An analysis of the relationship between neuronal and haemodynamic responses to stress from simultaneous recordings of Optical Topography and EEG signals

by

Ling Hwa Wei

13948

Dissertation submitted in partial fulfilment of
the requirements for the
Bachelor of Engineering (Hons)
(Electrical and Electronic)

MAY 2014

Universiti Teknologi PETRONAS
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

An analysis of the relationship between neuronal and haemodynamic responses to stress from simultaneous recordings of Optical Topography and EEG signals

by

Ling Hwa Wei
13948

A project dissertation submitted to the
Electrical and Electronic Engineering Programme
Universiti Teknologi PETRONAS
in partial fulfilment of the requirement for the
BACHELOR OF ENGINEERING (Hons)
(ELECTRICAL AND ELECTRONIC)

Approved by,

____

DR TANG TONG BOON
UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
MAY 2014

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

LING HWA WEI

ABSTRACT

Physiological studies had been done extensively by researchers in evaluating human stress using Electroencephalogram (EEG). However, the usage of Optical Topography (OT) to evaluate the human stress is still a new field. EEG has been an established measuring device for stress through the electrical response arising from neuronal activities. On the other hand, the haemodynamic response due to stress has yet been studied. This project analyses the simultaneous recordings of the EEG and OT in response to mental stress. Data was recorded from 12 subjects that underwent tasks based on Montreal Imaging Stress Task in order to invoke mental stress. The EEG and OT datasets were analysed through the power spectrum and oxyhaemoglobin level respectively. The alpha power band has been found to be lower in the control session compared to the stress sessions. While for the OT, the oxyhaemoglobin level has been higher in the control session compared to the stress sessions. The results are then used for correlation with the data from the OT. From the correlation result obtained, it showed little significant relationship between the neuron and haemodynamic response due to stress.

ACKNOWLEDGMENT

Foremost, I thank God for the sustaining me and granting me the opportunity to proceed successfully. This dissertation would not have been complete without the assistance and guidance of several people. I would therefore like to express my sincere gratitude towards them.

I would like to thank Dr. Nasreen for being my supervisor. Her patience and strictness has helped me to ensure that my work is able to be done in time. Having weekly meetings with her has ensured that my progress is in the right track.

My sincere thanks also go to Dr. Tang Tong Boon for taking over being my supervisor. Without his guidance and knowledge, I would not have been able to proceed further into completion of my dissertation. His advices have been a valuable help to me.

Lastly, I would like to thank my family for their continuing support. Without their encouragement, I would not have been able to come this far.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Brain activities can be investigated by measuring the haemodynamic response through imaging techniques such as OT or by measuring the neuronal (electrical) response using EEG. Currently, magnetic resonance imaging (MRI) system has been widely used in the measuring of the cerebral blood flow. However, MRI machines are not only large and immobile, they are very expensive. Furthermore, because it requires the subject to be positioned within a MRI chamber which utilizes magnetic field for imaging, it places many restrictions on the subject. As such, it is impractical to be used on subjects who are claustrophobic, children or psychiatric patients. Instead, with the use of OT which utilizes light sources for imaging, the data collected are not affected by changes in strong magnetic fields as in MRI systems. Moreover, it does not confine the subject and grants the subject much more freedom of movement aside from being less costly as well.

Neurovascular coupling has indicated that the neuronal activities of the brain are related to the changes in the cerebral blood flow. Thus, it would be interesting to find the relationship between the haemodynamic and neuronal responses in the brain. In this project, signal processing techniques will be applied to OT and EEG data collected simultaneously from a study involving social stress conditions.

The data from simultaneous recordings of OT and EEG signals had already been collected. The EEG data collected will need to be processed and analysed and is then validated with results from established researches with similar stress studies using EEG. Following that, the analysed EEG data will be correlated with the OT data to find whether any meaningful relationship exist between the two.

1.2 Problem Statement

The relationship between the haemodynamic and neuronal responses in the brain is still a very open research issue. Neuronal responses due to stress can be measured using EEG and this area has been very much researched upon. To study on the haemodynamic responses due to stress, the only available commercial option right now is the Magnetic Resonance Imaging machine. However, OT is a new technology that is more portable and cheaper compared to functional magnetic resonance imaging (fMRI) to measure haemodynamic responses. At the moment, its application in evaluating stress is not yet widely studied. On the other hand, EEG has been used and is very established in many types of stress studies. The problem is to find a correlation or a relationship between OT and EEG data collected from subjects undergoing stress conditions.

1.3 Objectives

To perform processing and analysis on both EEG and OT data collected from a stress experiment, and find a correlation between the two types of modalities.

1.4 Scope of Study

The EEG and OT data collection from the stress experiment has already been conducted and is not covered by the scope of this project. Thus, the scope of this project will cover the processing of the obtained recorded data. In addition to that, analysis will be done on the processed EEG and OT data to find any relationship between the 2 modalities due to stress.

CHAPTER 2

LITERATURE REVIEW AND THEORY

2.1 Stress

Stress is a normal psychological and physical response that the body produce towards certain stress stimuli, called stressor. Cortisol is one of the stress hormones that are produced by the brain when the person is subjected to either physical or psychological stress [1, 2]. Stress is an involuntarily bodily response that is caused by autonomic nervous system which is made up of sympathetic nervous system and the parasympathetic nervous system [3]. When a person is stressed, his body will react in a certain way and the reactions to stress can be measured through the neuronal brain activities and the haemodynamic response. The neuronal brain activities can be detected using the EEG while the haemodynamic response can be measured using the OT.

Stress could be divided into three categories, which are mental stress, psychological stress and physical stress [4]. The type of stress induced depends on how the stress is stimulated and the stressor used. Various researches have used various methods to verify the stress levels by correlating data from physiological signal and questionnaires-based method. Some of the questionnaires used are Cohen's Perceived Stress Scale [2, 5, 6], Spielberger State Anxiety Inventory [6], Cornell Medical Index and the Profile of Mood Stress [7]. The problem with these questionnaires is that the stress level measured is rather subjective to the various individual. This is because stress is actually perceived, and the perception of stress by the individual acts as the determinant, not so much as the actual stress [8]. Thus, an objective reference is needed to measure the stress level accurately. As such, since the EEG has been quite established to show positive results from comparisons to questionnaires-based method, it is chosen to be used as the reference to be correlated with the haemodynamic response collected using the OT.

2.2 Electroencephalogram (EEG)

The EEG is a non-invasive tool used to measure the electrical activities along the scalp of the head [9]. These electrical activities results from the synchronous activity of thousands or millions of neurons in the brain which is usually in microVolts [8]. These neural activities that are activated in the brain actually produce sufficient voltage which is picked up by the multiple electrodes placed on the scalp. EEG had been used in various clinical applications for diagnosis and research purposes. EEG is commonly used to diagnose epilepsy disorder, sleep disorder or encephalitis which are disorders related to the brain. Figure 1 shows an example of a EEG cap worn by a subject.

Figure 1. Example of an EEG cap

Mental stress which is invoked through stimuli creates a neuronal response in the brain and thus, the EEG could be used to measure it. Scalp EEG activities are represented by oscillations at various frequencies at each individual channel. These oscillations of the EEG recordings can be classified into frequency bands with each band attributed to certain state of the brain. The delta band, δ (0.5 – 4 Hz) is associated with dreamless sleep and loss of body awareness. The theta band, θ (4 – 8 Hz) is associated with the dreaming state of sleep or the rapid eye movement (REM) sleep. The alpha band, α(8 – 12 Hz), is associated with the state of relaxation or meditation while the beta band, β (12 – 30 Hz) is associated with alertness, concentration and anxiety [10]. Hence, the bands most closely related to the state of stress are the alpha band and the beta band. Figure 2 shows the different bands of frequencies of the EEG data.

