the electrode positions to be used for the ERD. Within the red circle are the electrode positions to be used for the SSVEP. (Original image from Malmivuo, J. & Plonsey, R. 1995).

One electrode is used as a reference and is attached to the ear.

One electrode is used as the ground and is positioned at AFz.

Nuprep™ ECG & EEG abrasive skin prepping gel is applied to subjects scalps at electrode positions with a Harttmann™ cotton bud. Afterwards ECI™ Electro-gel conductive gel is applied to the electrode positions, reducing the impedance below 5kΩ.

3.2 Experiment Protocol

3.2.1 Timeline

Figure 13, on the next page, shows a breakdown of the approximated durations for each part of the experiment. Breaks are maximized to 5 min before prompting the subject to start the next run. Subjects are asked to tell the researcher when they are

ready to begin the next run at the start of each break. This tends to reduce the length of the breaks and reduce overall experiment duration. The dull repetitive nature of the trials may cause subjects to become sleepy, so conversation is attempted with subjects during breaks to help them stay alert and prevent them from feeling too sleepy in the next run.

Once the set-up is completed the required sequence code can be sent to reprogram the microchip and to begin a run of trials. Each run has a different sequences of trials. When a run is completed there is a break of up to 5 minutes for the subject. A total of 4 runs are used to acquire 44 trials in each direction.

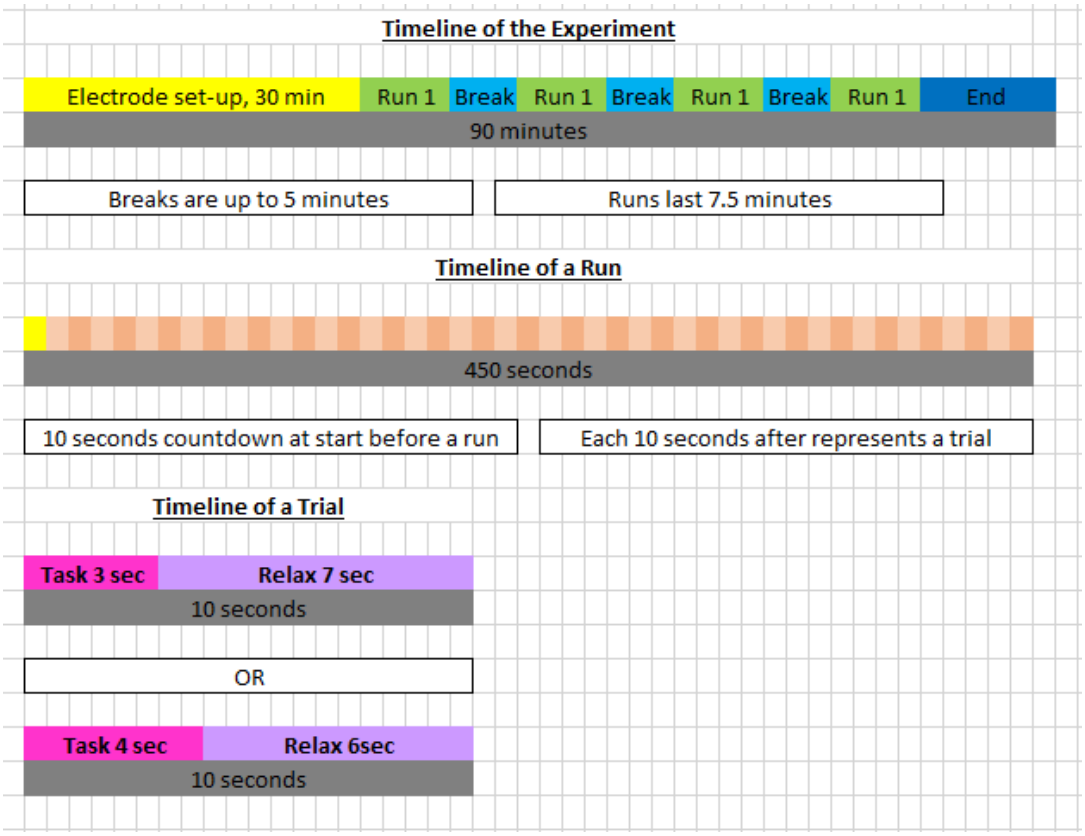

Figure 13. Illustrates the experiment timeline. Green block with 'Run 1' represent the run of one sequence lasting roughly 8 minutes. Light-blue block with 'Break' represent the duration when the subject does not have to do anything and can rest, have a drink, etc. Dark-blue block with 'End' represents the duration in which extra time can be taken for a break or a run, when needed. In the 'Timeline of a Run' the yellow block represents the 10 seconds providing the countdown for the run. The light and darker peach coloured blocks represent the 10 second durations for each trial during which one of the four LEDs could light up. The 'Timeline of a Trial' section shows the durations of the possible trials timings.

3.2.2 Cues

The cues for this experiment are the flashing LEDs. Subjects are asked to perform the motor task and visual task when a LED is flashing.

To indicate the start of a sequence the LEDs turn on one at a time in a clockwise fashion starting from the top LED. When they are all on for 1 second they then flash once. This indicates to the subject that the task sequence has begun.

At the end of a sequence all the LEDs turn on and stay on until the researcher turns them off or runs the next sequence. This indicates to the subject that the task sequence has ended and their break has begun.

3.2.3 Visual Task

The visual task subjects are asked to complete is to look directly at the flashing LED for the duration of the flashing. Subjects are informed that once the LED stops flashing they are to look back to the centre and hold their gaze there until the next cue.

3.2.4 Motor task

The motor task subjects are asked to complete is to perform a rapid movement of the wrist, in a direction that follows the position of the flashing LED from the centre of the cardboard, and hold for the duration of the flashing. Subjects are informed that once the LED stops flashing they are to move their hand back to the centre and hold it there until the next cue.

3.2.5 Recording

Recording is started on Spike 2 and Curry 7™, then the sequence is initiated on MPLab X™ to program the microchip to run the coded sequence.

Recording is stopped and saved, with the appropriate ID identification tag, once all the LEDs turn on.

4. Analysis

All analysis has been performed on epochs of -1 to 3 seconds from the trigger signal. This epoch range was chosen because using 3 seconds provides a reasonably short duration whilst keeping it within a range of which all desired signals can be measured.

Epochs are visually inspected and those with noticeable artefacts are removed.

MATLAB (version 2015a) is used to perform a Fast Fourier Transform (FFT) on the EEG data recorded from the occipital lobe to attempt to clearly identify SSVEP at the expected frequency. ERD is not be clearly defined when using FFT as the result does not show time variations of when frequencies increase or decrease, which is the nature of ERD.

All signals can be said to be made up of a combination of periodic sines and cosines. The FFT analysis extracts these periodic functions, via a mathematic equation, transforming the signal from a time-domain to a frequency-domain. This is a very powerful tool for showing what frequencies are occurring within a recorded signal, making it the ideal method for analysing data to find SSVEP.

Figure 14, on the next page, provides an example of the figures produced using the MATLAB FFT.

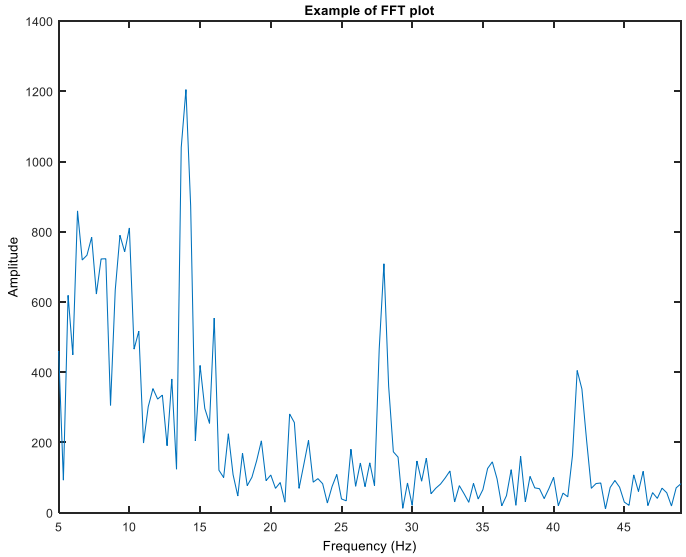

Figure 14. This image provides an example of the data produced when the FFT analysis is performed on an EEG data set.

EEGLAB (version 13.4.4b) a program run in MATLAB, is used to perform a time-frequency transform on the EEG data to generate plots of event-related spectral perturbation (ERSP) and inter-trial coherence (ITC). This is be used to show when ERD occurs and allows a look into the synergy between ERD and SSVEP across all recording channels.

ERSP is *"a generalization of ERS and ERD… a measure of event-related changes in the amplitude of EEG frequency spectra as a function of time. ERSP is computed by the following steps: (1) compute baseline time-frequency spectra over the pre-stimulus interval, (2) compute the trial time-frequency spectra over the post-stimulus interval, (3) normalize the trial time-frequency spectra by dividing by their respective mean baseline spectra, (4) compute the average of the normalized trial spectra for many trials."* (Dickter and Kieffaber, 2013)

ITC is *"a measure of phase dynamics irrespective of amplitude… a measure of the consistency of the instantaneous phase across trials at each frequency and time-point. ITC ranges between zero and one, with a value zero indicating random phase*

across trials and value of one indicating perfectly consistent phase across trials." (Dickter and Kieffaber, 2013)

Figure produced by performing the time-frequency transform have various plots showing graphical information of the result:

- The top large middle plot shows ERSP of the data in dB. Mean baseline spectral activity is subtracted.
- The lower large middle plot shows ITC of the data.
- The top left plot shows mean spectrum during the baseline period, as a blue line, and if significance is set, the significance threshold at each frequency, as a dotted green-black line.
- The plot directly below the ERSP plot shows the maximum, in green, and minimum, in blue, ERSP values relative to baseline power for each frequency.
- The bottom left plot shows mean ITC across the shown time range, in blue, and the significance threshold, as a dotted green-black line.
- The plot under the ITC shows event-related potential (ERP) in μV, produced by ITC across the data spectral pass band.
- The purple dotted line across the ERSP and ITC plots represent the trigger and thus the start of the task duration.

The significance threshold is set to 5% for all data analysed. Figure X provides an example of the figures produced using the EEGLAB time-frequency transform.