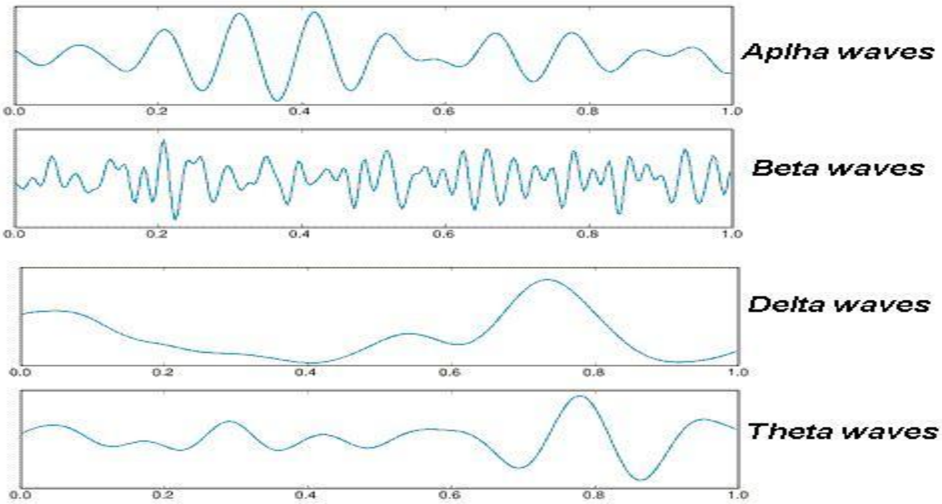

Figure 2. Different EEG frequency bands

Stress due to mental stress has shown to be directly related to increase in the beta wave and a decrease in the alpha wave [3, 4]. Findings have also shown a high level of beta wave activity in stressnous condition [1]. In addition, researchers have shown spectrum power which is collected from 2 groups of moderately stressed and highly stressed group measured at prefrontal sites showed linear features of asymmetry of power at alpha band to be significant [11]. From the change in asymmetry level, the frontal lobe was found to have a greater right activity which was associated with increasing stress [6]. Mental stress simulation showed an increase of power in the beta wave band while showing a decrease in the alpha band [2]. Furthermore, in classifying the EEG power spectra, the Artificial Neural Network (ANN) classifier was found to be effective with an average of 97% when heat stress was used as the stressor [12]. Heat stress produces the same physiological and hormonal change in the person. With stress studies using EEG being extensively researched, it is now being used as the reference for stress level to be correlated with the haemodynamic response from the OT.

2.3 Optical Topography (OT)

OT on the other hand, measures the haemodynamic response of the cerebral blood flow, also known as the Blood-Oxygen-Dependent Level (BOLD). The OT applies near infrared light with a wavelength of 700 nm to 900nm to measure the blood haemoglobin changes in the brain. The wavelength range of the near infrared light is chosen because this is the range where the bone, tissue and skin are the most transparent. The OT consists of pairs of source and detector optodes attached to the scalp of the head. The source is a laser diode which will direct the light onto the head and the light will penetrate the skull, reaching into the cerebral cortex. The penetration of the light is only about a depth 30mm and is scattered by the haemoglobin in the blood whereby the light will be partially reflected back through the scalp, being picked up by the detector optodes.

Figure 3. Example of OT probes

2.4 Summary

The change in the haemodynamic response is related to the neuronal activity of the brain and thus makes it possible to investigate the relationship between the two [9]. When the activity of the brain at a specific area is high, blood vessels which are distributed over the cerebral cortex will supply more blood to the area. Hence, the level of oxy-haemoglobin increases while at the same time, deoxy-haemoglobin also increases due to the consumption of oxygen by the cerebral activity. These changes in the conditions are measured as a topographical image [13]. The recording of the OT data is then correlated with the data from the EEG.

Therefore, the aim of this project is to find a relationship between neuronal and haemodynamic responses to stress from data collected using OT and EEG signals.

CHAPTER 3

METHODOLOGY

The data from the EEG and OT had already been collected through a designed experiment. The participants were given mental arithmetic questions to invoke mental stress. The arithmetic questions posed were categorized into “Easy”, “Medium” and “Hard” based on The Montreal Imaging Stress Task [14]. The participants were divided into two groups, the control group and the stress group, where the stress group was given a reduced time of 20% compared to the control group to answer the arithmetic questions. At the end of both control and stress sessions, a questionnaire is given to the participants to gauge their mindset and condition.

In the done, the EEG measures only the frontal and prefrontal region of the brain. This is because the frontal lobe is the part of the brain associated with reasoning, emotion, feeling and problem solving. As such, it is the part of the brain that will be directly affected by the mental arithmetic tasks which will invoke stress. The frontal lobe is only one of the four major lobes of the brain. The other lobes include occipital lobe, parietal lobe and temporal lobe. Occipital lobe is associated with visual processing while parietal lobe with movement and orientation. Lastly, the temporal lobe is associated with perception and recognition of auditory stimuli, memory, and speech. Therefore, the other 3 lobes are not as important to be measured. Figure 4 shows where different lobes of the brain are located.

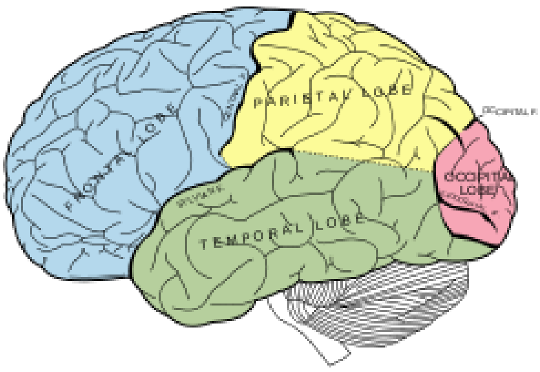

Figure 4. Different lobes of the brain

The EEG electrodes need to be attached in the area that needs to be measured. This is done using the 10-20 system. Figure 5 shows the position of the EEG electrodes attached. The 10-20 system is an internationally recognized method to describe and apply the location of scalp electrodes in the context of an EEG test or experiment. This system is based on the relationship between the location of an electrode and the underlying area of cerebral cortex. The ‘10’ and ‘20’ refer to the fact that the actual distances between adjacent electrodes are either 10% or 20% of the total front-to-back or right-to-left distance of the skull. In this study, the region measured is only the frontal and prefrontal region. Therefore, the electrodes are only attached at Fp1, Fp2, F3, F4, F7, F8 and Fz.

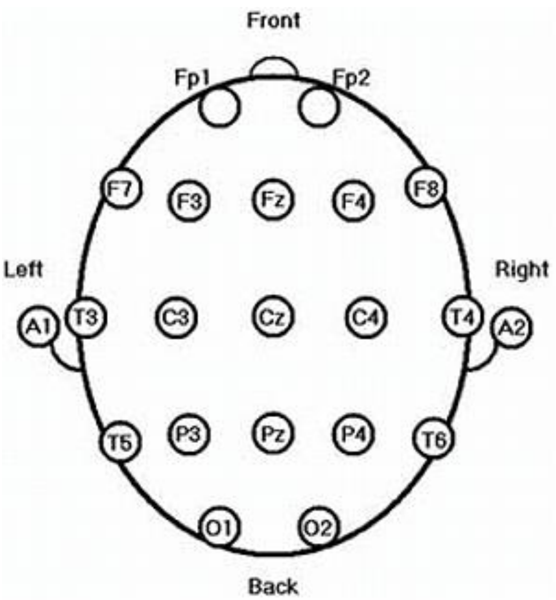

Figure 5. 10-20 system for the EEG

The EEG signal data obtained need to be pre-processed first of all. Preprocessing involves removing artifacts from the signal and passing it through a filter. Examples of filter used is the Butterworth filter [15]. The filter is needed to remove the higher frequencies and also the line frequency. The EEG needs to be cleaned through rejection of artifacts before processing it. Artifacts are unwanted signals that were picked up by the EEG signals which do not originate from the cerebral activity. Artifacts usually are made up of eye movements such as blinking, muscle movements and even electrocardiographic activities. EEG data is decomposed using Independent Component Analysis (ICA) to separate the data into several components. These artifacts need to be removed in order to have a clean EEG brain signal data in order to properly study the stress induced. Figure 6 shows the detailed steps taken in preprocessing whereby after ICA decomposition, the various artifacts are rejected step by step.

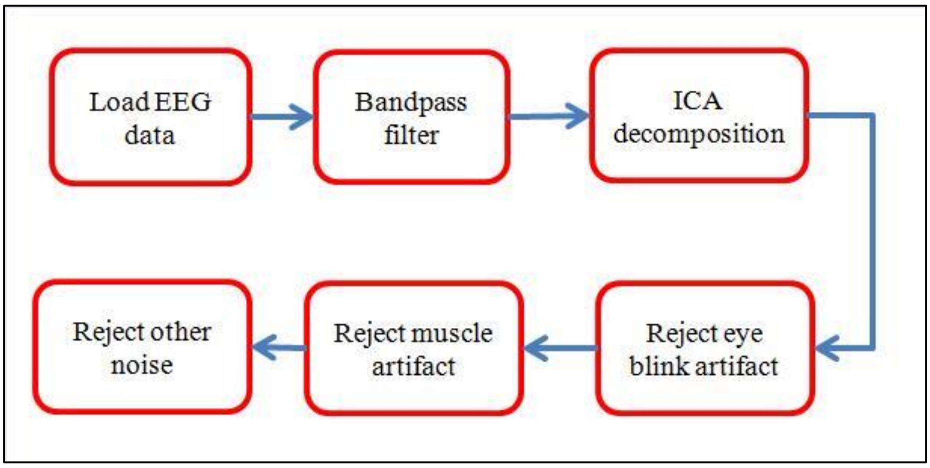

Figure 6. Steps for preprocessing of EEG data

Next, the EEG data signal is transformed from time domain into frequency domain using Fourier Transform with a suitable window. After Fourier Transform, the EEG data signal may be analysed by looking at its power spectrum [16]. The power spectrum of the EEG data signal can be converted in terms of Energy Spectral Density (ESD), Spectral Centroids [4] or asymmetry level of alpha and beta power band for analysis [17, 18]. Windowing function is applied to prevent spectral leakage.

After Fourier Transform is applied, the EEG signal data is passed through the feature extraction process where the data supplied will be represented by a set of features. The extraction of these features involves using algorithms to select and identify patterns within the signals. Following that, the EEG signal data were passed through a filter to separate them into their respective bands which are Delta band, δ (0.5 – 4 Hz), Theta band, θ (4 – 8 Hz), Alpha band, α(8 – 12 Hz), Beta band, β (12 – 30 Hz) to identify significant frequency bands [19]. Significant features related to mental stress can be identified through power bands and individual channels. It is also necessary to extract the features so that the classifier can classify the EEG signal data into distinct groups. Either linear or non-linear features can be used to extract the EEG parameters [10]. Feature extraction methods are critical because it will determine the stress features selected from the physiological signal whereby, the extracted features will be input into a chosen classifier [20].

The classifier helps to classify the EEG signal data into distinct categories, which is either "stress" or "no-stress". There are a variety of classifiers available such as Artificial Neural Network (ANN), k-Nearest Neighbor (k-NN), Bayesian and Linear Discriminant Analysis (LDA) [20]. Artificial Neural Network is popularly used classifier because it is a universal approximators where it can adapt to a wide scope of problems while not being limited to a number of classes [21]. Once the EEG signal data have been classified into either "stress group" or "no-stress group", it can then be used to correlate with data collected from the OT. Figure 7 shows the flowchart of all the steps taken to process the EEG data.

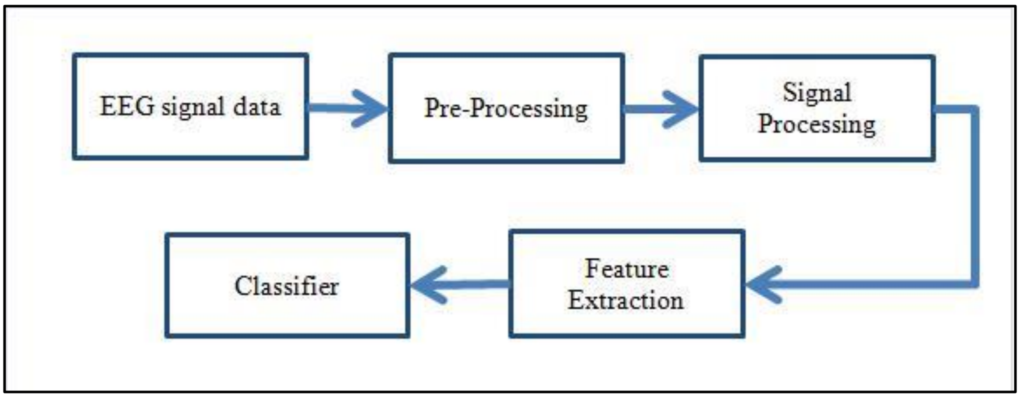

Figure 7. EEG signal data processing flow diagram

Basically, the steps taken to process the OT data is similar to the overall steps taken to process the EEG data. The data collected from the OT will also need to undergo pre-processing. The OT data will be passed through a either a low-pass filter or band-pass filter to remove the artifacts [22, 23]. The processing of the OT data will be done using Platform for Optical Topography Analysis Tools (POTATo). Through POTATo, the processing steps will be applied to the OT data sets. The first step is to apply polynomial curve fitting to the data to prevent drifting of the data and to try to get the best fit plot. Next, a moving average function is applied over the data to smoothen the data. Baseline fitting is followed next to correct the baseline to a better fit. Finally, continuous time data is needed to be converted into ‘blocks’, so that the average of all the ‘blocks’ during the mental arithmetic tasks can be obtained. After processing, the features will be extracted and correlation will be done for data from the OT and “stress group” EEG data. Figure 8 shows the general steps taken to process the OT data.