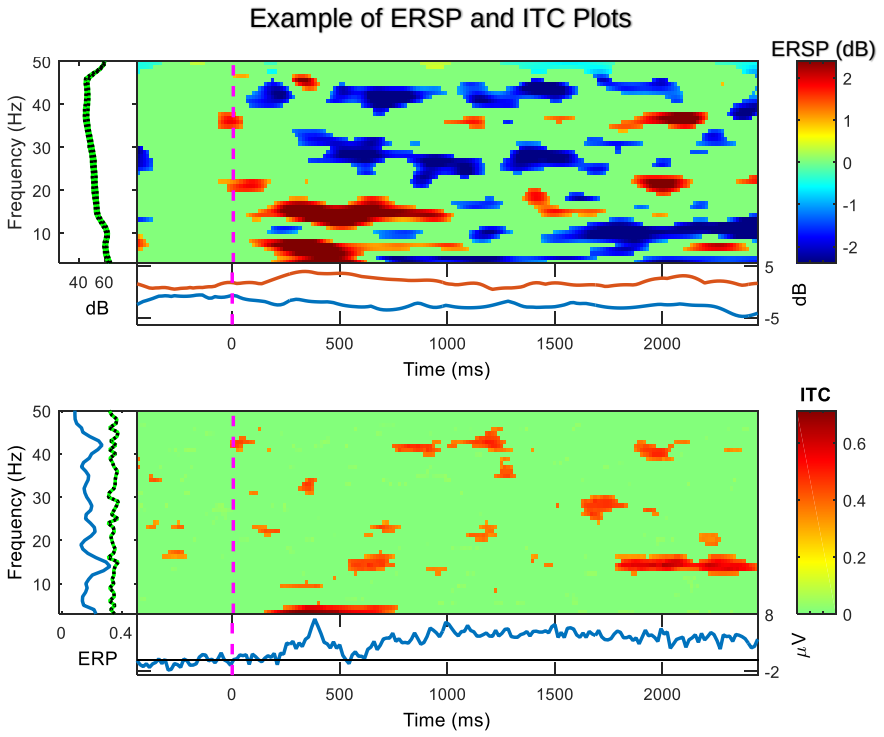

Figure 15. This image shows an example of the ERSP and ITC plots produced by the time-frequency transform in EEGLAB.

5. Results

5.1 Results 1

In this section the results of the analysis is presented. Results are displayed in the form of graphical figures, as described in the analysis. Results have been visually inspected and channels considered to provide the best set of data are presented. Frequencies of the X-axis are limited between 5 and 49 Hz to avoid the large spike of noise between 0 and 5 Hz. Figure 16 shows the extent of the noise found in the 0 to 5 Hz range. The filtering of EEG recording was set from 1Hz to 49Hz.

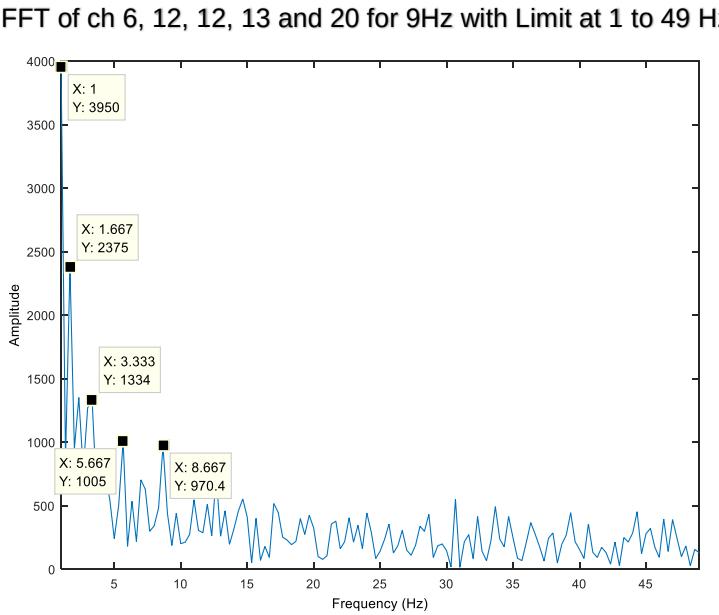

Figure 16. This image provides an example to the use of the limit. The peaks between 0 and 5Hz reach over 4 times the amplitude of the desired frequency, in this circumstance the peak at 8.667Hz. This was an FFT from the 9Hz of subject ID01.

Each subject's results are split into two sections for presentation; one is the FFT and the other is the time-frequency transform analysis.

The FFT sections show figures of FFT results for a single or a combination of the channels 6, 12, 13, 14 and 20. These channels correspond to positions POz, O1, Oz, O2 and Iz respectively. The channels used are shown in the title of the figures.

The time-frequency transform section show figures of the ERSP/ITC results for the clearest motor channel(s) and occipital channel(s). The channel used are shown in the title of the figures.

5.1.1 FFT figures for ID01

The best set of data for FFT came from combining all channels of the occipital region.

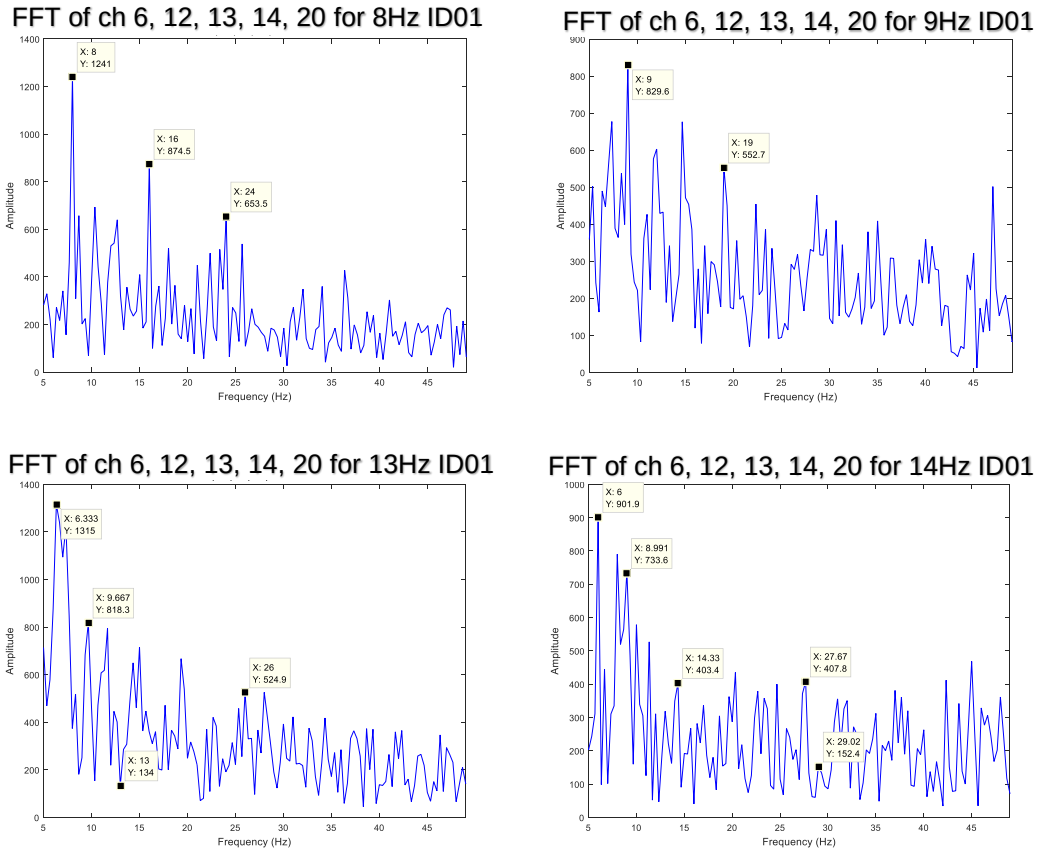

Figure 17 a (top left), b (top right), c (bottom left) and d (bottom right) correspond to data generated from tasks using frequencies of 8Hz, 9Hz, 13Hz and 14Hz respectively. These figures show the FFT of the data from channels 6, 12, 13, 14 and 20.

Figure 17a has identifiable peaks at expected value of 8Hz and harmonics 16Hz and 24Hz. Figure 17b has a peak at 19Hz but not at the expected harmonic of 18Hz. SSVEP frequencies cannot be identified from amongst the noise of figures 17c and 17 d, they also show amplitudes over 700 at approximately 6Hz and 9Hz.

5.1.2 Time-Frequency Transform for ID01

The best channels for this subject appear to be channel 11, C2 position, for ERD and channel 12, O1 position, for SSVEP.

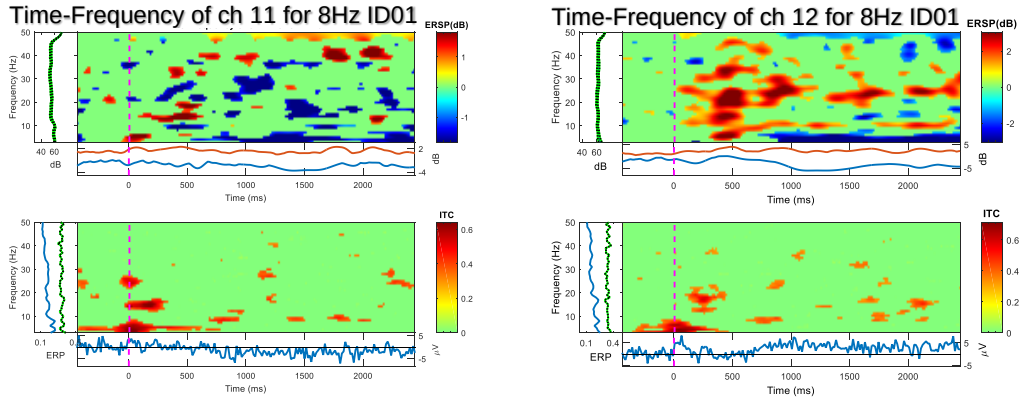

Figure 18 a (left) and b (right). These images show the time-frequency transforms for 8Hz from data of the C2 motor region (left) and O1 occipital region (right).

Bands of ERD in figures 18a and 18b are between 3-5Hz, starting at ~900ms. Figure 18b has an inconsistent ERS band signal at about 10Hz in the ERSP, verified by the ITC.