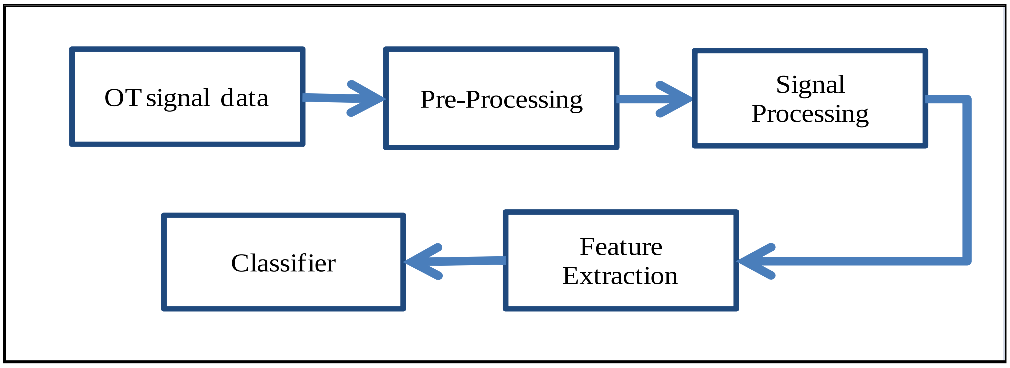

Figure 8. OT signal data processing flow diagram

KEY MILESTONE & GANTT-CHART

5.1 FYP 1

Key Milestones:

- Pre-processing of EEG data finished
- Processing of EEG data finished
- EEG data classified

Project Activities:

- Preliminary research work
- Literature Review and Methodology design
- Pre-processing of EEG data
- Processing of EEG data
- Classifying EEG data

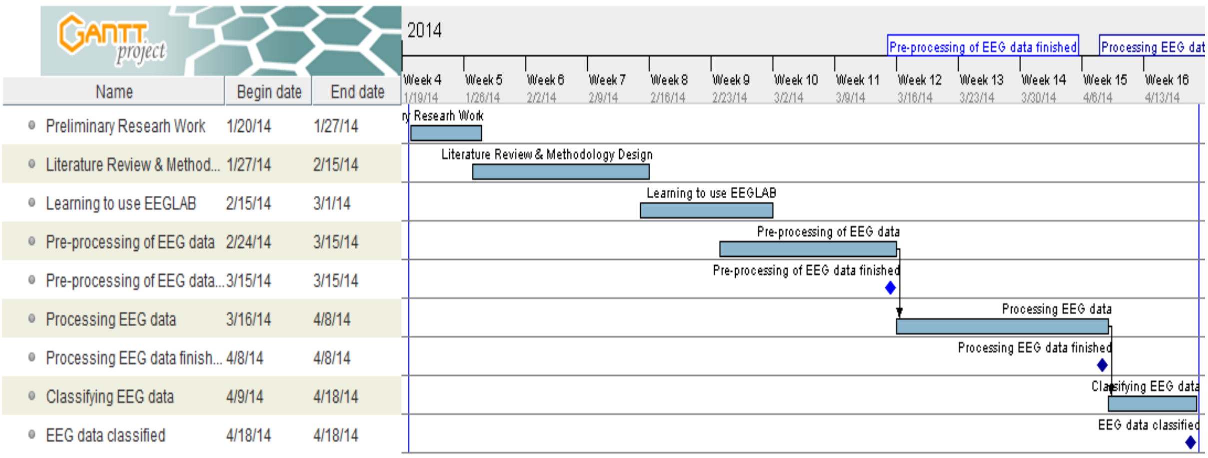

Figure 15: Gantt Chart for FYP 1

5.2 FYP 2

Key Milestones:

- Pre-processing of OT data finished
- Processing of OT data finished
- OT data classified

Project Activities:

- Pre-processing of OT data
- Processing of OT data
- Classifying OT data
- Performing correlation
- Analysing results and finding a correlation

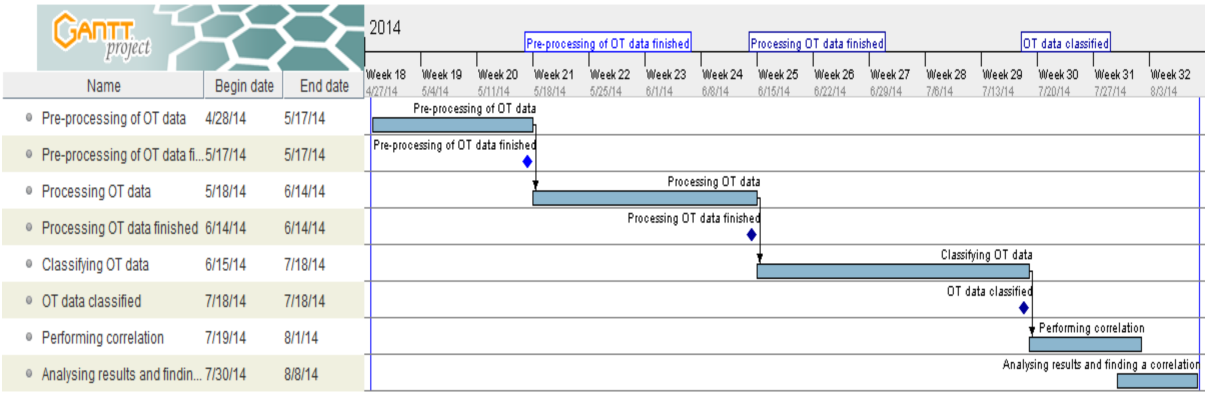

Figure 16: Gantt Chart for FYP 2

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Loading EEG data

The raw EEG data obtained from the stress experiment needs to be pre-processed before being analysed to find any significant relationship between the control group and the stress group. The raw EEG data is being processed using EEGLAB toolbox in MATLAB. First of all, the EEG data needs to be imported and loaded into MATLAB. Figure 9 shows an example of how a raw EEG data looks like.

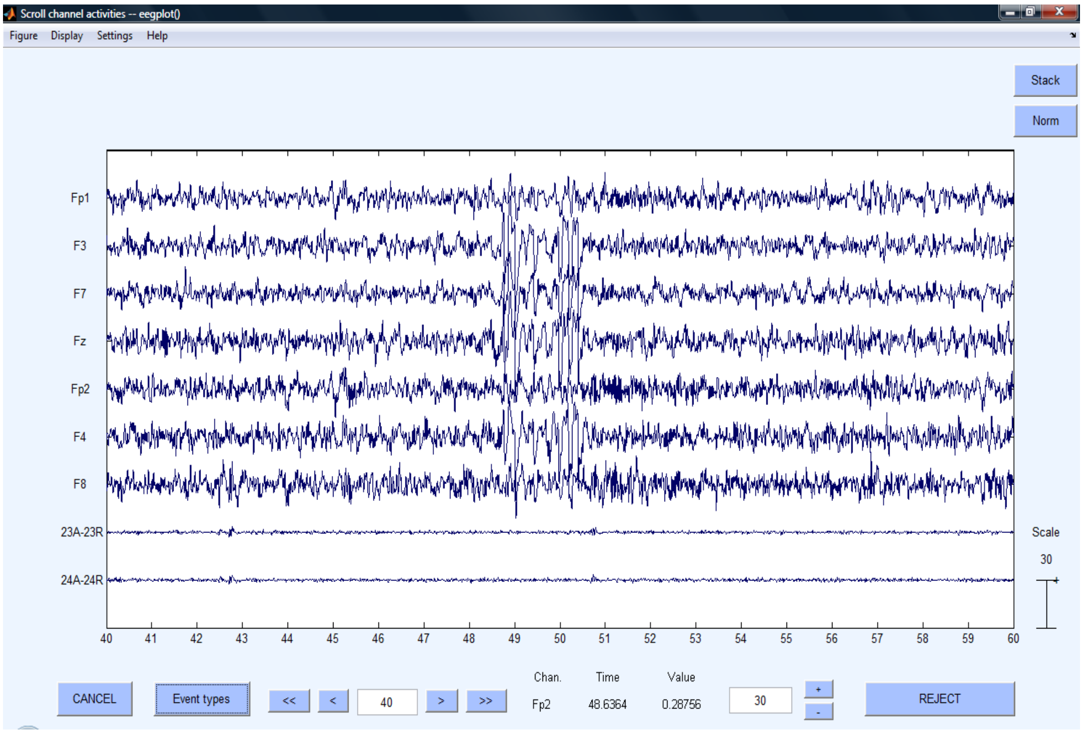

Figure 9. Raw EEG data

4.2 Band-pass filter the EEG data

The raw EEG data is then preprocessed to remove artifact such as line frequency, eye blinks, muscle movements and other noise signals. The first step is to remove the line frequency by applying a band-pass filter of with cutoff frequencies of 1 Hz and 40 Hz. This will remove the DC component of the signal which is at 0

Hz and also the line frequency which is 50 Hz. The line frequency is introduced from the power lines and is a form of noise to the EEG data. Most of the higher frequencies of the EEG data are irrelevant [16, 24]. Figure 10 shows the power spectrum plot after it has been band-pass filtered where the power magnitude before 1 Hz and after 40 Hz had been reduced due to the filter.

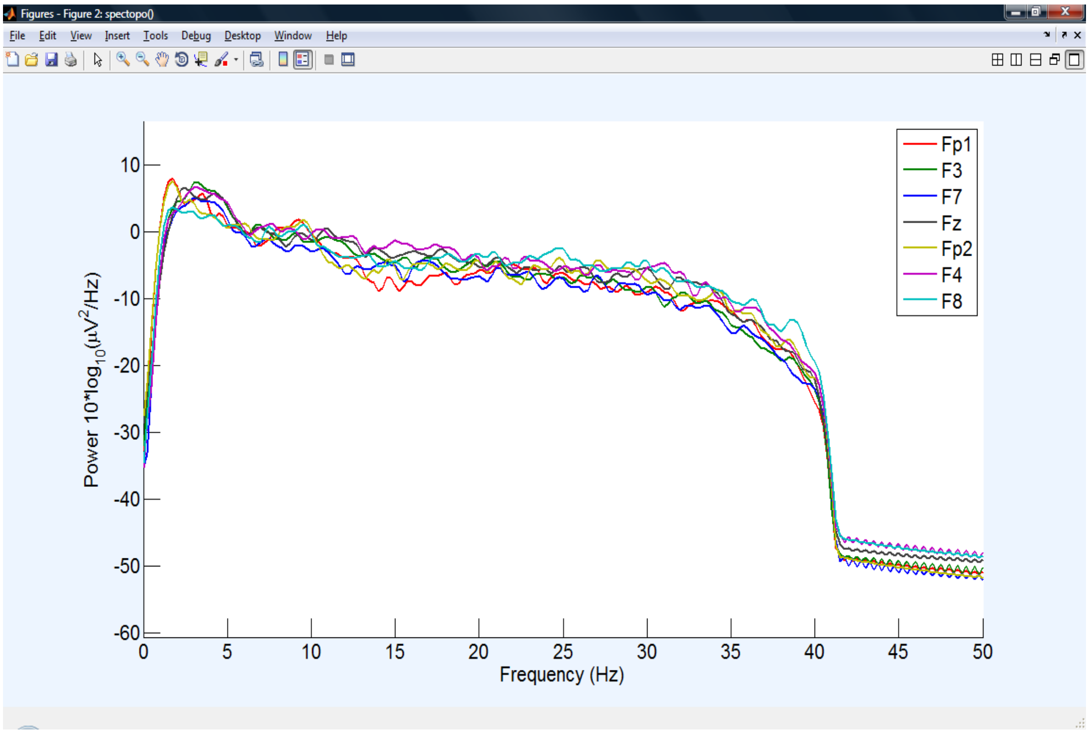

Figure 10. Power spectrum of the EEG data after it has been band-pass filtered

4.3 Independent Component Analysis (ICA) decomposition for the EEG data

Next, ICA is run to decompose the data into several components. Through ICA decomposition, the information sources are determined from synchronous or partially-synchronous activity surrounding a particular channel. Basically, data collected at a single-scalp channel will be transformed to spatial filter. The ICA method assumes that the time series scalp recording actually consists of a mixture of activities of temporally independent cerebral and artifact sources that are stable spatially. This mixing of information sources is via volume conduction which is recorded at the scalp channels and is linear, passive and does not add any additional information to the EEG data recorded.

4.4 Eye blink artifact rejection from the EEG data

From the analysis of the decomposition of ICA, certain artifacts can be decomposed into components, especially eye blink movements. Eye blinks are generally predominant at the prefrontal sites, recorded by Fp1 and Fp2 channels. Eye blinks, in nature are recorded as having large amplitude of more than 50mV on the EEG recordings as identified in Figure 11. Through the use of ICA, the eye blink component could be rejected without losing any other additional information. As shown in Figure 12, the eye blink component is evident after the ICA decomposition was done. Through the rejection of the eye blink component, only the eye blink artifact will be rejected while the rest of the EEG data retains its information. Figure 13 shows how the EEG data appears after the removal of the eye blink artifact.