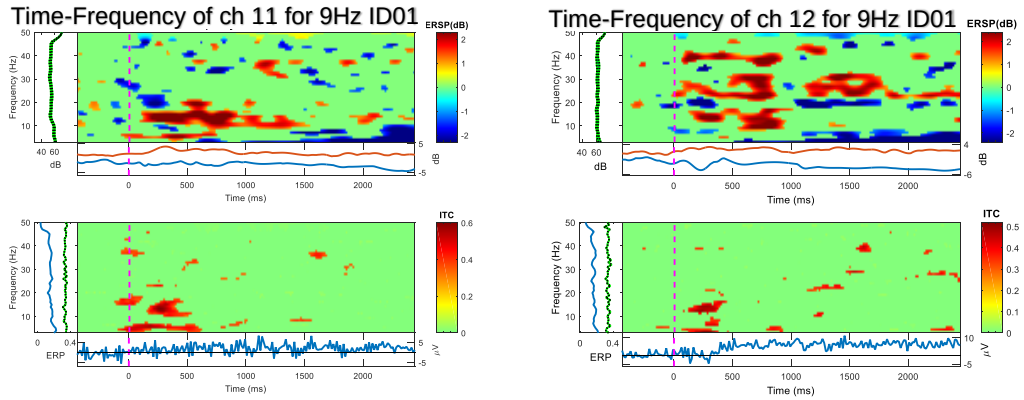

Figure 19 a (left) and b (right). These images show the time-frequency transforms for 9Hz from data of the C2 motor region (left) and O1 occipital region (right).

There is a larger area taken up by ERS than ERD, in figure 19a, in the 11-16Hz band. ITC shows that this is a common occurrence across most of the trials

between 250-450ms. Some bands of ERS can be seen in figure 19b between 0 and 1000ms. These do not match the flicker frequency or its harmonics.

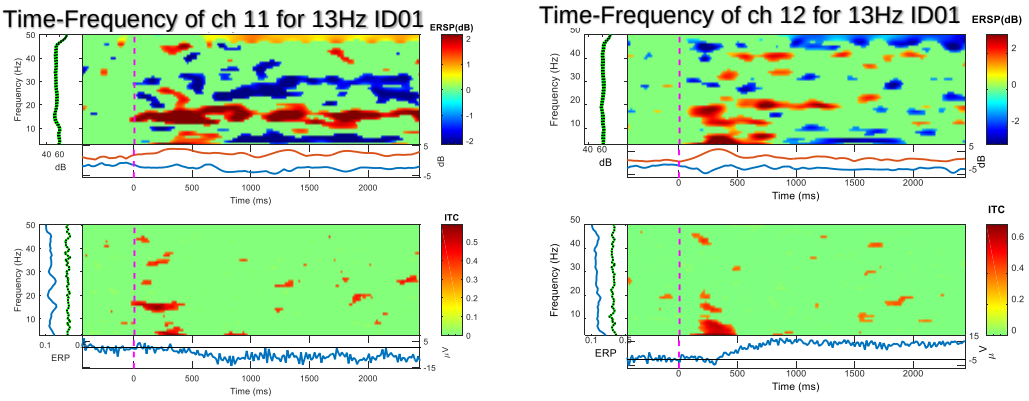

Figure 20 a (left) and b (right). These images show the time-frequency transforms for 13Hz from data of the C2 motor region (left) and O1 occipital region (right).

Figure 20a has a lot of ERS and ERD throughout the task duration at 12-17Hz and 23-32Hz respectively. Figures 20a and 20b show a band of ERS between 4-6Hz from 976-1925ms.

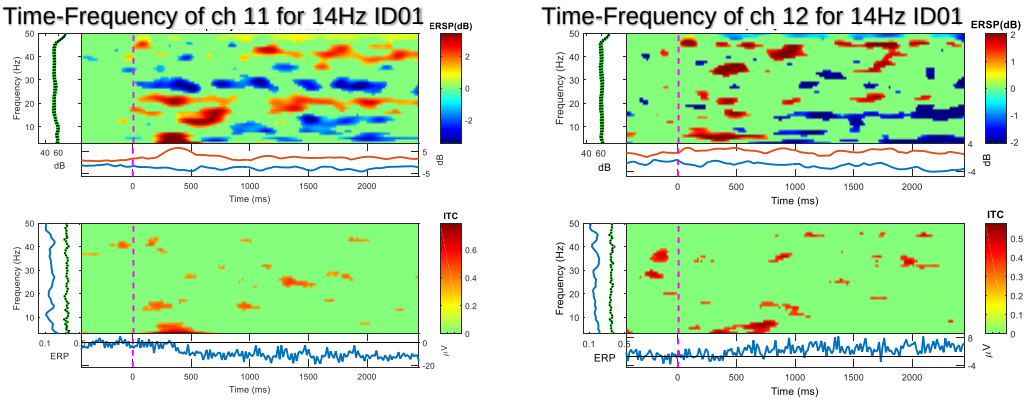

Figure 21 a (left) and b (right). These images show the time-frequency transforms for 14Hz from data of the C2 motor region (left) and O1 occipital region (right).

Figure 21a shows ERD occurring throughout at 26-31Hz, from 1490ms at 11-14Hz and from 1800ms at 4-6Hz. Figure 21b shows the occipital region has an ERD from

900ms at 14-16Hz, where the ERS for the SSVEP is to be expected, and at 3-5Hz after 1750ms.

5.1.3 Discussion of Results 1

The results for ID01 show a lot more ERS than was expected. Most of the ERSP plots show activity in the 3-5Hz region which, as mentioned in the background, is related to high emotional or sleep states in young adults (Setare et al., 2013). The subject could have been feeling quite stressed which would explain a lot of noise in the results, or sleepy as ERS is linked to inactivity in the motor cortex (Setare et al., 2013).

This could be an issue of BCI illiteracy, as discussed in the literature review, meaning that the chosen BCIs are unable to effectively produce usable data. Overall these results have not been conclusive and changes should be made to improve the experiment.

To improve the next experiment;

- A larger contrast between the background and the LED may increase the signal generated.
- More attention should be put into keeping the subject awake and alert over the break periods.

5.2 Experiment 2

In order to attempt to generate more distinct SSVEP the subject is to perform the tasks with the light off in the room and the blinds rolled down on all windows. The darker room increases the contrast between the LED and its environment. This improves SSVEP generated (Wu et al., 2008).

Some light would still come through the sides of the blinds. This is accepted as it allows the subject to see the white ‘X’ in the centre of the cardboard and recognise the directions in which the LEDs would be from this white ‘X’.

During the breaks the lights in the room are turned on and the subject is asked general questions or conversation is made in order to keep them awake and alert.

Aside from these changes the method used in experiment 1 remains the same.

5.2.1 Results 2

This section presents results from Experiment 2 in the same format as Results 1.

5.2.2 FFT figures for ID02

The best set of data for FFT came from combining all channels of the occipital region.

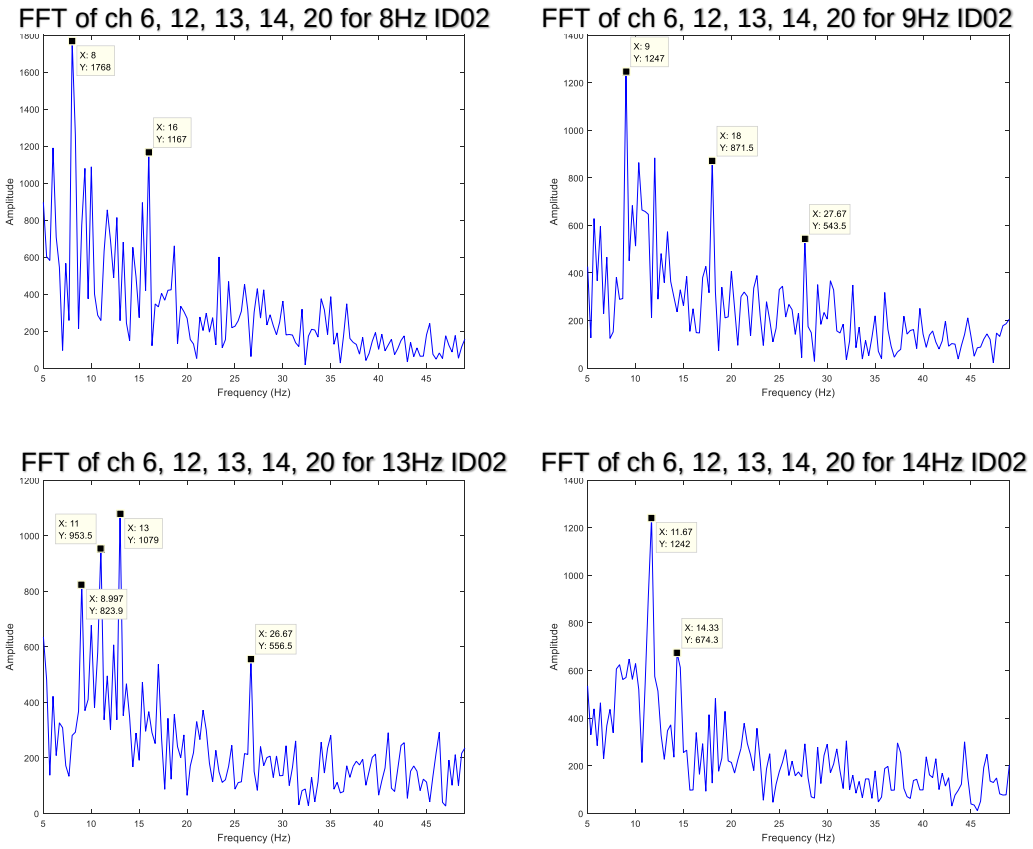

Figure 22 a (top left), b (top right), c (bottom left) and d (bottom right) correspond to data generated from tasks using frequencies of 8Hz, 9Hz, 13Hz and 14Hz respectively. These figures show the FFT of the data from channels 6, 12, 13, 14 and 20.

The frequencies and 2nd harmonics are identifiable in figures 22a to 22d. Figure 22b also has an obvious 3rd harmonic. Noise in the lower frequencies still remain quite high in comparison to the amplitudes of the expected SSVEP frequencies. In figure

22c the two peaks before the expected 13Hz are relatively high at values of 11Hz and ~9Hz. In both figures 22c and 22d there is a peak at 11Hz that is unusually high, amplitude of 953.5 and 1242 in the respective figures.