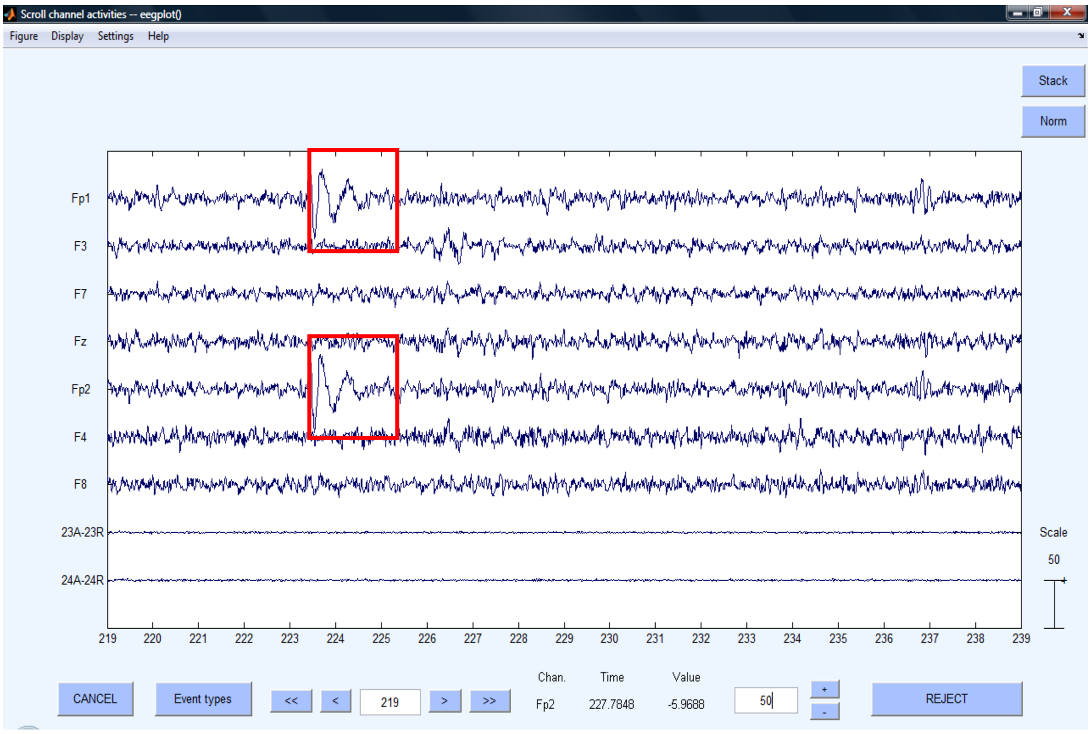

Figure 11. EEG data showing eye blink artifact

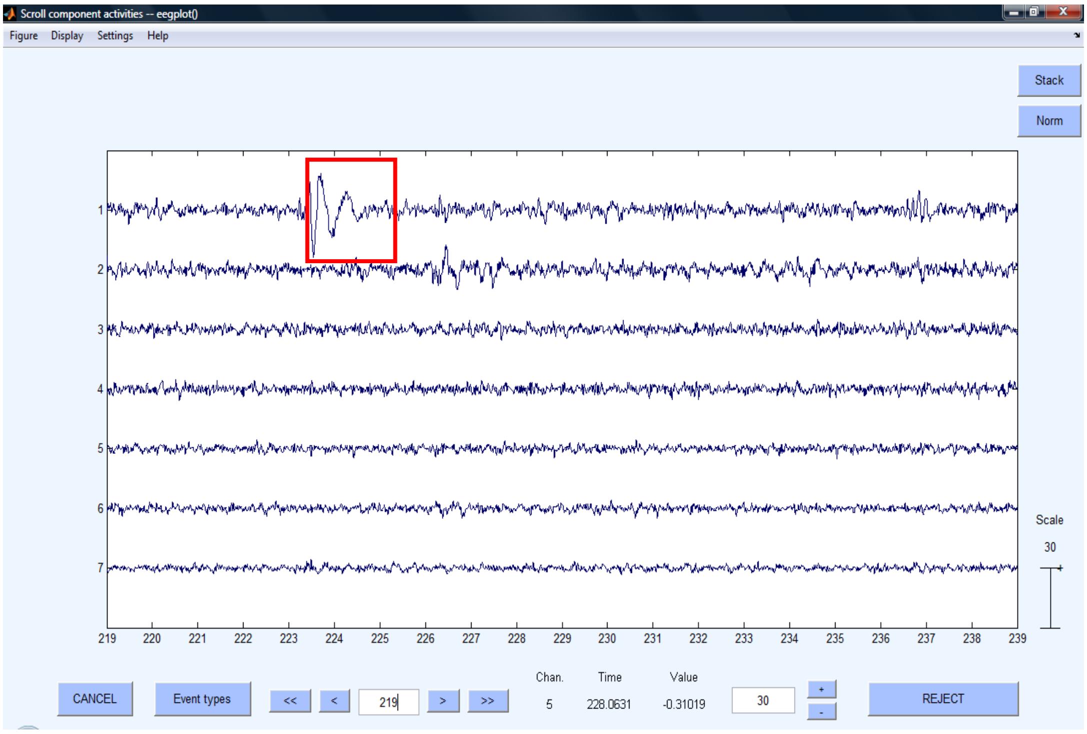

Figure 12. Eye blink component evident after ICA decomposition

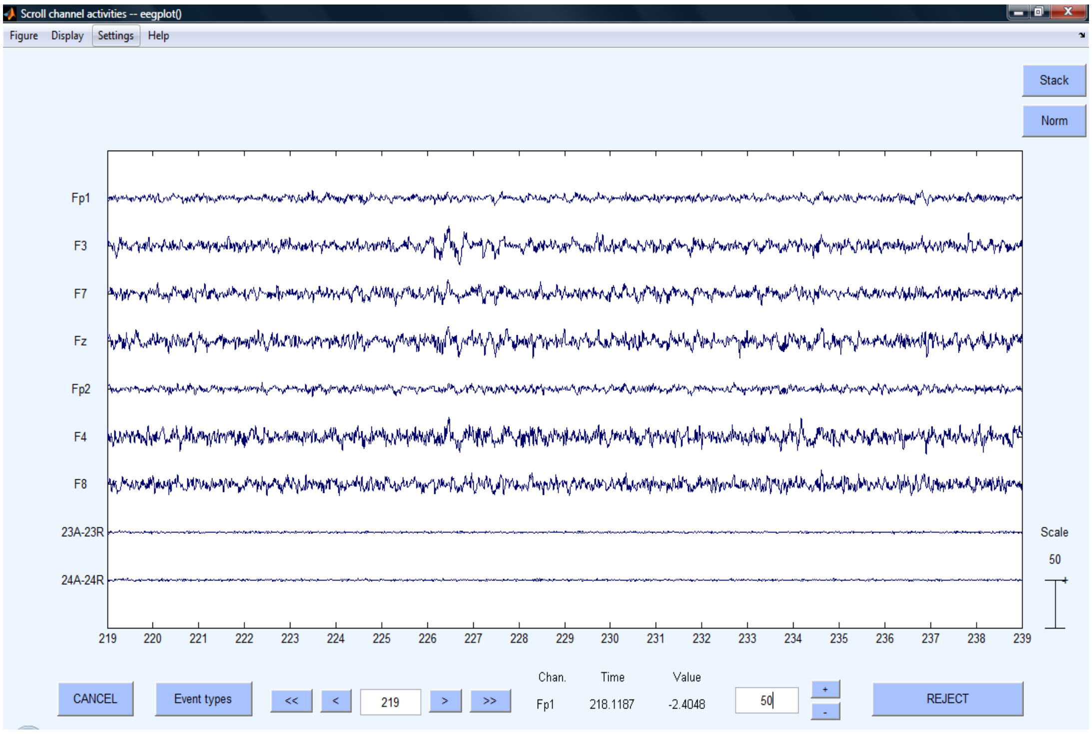

Figure 13. EEG channels data after removal of eye blink component

4.5 Muscle movement artifact rejection from the EEG data

Another artifact that affects the EEG data is the artifact arising from muscle movements known as electromyographic (EMG) signal. EMG potentials are generally in very short duration of 2 to 20 microseconds. EMG artifacts also have a very high frequency component. Figure 14 shows an example of recorded muscle movement artifact in the EEG data. EMG artifact that is present are removed through manual inspection of the data and removed. The information of data lost in this case is still acceptable as EMG artifact have very short pulses in nature.