5.2.3 Time-Frequency Transform for ID02

The best channels for this subject appear to be channel 8, C3 position, for ERD and channel 12, O1 position, for SSVEP.

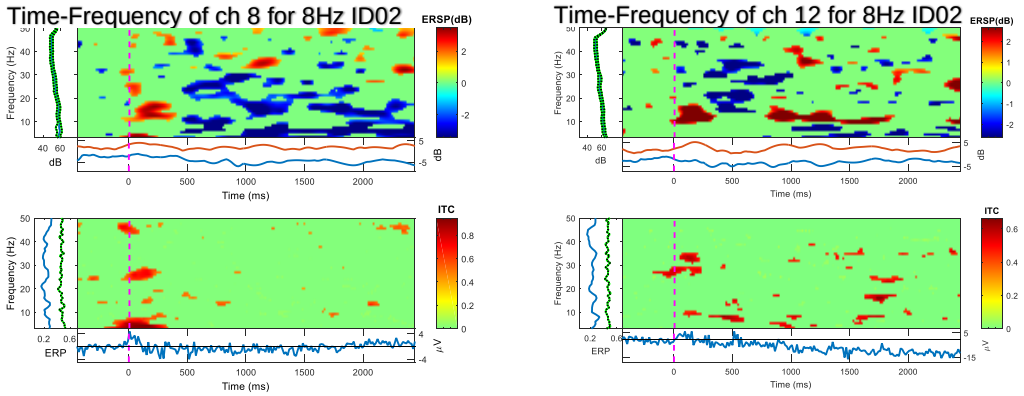

Figure 23 a (left) and b (right). These images show the time-frequency transforms for 8Hz from data of the C2 motor region (left) and O1 occipital region (right).

Figure 23a is showing a lot of patches of ERD starting from 488ms ranging from 3-30Hz, and a consistent band of 5-7Hz from 982ms. Figure 23b shows some bands of ERS at 9-13Hz from 790-1865ms. The ITC in figure 23b shows a few streaks of 8Hz at 500ms, 1000ms and 1600ms, at 1631ms to 1950ms there is also a few short streaks at 16Hz and 24Hz.

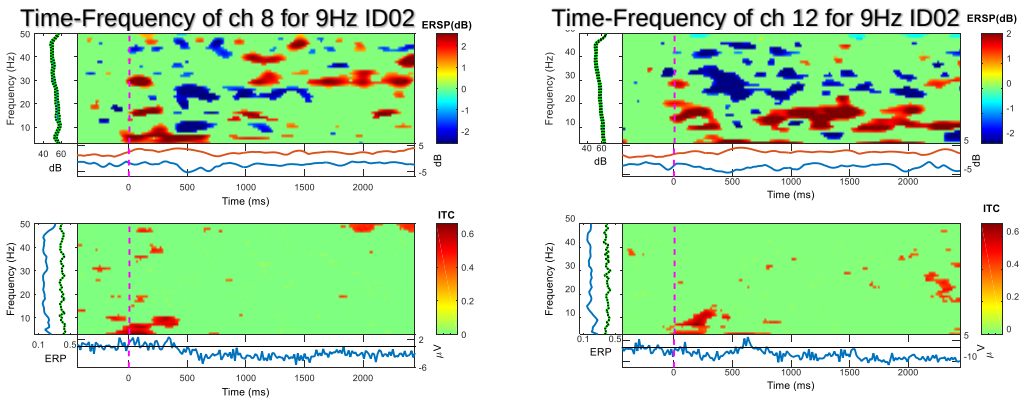

Figure 24 a (left) and b (right). These images show the time-frequency transforms for 9Hz from data of the C3 motor region (left) and O1 occipital region (right).

Figure 24a and 24b do not show much of what is expected. Figure 24a shows some ERD at 7-12Hz between 398-754ms and more at 22-27Hz from 398ms to 1557ms. The ITC plot shows a very short band of 17-19Hz and a streak at 36Hz from 50ms to 150ms. Figure 24b shows a lot of ERS between 9-18Hz for most stimulus duration, and its ITC plot has a short streak at 8-9Hz from 761ms to 906ms.

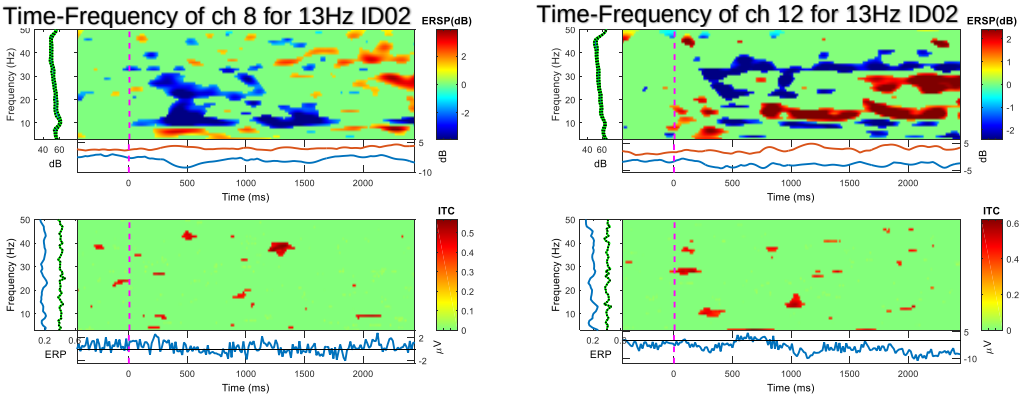

Figure 25 a (left) and b (right). These images show the time-frequency transforms for 13Hz from data of the C3 motor region (left) and O1 occipital region (right).

Figure 25a has an ERD band of 9-12Hz from 36ms to 935ms and again from 1065ms to 1790ms, and also a lot of ERD between 12-34Hz within 118ms to

1138ms. Figure 25b has ERD bands between 8-11Hz starting at 370ms, 906ms, 1602ms and 2080ms lasting up to 500ms. Figure 25b also has a lot of ERS between 11-18Hz starting from 746ms.

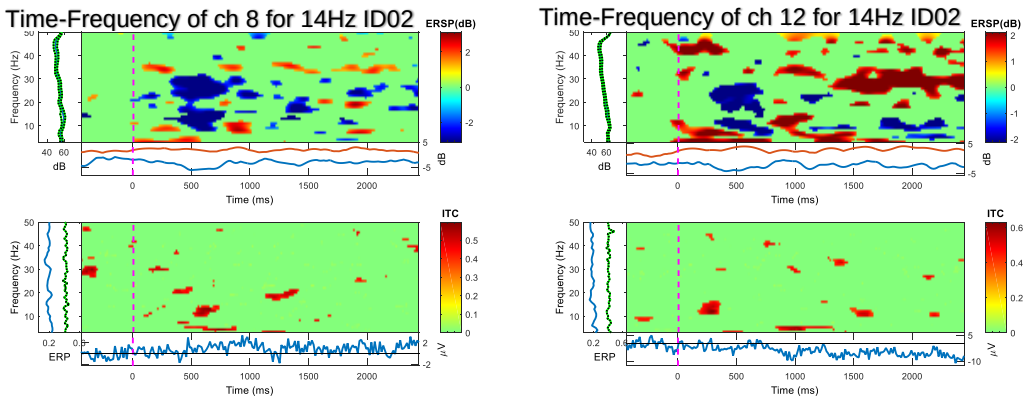

Figure 26 a (left) and b (right). These images show the time-frequency transforms for 14Hz from data of the C3 motor region (left) and O1 occipital region (right).

Figure 26a has a large area of ERD between 8-32Hz from 325ms to 790ms. Figure 26b has a similar area of ERD between 6-28Hz from 628ms to 732ms. Figure 26b has a lot of ERS between 25-35Hz from 1341ms, also with a few smaller bands between 6-8Hz at 152ms to 456ms and 1022ms to 1515ms, as well as a small area that includes the expected 14Hz from 848ms to 1152ms.

5.2.4 Discussion of Results 2

Looking firstly at the FFT graphs, in figure 22, it shows the SSVEPs at higher signal to noise ratios than when compared to the FFT graphs from ID01. This suggests that the increase in contrast did improve the SSVEP signal. It was a surprise to see that the suggestion by the FFT results is not matched by obvious bands in any of the ERSP and ITC plots. There is data in the ERSPs, and less in the ITCs, showing that there could be ERS caused by the LEDs, but there is too little to clearly show that the SSVEP has been generated.

There does seem to be an improvement when looking at the ERPs across the ERSP plots from figures 23 to 26 and occurring in each ‘a’ figure around the 500ms mark between frequencies 8-30Hz. This could be suggestive at an attempt of a movement, however, it does not appear to be sustained throughout the task duration, as would be expected. The Spike 2 data validates that the movements have been made and sustained for the correct directions and the entire duration of each trial. Epochs in which the movement did not satisfy these conditions were removed. The little ERD observed could still be an issue of BCI illiteracy, as discussed in the literature review.

Figures 23 a and 23b are the only ones to show an ERD band in the theta range, indicating the subject is feeling sleepy or is in a highly emotional state. This suggest that the attempts at keeping the subject awake and alert were successful.

As it stands these results would suggest that the two BCI methods do not have good synergy, but are able to function separately.

Further improvement should be made to increase the SSVEP generated.

5.3 Experiment 3

In order to attempt to generate better results, than seen in Results 2, the experiment is repeated using LEDs with a higher luminous intensity. The new LEDs luminous intensity value is 1900 mcd. This is over a 9 times increase in intensity from the previous LEDs. This should further increase the contrast between the flickering LED and the darkened background to improve the SSVEP (Wu, 2014).
Aside from these changes the method used in experiment 2 remains the same.

5.3.1 Results 3

The same format as Results 1 is used.

5.3.2 FFT figures for ID03

The best set of data for FFT came from channel 6, POz position, of the occipital region.

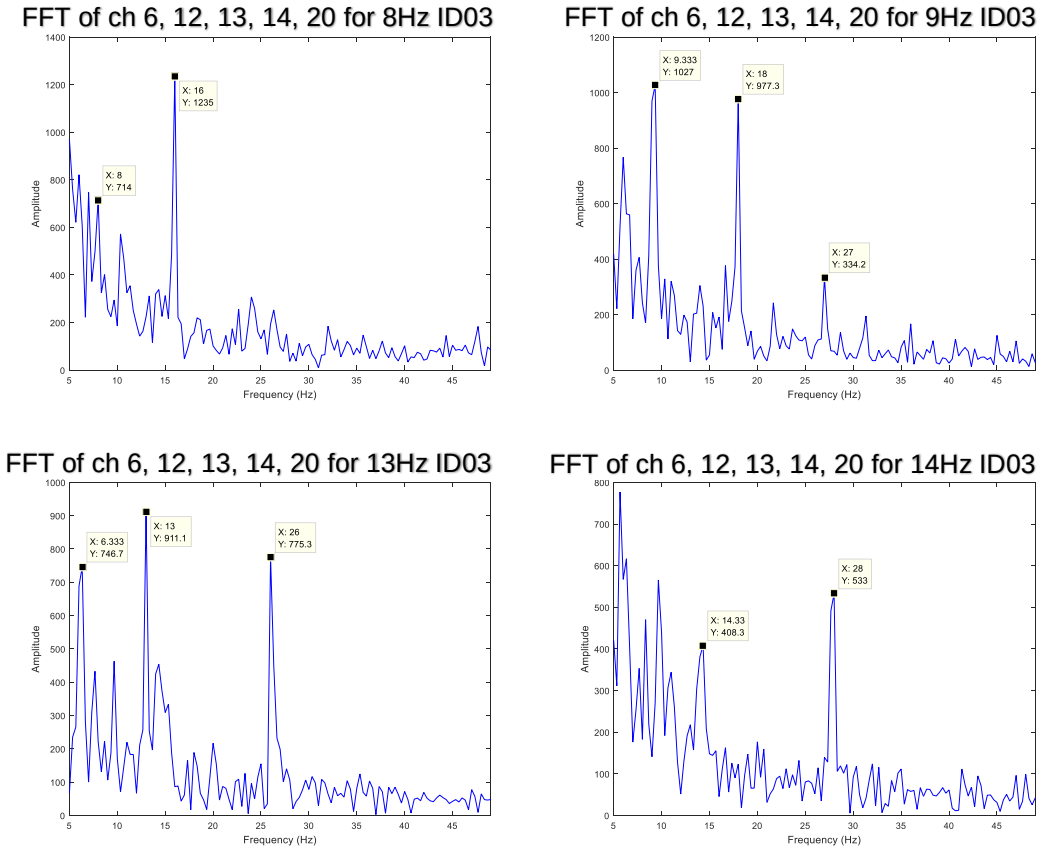

Figure 27 a (top left), b (top right), c (bottom left) and d (bottom right) correspond to data generated from tasks using frequencies of 8Hz, 9Hz, 13Hz and 14Hz respectively. These figures show the FFT of the data from channels 6, 12, 13, 14 and 20.

In Figure 27b 27c and 27d SSVEP frequencies are identifiable. For all of figure 27 the noise in the range of 5-15Hz is quite high, highest at 6Hz decreasing to 15Hz. Figure 27a the signal to noise ratio is too low at the expected 8Hz point, but a strong harmonic is present.

5.3.3 Time-Frequency Transform for ID03

The best channels for this subject appear to be channel 8, C3 position, for ERD and channel 6, POz position, for SSVEP.

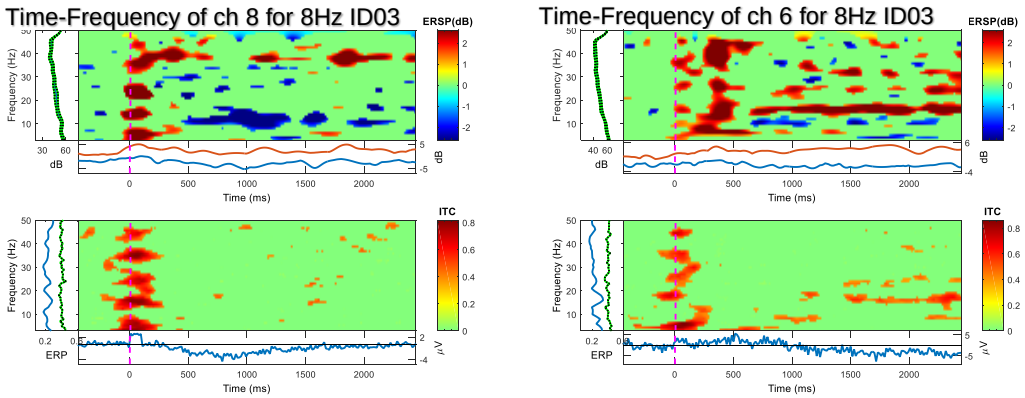

Figure 28 a (left) and b (right). These images show the time-frequency transforms for 8Hz from data of the C2 motor region (left) and O1 occipital region (right).

All graphs in figure 28 show a large column of ERS starting at the trigger point, confirmed to occur through most of the trials by the ITC plots, these occur mainly in bands of 3-9Hz, 13-18Hz, 22-28Hz, 33-38Hz and 42-46Hz all within -100ms to 210ms. Figure 28a has the expected ERD in the range of 10-13Hz from 456ms to 1370ms and a few spots afterward, this band stretches out at various point up to 16Hz and from 1007ms to 1239ms. Figure 28b shows a band of ERS at 14-18Hz from 645ms throughout, the ITC confirms that this ERS is common in most trials from 1486ms. Figure 28b has bits of ERS at various points throughout that are about the bands where harmonics of the SSVEP are expected. ITC in figure 28b also shows that there is a common activity in the 8Hz region from 848ms to 1239ms and from 2138ms onward.

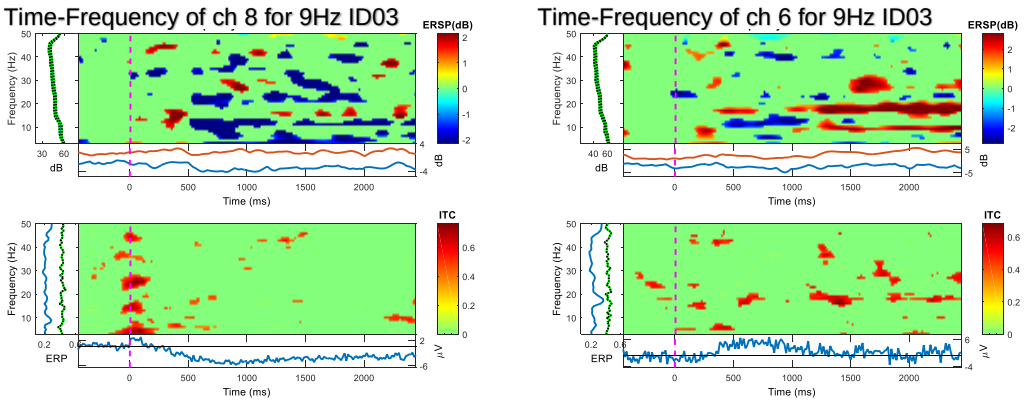

Figure 29 a (left) and b (right). These images show the time-frequency transforms for 9Hz from data of the C3 motor region (left) and POz occipital region (right).

Figure 29a has a large amount of ERD activity, mainly about the 11-13Hz and 20-24Hz at various points throughout the task duration from 529ms. It also shows a bit of ERD in the 3-6Hz band between 1239ms to 2008ms. ITC plot in figure 29a shows a column of activity at bands of 3-6Hz, 13-16Hz, 23-28Hz, 35-37Hz and 43-46Hz all within -65ms to 125ms. In figure 29b bands of ERS are clear and within the bands of 17-19Hz and 9-10Hz both becoming continuous from 978ms and 1254ms, respectively, then continuing throughout. ERD is visible, in figure 29b, in the 10-14Hz band between 427ms and 1109ms. The ITC plot of figure 19b shows that most of the trials show activity in the band of 17-19Hz at multiple points throughout the epochs.

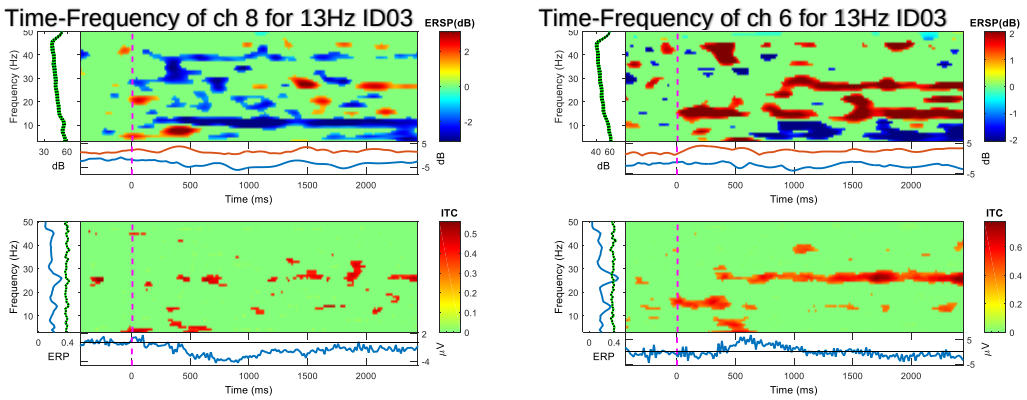

Figure 30 a (left) and b (right). These images show the time-frequency transforms for 13Hz from data of the C3 motor region (left) and POz occipital region (right).

Figure 30a shows a distinctive band of ERD throughout the task duration within 9-13Hz, there is also band of ERD through half the task duration in the range of 38-40Hz. A lot of spots of ERD are visible between 13-38Hz from 210ms to 1312ms. There is very little ERS. The ITC of figure 30a shows a few streaks of activity across the 13Hz and in the band of 25-27Hz. Figure 30b shows a lot of ERS in the bands of 13-16Hz throughout most of the task duration, with a band at 25-28Hz starting from 920ms. A lot of ERS is seen between 4-11Hz after 862ms. The ITC plot of 30b shows activity mainly at 25-28Hz starting from 340ms, there are also large areas of activity at 14-16Hz and 5-8Hz from -50ms to 427 and 355ms to 543ms respectively.