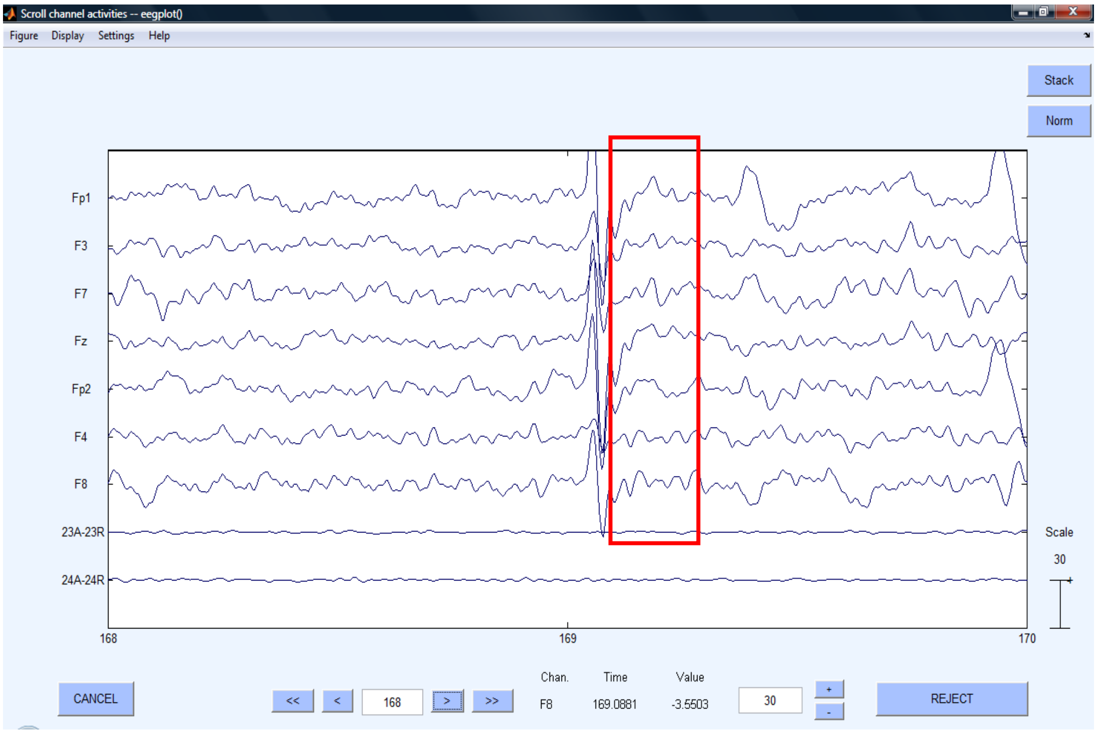

Figure 14. EEG data showing muscle movement artifact

4.6 Noise artifact rejection from the EEG data

There is also other noise artifact that affects the data which does not resemble eye blinks or muscle movements. These artifacts may arise from other sources through head movements or teeth clenching or even tongue movements. The amplitude of these noises is higher in amplitude than that of normal scalp EEG recordings. Figure 15 shows an example of noise artifact found in the EEG data. These noise artifacts are identified through manual inspection and rejected manually.

These noise artifacts are removed as they corrupt the EEG data and do not contribute to the stress condition analysis.

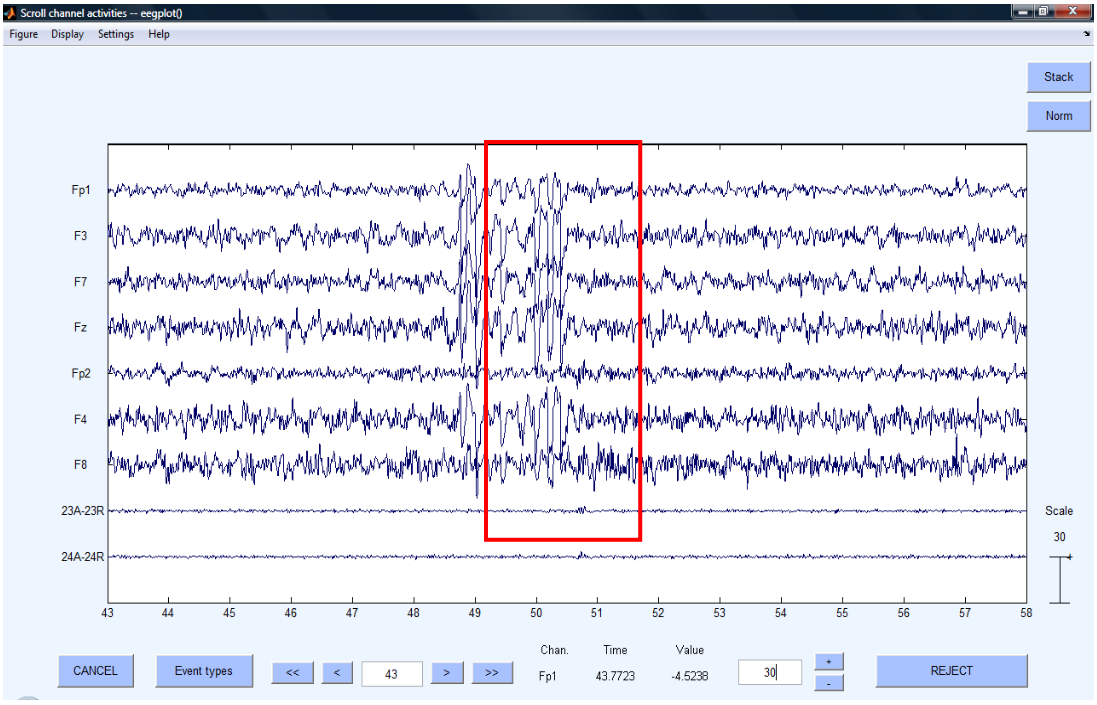

Figure 15. EEG data showing noise artefact

4.7 Processing of EEG data

After the EEG data has been cleaned, the EEG data can now be processed for further analysis. A study set was created and the EEG datasets were grouped into a control group and stress group. The data were divided into respective power spectrum bands. The power spectrum bands are Delta band, δ (0.5 – 4 Hz), Theta band, θ (4 – 8 Hz), Alpha band, α (8 – 12 Hz), Beta band, β (12 – 30 Hz) [19]. Welch's method is applied to estimate the power spectra in each power spectrum bands. The EEG data is split into overlapping segments where the segments are overlapping by 50%. A moving window is then applied across the segments of data. The overlapping of the data helps to mitigate loss of information as the window function have more significant influence on the center of the data set rather than those at the edges. Next, it transformed from the time domain to the frequency spectrum using Fast Fourier Transform, giving the calculated power in each power spectrum bands.

4.8 Paired t-Test for the processed EEG data

The control group and the stress group were then analysed using paired-t test statistics. The power spectrum bands were analysed according to their respective channels. A power spectrum band is said to have significant relationship between the control and stress group if its p-value is less than 0.05. The significant relationship indicates that there is a distinct difference of the neuronal state of the brain during a non-stress period and stress period.

The table below shows the p-value calculated from the data of all the subjects, comparing the control and stress sessions. The highlighted cells indicates the p-values of the power band that is less than 0.05 at which channel location. The power band of interest here is the alpha and beta power spectrum as these are the frequency bands that correlates with the relaxation and stressed states. As observed, the p-value of Alpha power band is less than 0.05 at Fp1 and Fp2 as well as the p-value of Beta power band at Fp1. This reveals that there is distinct difference in the magnitude of the power band between the control and the stress sessions. The control and stress sessions in itself further consists of 3 sessions each, referring to the 3 levels of difficulty of the arithmetic tasks assigned.

Table 1. P-value for the 7 channels

	Fp1	F3	F7	Fz	Fp2	F4	F8
Delta	0.013743	0.367206	0.007596	0.985172	0.024179	0.779521	0.030378
Theta	0.003151	0.951868	0.18117	0.670909	0.008686	0.526224	0.10129
Alpha	0.003555	0.679744	0.060809	0.753644	0.041202	0.599149	0.172387
Beta	0.047723	0.54314	0.403348	0.640558	0.341521	0.152083	0.66767
Relative Delta	0.344911	0.233115	0.011323	0.988118	0.351957	0.679269	0.075264
Relative Theta	0.093775	0.967242	0.238884	0.68715	0.912349	0.224787	0.087697
Relative Alpha	0.110137	0.316354	0.218579	0.721654	0.824237	0.883109	0.215207
Relative Beta	0.550962	0.296877	0.060793	0.688017	0.302816	0.292775	0.488641

Figure 16 and Figure 17 shows the comparison of the power magnitude in the alpha and beta band between the control and stress sessions. However, from Figure 16, it is noted that subject 9 and 10 showed a large difference in power magnitude. From Figure 17, it is also seen that the magnitude of the beta band power is abnormally high for subject 9 and 10 when comparing the control and stress sessions.