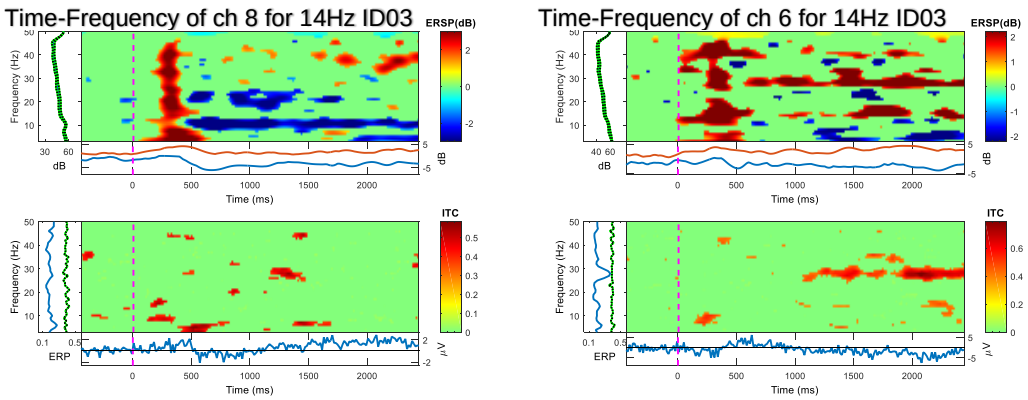

Figure 31 a (left) and b (right). These images show the time-frequency transforms for 14Hz from data of the C3 motor region (left) and POz occipital region (right).

Figures 31a and 31b show a large column of activity through most of the frequencies within 210ms to 427ms. Figure 31a shows a clear band of ERD at 8-12Hz from 456ms, and a few areas of ERD between 17-25Hz. ITC for figure 31a shows a small area of activity at 26-30Hz from 1181ms to 1442ms. Figure 31b shows a clear band of ERS at 26-30Hz, mainly between 27-29Hz, starting from 587ms, and some activity within 13-19Hz at various points. The ITC plot of figure 31b has a band of activity at 26-30Hz starting from 1080ms, and three short streaks at 14Hz.

5.3.4 FFT figures for ID04

The best set of data for FFT came from combining all channels of the occipital region.

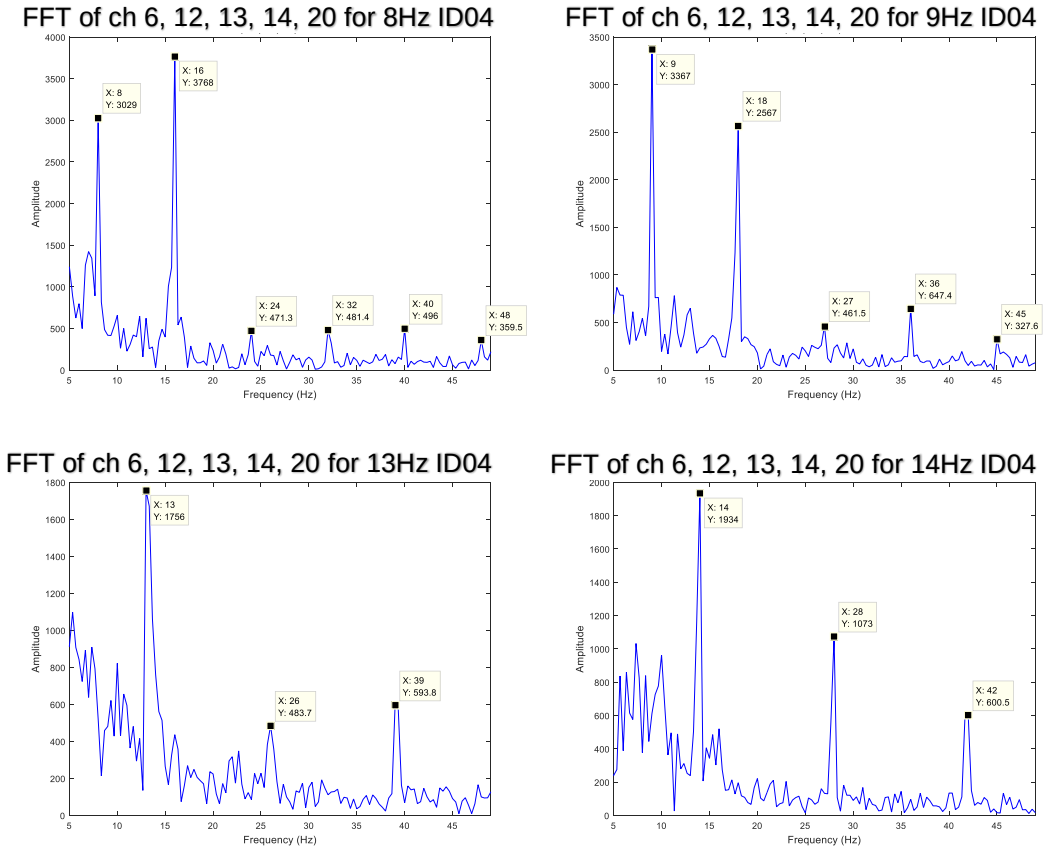

Figure 32 a (top left), b (top right), c (bottom left) and d (bottom right) correspond to data generated from tasks using frequencies of 8Hz, 9Hz, 13Hz and 14Hz respectively. These figures show the FFT of the data from channels 6, 12, 13, 14 and 20.

Graphs in figure 32 all show a good signal to noise ratio. All expected values of SSVEP have obvious peaks, at least twice the amplitude of the immediate surrounding frequency values. They all also have a lot of noise between 5-17Hz, the lower frequencies reaching amplitudes of up to 1424 in figure 32a. Figures 32a and 32b show the highest amplitudes in the fundamental and 2nd harmonic frequencies, whilst figures 32c and 32d have the highest amplitudes for the 3rd harmonics.

5.3.5 Time-Frequency Transform for ID04

The best channels for this subject appear to be channel 8, C3 position, for ERD and channel 6, POz position, for SSVEP.

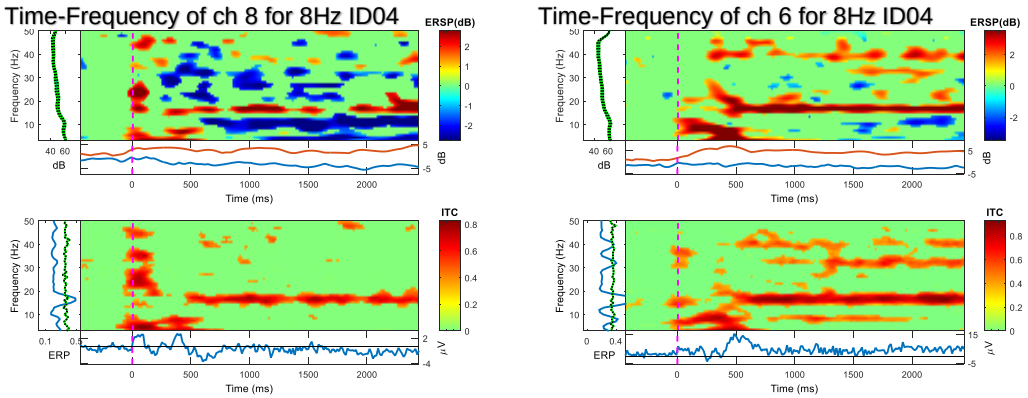

Figure 33 a (left) and b (right). These images show the time-frequency transforms for 8Hz from data of the C3 motor region (left) and POz occipital region (right).

Figure 33a has a column of ERS at the start of the trial in the ERSP and ITC. Figure 33a shows a lot of ERD activity through the task duration at various frequencies, the most prominent at the 7-12Hz band after 616ms. There is also a band visible between 3-4Hz from 1094ms. There is also a lot of ERS throughout the task duration between 14-18Hz. The 14-18Hz band is also obvious in the ITC, of figure 33a, starting from 471ms. Figure 33b shows very little ERD that is mainly between 9-13Hz and only towards the end of the epoch. Figure 33b has an extremely distinctive band of ERS between 15-18Hz starting from 471ms, which is also very clear in the ITC plot. Figure 33b has high amount of ERS between 37-41Hz, less between 31-34Hz and 3 spots of activity between 21-24Hz. The ITC plot of figure 33b shows 3 other distinctive bands of activity, aside from the 14-18Hz band mentioned earlier, at 7-9Hz, 30-34Hz and 38-42Hz.

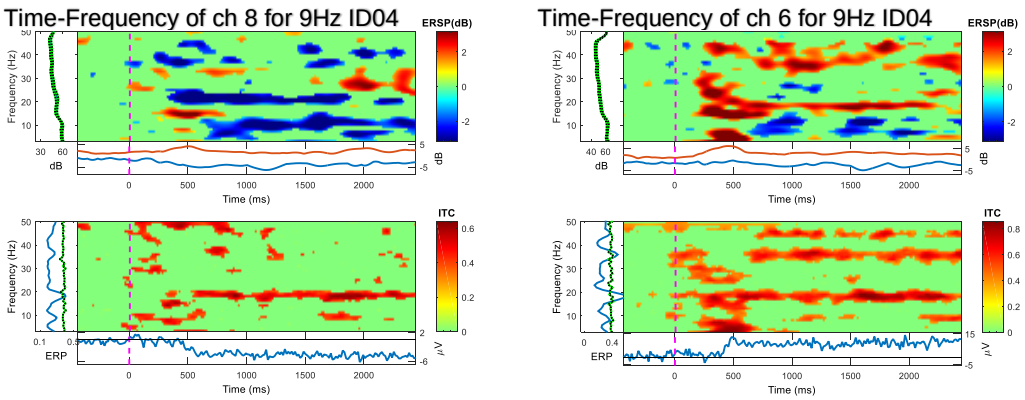

Figure 34 a (left) and b (right). These images show the time-frequency transforms for 9Hz from data of the C3 motor region (left) and POz occipital region (right).

Distinct bands of ERD are visible, in figure 34a, at frequencies of 7-13Hz and 20-23Hz, occurring from 355-1848ms and 703ms, respectively. A small area of ERS is present at 13-16Hz towards the start of the task, the remainder of this band is at 0dB ERSP, and another slightly larger area is visible at frequencies 24-34Hz towards the end of the epoch, the remainder of this band is also at 0dB ERSP. The ITC of figure 34a shows a distinct band of activity between 16-20Hz and a few streaks in the 7-10Hz and 36-39Hz bands. Figure 34b has a distinct band of ERS between 17-29Hz throughout the task duration. Some ERS is visible at frequencies 33-39Hz and 41-46Hz. Areas of ERD are visible, in figure 34b, at frequencies 5-9Hz and 9-13Hz. The ITC plot of figure 34b shows 3 distinct bands of activity at frequencies 16-20Hz, 33-39Hz and 43-47Hz. Also visible, in the ITC plot, are few short streaks of activity at 8-10Hz and one small area in the band of 24-27Hz.

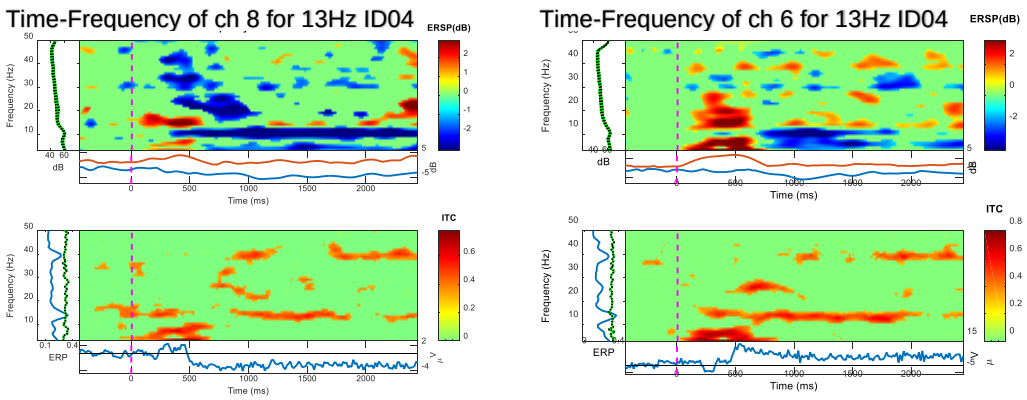

Figure 35 a (left) and b (right). These images show the time-frequency transforms for 13Hz from data of the C3 motor region (left) and POz occipital region (right).

Figure 35a has two visibly distinct bands of ERD in the ranges of 3-6Hz and 8-12Hz. There is a large amount of ERD over 16Hz at 253-1007ms. Whilst smaller areas of ERD are visible throughout the ERSP plot at 30-39Hz and 18-20Hz. Some ERS is visible at 13-17Hz at the start, by the trigger signal, and 14-15Hz at a three points across the rest of the ERPS plot. The ITC plot of figure 35a show distinct bands of activity at 12-15Hz and 38-41Hz, with a few areas of activity in the 25-28Hz region. Figure 35b shows a column of ERS at 123-630ms that reaches up to 28Hz, there is a break in this column where a small streak of ERD is visible at 10Hz. The rest of the ERS are mainly visible at 12-16Hz, 24-28Hz and 38-44Hz. Quite a lot of ERD is visible after the column of ERS at 4-12Hz and various small areas of ERD spread throughout the 29-36Hz region. The ITC plot of figure 35b has a distinct band at 11-15Hz throughout most of the plot, with a shorter band visible at 24-29Hz and 37-41Hz.

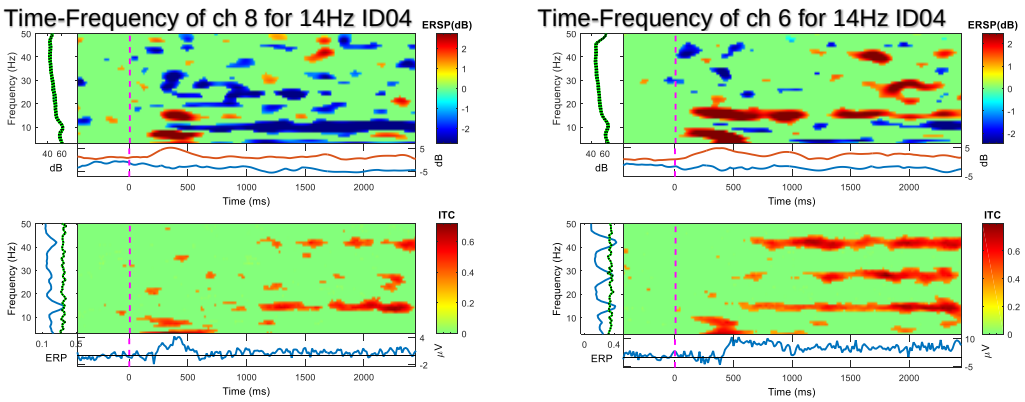

Figure 36 a (left) and b (right). These images show the time-frequency transforms for 14Hz from data of the C3 motor region (left) and POz occipital region (right).

Figure 36a has a distinct band of ERD at 7-13Hz and at 3-4Hz, as well as many small areas of ERD throughout the task duration over 16Hz mainly between 19-34Hz. Figure 36a has very few areas of SSVEP the most prominent being the two areas between 282-601ms at 3-10Hz and 13-17Hz. Less prominent areas of ERS occur at 14-15Hz at two other points after 601ms. Figure 36b has a few areas of ERD in similar regions to figure 36a, but there are much fewer ERD areas visible. Figure 36b has a distinct band of ERS at 13-17Hz, an area at 26-30Hz and 39-43Hz towards the end of the task duration. Figure 36b, also seen in figure 36a, has a strong ERS at 3-10Hz from 108ms to 558ms. The ITC of figure 36b has 3 distinct bands of activity, all starting soon after 600ms, at 13-16Hz, 26.29Hz and 40Hz. The ITC plot of figure 36b also shows two areas of activity at 6-8Hz.

6. Discussion

This section discusses the results in terms of the improvements made for experiment 3, and relates the results to whether the objectives of this pilot study have been satisfied.

6.1 Improvement to SSVEP response

Looking at the FFT graphs, produced from ID03 and ID04 data sets, it is obvious that the SSVEP signal is recorded and, in most of these graphs, the expected peaks were easily identified from amongst the noise. Comparing results from experiment 3 to experiments 2 and 1 suggests that the large increase in luminosity of the LEDs has greatly improved the SSVEPs response. The plots of the ESRP and ITC also show distinct bands for most of the SSVEP frequencies and harmonics, which are not present in results from experiment 1 or 2, supporting this concept.

6.2 Improvement to ERD response

Focusing now on the time-frequency graphs, produced from ID03 and ID04, there is a common distinct band of ERD around the 8-13Hz which corresponds to the suppression μ rhythms, as discussed in the background, to suggest a movement is being made or attempted. There was not much of a difference between the methods used in experiments 2 and 3 to improve ERD response, but the results show an obvious distinction of ERD bands that were not present in the previous experiments. This makes the reason to the improvement uncertain.

There was a slight increase noticeable in the ERD seen in results 2 when compared to results 1. This suggests that changes made to the experimental method, in order

to keep the subject more awake and alter, might have had some benefit. Perhaps the increase in ERD generation, shown across results 3, are from the subjects being more focused on the task, however, this cannot be proven by the results in this experiment and it has not been as testing criteria in any of the works discussed in the literature review.

Another consideration is that, due to the nature of the experiment, it is quite easy for the subjects to feel sleepy and lose focus. Most of the time-frequency graphs from Results 3, e.g. figures 29, 30, 31, 33, 35 and 36, show ERD at 3-7Hz which falls into the Theta band, related to high emotional or sleep states in adults (Setare et al., 2013), whilst also showing distinct bands of SSVEP and ERD in the expected SSVEP and ERD frequencies. This suggests that the subject feeling sleepy does not have much of an effect on the results, as thought when the methods where changed for experiment 2.

A possible answer to all this uncertainty, of why the results improved, is in relating the fact of BCI illiteracy; the first two subject are BCI illiterate, even under the improved conditions, and the latter two subject are BCI literate. Using a larger number of subject for each of the experiments would most likely clarify this.

6.3 Satisfaction of Objectives

Results from experiments 1 and 2 suggest that the SSVEP and ERP hybrid does not work particularity well. Considering others research into the SE-hBCI it is more suggestive of a flaw in the experimental procedures used. The idea that methods 1 and 2 having a flaw is supported in the results generated by experiment 3.

The time-frequency transformation graphs from experiment 3 suggest that the hybrid of SSVEP and ERD is possible. Distinct bands of ERD, produced by the motor task, and ERS, representing the SSVEP, visible at each of the different frequencies or

their harmonics, and corresponding directions, show that both signals can be acquired simultaneously. This is further supported by the work of others on the SE-hBCI, as discussed in the literature review (Pfurtscheller et al., 2010a, Allison et al., 2010).

The main issues appeared to be due to the method, and is the reason why the method was changed twice to attempt to improve the results generated.
The method based challenges faced when developing the SE-hBCI, in this pilot study, are:

- Lower luminosity LEDs are unusable as the SSVEP inducing component of the hBCI; requiring higher luminosity values at the cost of subject comfort.
- The EEG cap was never an optimal fit for the subject. This leads to electrodes being further away from the scalp and makes them more susceptible to movement and drift. Getting good fittings for the subjects may improve clarity of results.
- Using such a small number of subjects means that there is a high possibility that results are greatly affected by BCI illiterate subjects. This leads to uncertainty of the results.
- Using different subjects for each of the experiments. This means that it is difficult to compare data between the different experiments, especially with so few subjects. Having one or two subjects to partake in each the experiment would allow for more accurate comparisons to determine the effect of differences made to the method.

There is also the challenge of analysing the ERD. ERD is expected to occupy the 8-12Hz range as a result of the motor cortex being de-synchronised by attempt or

intention of movement, although, looking at most of the results it is clear that ERD can also occur in other frequencies.

Other challenges are related to the synergies in using two BCI modalities.

At first glance through the time-frequency graphs the two modalities appear to be able to function well with each other. The expected bands of ERD, for the motor task, and ERS, for SSVEP, are both distinct across most of the time-frequency graphs of results 3. Especially when compared to the results of experiments 1 and 2. Taking a longer look at the time-frequency graphs, more specifically at figures 28, 29, 33 and 34, it becomes apparent that there may be some cancelling of signals where ERD and SSVEP overlap. These graphs show the most prominent types of signal related to the event, be it synchronisation or de-synchronisation. This means that there is not a situation where both are shown in the same area with equal value. Instead they cancel each other out and appear green across the ERSP and ITC plots, seeming as if there is no response in these areas. This is also somewhat apparent when noticing that there is always some area of green between areas of ERD and ERS, suggesting that the edges of them are cancelled out by each other. Looking at the FFT of the SSVEP from the occipital lobe shows what frequencies are obtainable from that location. When comparing the FFT to the time-frequency graphs it can be seen where the ITC plots should be showing activity at the frequency matching the flickering stimulus and its harmonics. Looking at figure 32a, showing the FFT for the 9Hz data set of ID04, it can be assumed that the ITC of figure 33b, the time-frequency graph using the same set of data, should have distinct bands of activity about frequency values or 8Hz, 16Hz, 24Hz, 32Hz and 40Hz. When comparing the data shown in figure 34b it is visible that the ITC plot is missing the majority of activity in the bands expected about 8Hz and 24Hz, and then comparing the ERSP plot in figure 33a it is visible that ERD bands occupy the frequencies or they are green. This might not be surprising for the 24Hz band

because of the low amplitude it had, but the amplitude of the 8Hz peak should be showing up in a very similar manner as the 16Hz band, which appears to have also been very prominent in the motor cortex as seen in figure 33a. The prominent appearance of the 16Hz band of ERS in figure 33a means that no ERD would be obtainable in that band, and is possibly a result of the strong SSVEP synchronisations causing a synchronisation in the motor cortex. The effect of this problem has been discussed in the literature review as 'dual task interference' (Allison et al., 2012), however, no papers discussed in detail what the causes may have been. The results of experiment 3 suggest that the cancellation of ERD with SSVEP generated ERS, and possibly vice versa, may be the cause of this 'dual task interference' mentioned in the literature review (Brunner et al., 2010, Allison et al., 2012). Looking more into depth of the dual task interference is a good aim of future work; to learn how to improve the synergy of BCIs by discovering how to combat their interference with each other. In the case of SSVEP and ERD it may be to test different simulator frequencies with a larger difference from the expected ERD frequency bands.

In order to avoid this problem Brunner at al., 2010, suggests that a sequential task could be used as an alternative to mitigate dual task interference.

If the previously discussed concept is correct in that;

- signals generated in the occipital lobe can also be detected in the motor cortex in addition to the ERD generated from a motor task
- and inversely the possibility of ERD generated in the motor cortex to be detected in the occipital lobe in addition to the induced SSVEP

Then this should increase the amount of detectable information at any one moment, increasing the information transfer rate of the hBCI. This idea is too dependent upon the possibility of the signals generated in one area of the brain being detected in

another, therefore, as a future experiment it would be worth confirming this occurrence.

Overall if these concepts are or are not true, there is still evidence to suggest that ERD and SSVEP signals are able to be detected simultaneously

7. Conclusion

Results have shown that the SSVEP and ERD modalities are able to work together, although with the methods used, the synergy of them together might not be optimal. The concept of potentials recorded in the other areas of the brain would allow for more information of each signal to be gathered possibly increasing the information transfer rates of both modalities. When continuing this experiment in future it is important to use a statistically significant number of subjects and to perform appropriate controls in order to properly asses the results generated. Finally, the concept of signal cancellation, and dual task interference, should be kept in mind, therefore, selection of frequencies to induce SSVEP should be revised to avoid cancelling the ERDs, and vice versa. Results of experiment 3 show that the two modalities are still able to produce detectable ERD and SSVEP simultaneously.

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9. Appendices

9.1 Appendix A – Documents

Screening Questionnaire

Date: _____

Masters Project: A Pilot Study on the Hybrid of SSVEP and ERD based Brain Computer Interface

This short questionnaire will determine if you are able to participate in this pilot study. All information provided is confidential and only the researchers involved in the pilot study will be allowed to see.
Please circle the appropriate answers.

1. Are you over 18 years of age? Yes No
2. Are you right handed? Yes No
3. Do you have proper function in your upper right limb? Yes No
4. Are you currently on any medication? Yes No
5. Do you have epilepsy? Yes No

   Don't Know
6. Do you suffer from any mental health issues? Yes No
7. Do you have any problems with viewing flashing lights? Yes No

   Don't Know
8. Do you have any allergies to conductive/abrasive gels? Yes No

   Don't Know
9. Have you had a head injury within the last 4 weeks? Yes No
10. Are you able to stay seated for over 1hr without problems? Yes No

Thank-you for your time!

The number below will be used to reference the data above and to avoid the use of your name/identity. This will allow for anonymity when presenting results in public documents.

Identification number: _____

Consent form

Identification number: _____

Masters Project: A Pilot Study on the Hybrid of SSVEP and ERD based Brain Computer Interface

Please write “YES” in all boxes to the right of statements that you agree too.

1. I understand that my participation is voluntary and that I am free to withdraw consent at any time without reason. | |
2. I agree to take part in the experiments for the Masters Project: A Pilot Study on the Hybrid of SSVEP and ERD based Brain Computer Interface | |
3. I confirm that I have read and I understand the information on the documents titled: “Screening Questionnaire”, “Participant Information Sheet” and “Consent Form”. | |
4. I have had the opportunity to consider the information, ask questions and these have been answered to my satisfaction. | |
5. I accept that all the information I have provided in the documents mentioned in statement 3 is: correct, can be used as part of this pilot study, and be viewed by all members of the research team. | |

The member of the research team (signed below) has overlooked the answers to the Screening Questionnaire and decided you are able to participate in the experiment.

Researcher Signature: _____

Date: _____

By signing below you accept and understand the statements you have agreed to.

Participant Signature: _____

Date: _____

Participant Information Sheet

Masters Project: A Pilot Study on the Hybrid of SSVEP and ERD based Brain Computer Interface
Biomedical Engineering Department
Student: Adam Mitchell E-mail: adam.mitchell.2014@uni.strath.ac.uk
Supervisor: Dr. Heba Lakanay

Participation

Participation is voluntary and as such it is entirely your choice to take part or not. You will be allowed to stop and leave the experiment at any point and for any reason.

Introduction

The aim of this pilot study is to look into the advantages and problems with combining two brain computer interfaces (BCI). These two systems are a steady state visual evoked potential (SSVEP) based system and an event related de-synchronisation (ERD) based system. Both systems use EEG to record brain signals.

Method

As part of the setup I will need to:

- Sit you by a manipulandum to hold. The manipulandum will be used to record the type of movement made by your wrist. This data will validate the ERD detected by the EEG.
- Have you wear an 'EASY Cap'. This cap is what will hold the electrodes in place.
- Attach 21 electrodes to the 'EASY Cap' and one to your earlobe. These will allow recording of your brain activity.
- Apply an abrasive gel at each location of an electrode, to remove any dead skin cells.
- Apply a conductive gel at each location of an electrode, to reduce impedance.

As part of the experiment's task I will need you to:

- Look at the marked centre of the board when there are no flashing LEDs
- Hold your hand/wrist in a neutral position when there are no flashing LEDs
- Look at the flashing LEDs when they are on
- Quickly flick your wrist in the direction of the flashing LED and keep your wrist bent until the LED stops flashing

Durations

There will be regular breaks (approximately every 7.5 minutes) for you to have a drink and a rest.
Set-up may take up to 30 minutes and the experiment may take up to 40 minutes (including breaks), both without complications.
Total time predicted would be between 1hr to 1hr 30 mins, but **please put aside 2 hours for the experiment if you wish to volunteer**, as problems can always arise.

Reimbursements

I am depending on volunteering as there are no funds to reimburse or rewards participants. I will supply some refreshment at my personal cost, if you have a particular soft drink you would like during the experiment please let me know in advance.

Safety

Recording equipment is electrically isolated, and no part of this experiment will be invasive. If you circled "Don't Know" on your screening questionnaire on the allergies question; I will apply the abrasive gel with a cotton swab and then add conductive gel to an area of your skin before we start the experiment to ensure that you have no allergic reaction to them.
If you have been accepted after completing the screening questionnaire then there should be no reason to worry for your health. Those who may have risk to their health by participating

in this experiment will be excluded, e.g. those who suffer from epilepsy, or have allergies to the gels.

Recommendations, Advice and Requirements

Please try to avoid drinking too much, and also be sure to use the toilet, just before participating in an experiment as we won't be able to have toilet breaks. A toilet break would mean having to disconnect all the electrodes, then to reattach them all and prepare them for the experiment again leading to an increase of approximately 30mins before the experiment can be completed (not including the time taken in the restroom).
Please try to avoid the use of conditioners when cleaning your hair before the experiment. The fats in the conditioner act as an insulator and reduce the quality of the EEG recording. Shampoo is perfectly fine to use.
During recording phases please try not to:

- Fidget
- Move your head
- Contract your jaw
- Look around the room
- Blink
- Swallow

As such events will generate artefacts in the recordings.
You may experience discomfort from:

- Flashing LEDs being/becoming irritating
- Having to move your wrist in a repeated manner
- Wearing the Easy Cap

There will be regular breaks for you to wiggle, have a drink, relax and rest to help relieve any discomforts.

Questions

If you have any questions about the experiment or use of the recorded information please feel free to ask or E-mail me.

Thank-you for your time and consideration!

9.2 Appendix B – Code

FFT code for MATLab:

```
s=EEG.data;

ch=[6 12 13 14 20];

fx=0:1/3:2000;

s_ssvep=s(ch,2001:8000,:);

s_mean=mean(mean(s_ssvep,3),1);

s_fft=fft(s_mean);

figure;

plot(fx(1:end-1),abs(s_fft(1,1:6000)));

xlim([5 49]);
```

MPLAB X code for microchip settings:

```
#define SYS_FREQ        8000000L
#define FCY             SYS_FREQ/4

/* System Function Prototypes                                */

#pragma config FOSC = INTIO67, FCMEN = OFF, IESO = OFF // CONFIG1H
#pragma config PWRT = OFF, BOREN = SBORDIS, BORV = 30 // CONFIG2L
#pragma config WDTEN = OFF, WDTPS = 32768 // CONFIG2H
#pragma config MCLRE = OFF,LPT1OSC = OFF, PBADEN = ON, CCP2MX = PORTC //
CONFIG3H
#pragma config STVREN = ON, LVP = OFF, XINST = OFF // CONFIG4L
#pragma config CP0 = OFF, CP1 = OFF, CP2 = OFF, CP3 = OFF // CONFIG5L
#pragma config CPB = OFF, CPD = OFF // CONFIG5H
#pragma config WRT0 = OFF, WRT1 = OFF, WRT2 = OFF, WRT3 = OFF // CONFIG6L
#pragma config WRTB = OFF, WRTC = OFF, WRTD = OFF // CONFIG6H
#pragma config EBTR0 = OFF, EBTR1 = OFF, EBTR2 = OFF, EBTR3 = OFF // CONFIG7L
#pragma config EBTRB = OFF // CONFIG7H

void ConfigureOscillator(void);
```