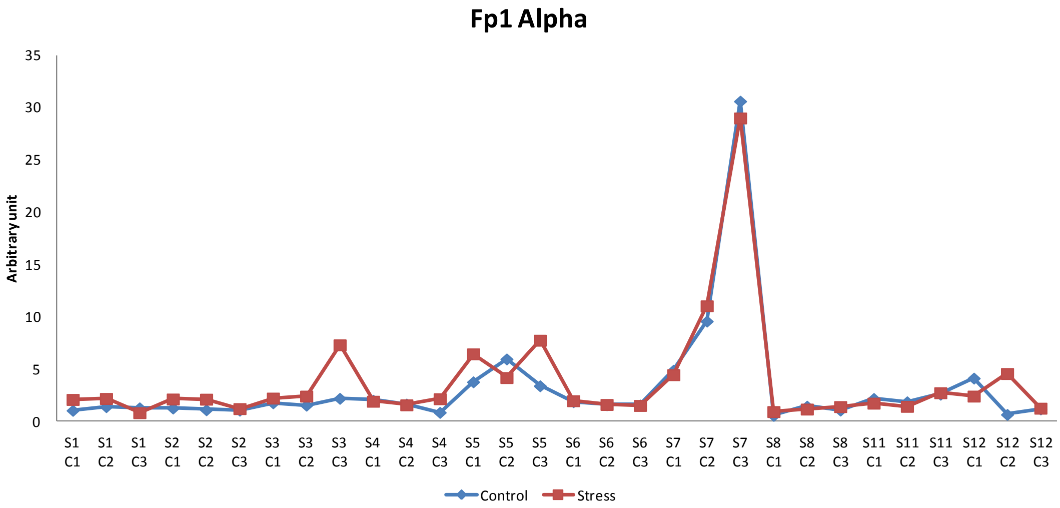

Figure 16. Absolute alpha power at channel Fp1

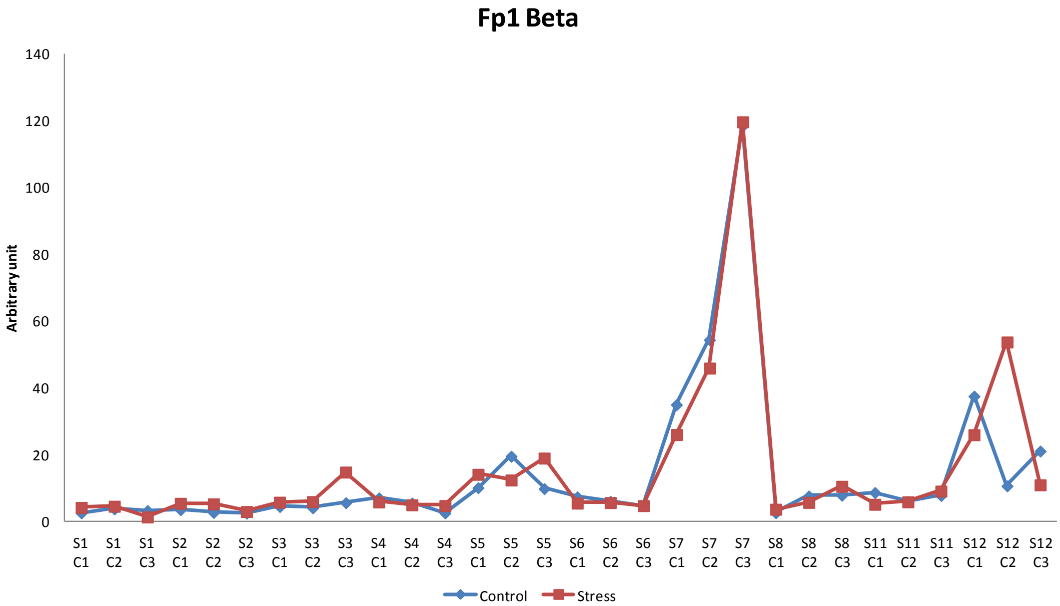

Figure 17. Absolute beta power at channel Fp1

Thus, the alpha power band at channel Fp2 is also used to complement the comparison of the alpha band power at Fp2. From Figure 18, this is also observed in the alpha power band at channel Fp2 whereby subject 9 and 10 again showed a large difference in terms of the magnitude of the power between the control and stress session.

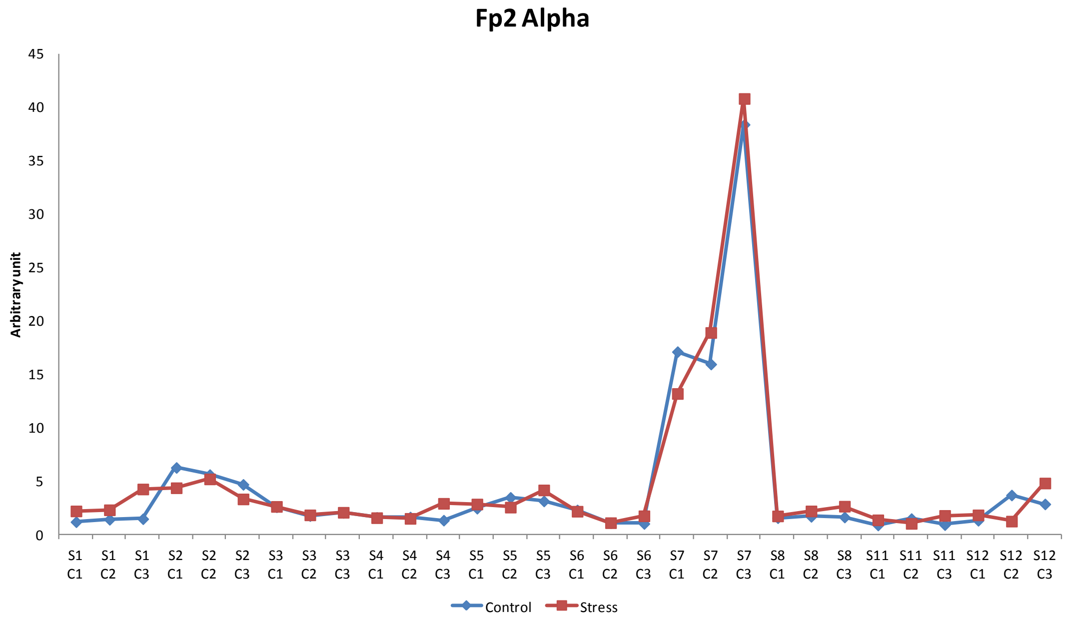

Figure 18. Absolute alpha power at channel Fp2

Subject 9 and 10 is considered as outlier as their power magnitude of absolute alpha power showed an abnormal difference at Fp1 and Fp2. Gauging from the questionnaires handed to the subject after the control and stress sessions, it is noted that Subject 9 indicated that he experienced discomfort from the EEG /OT cap that he wore which may lead to movements of the cap leading to contribution of artifacts. On the other hand, subject 10 indicated that he felt sleepy during the rest time in between of each question in each session. As such, both the subjects are removed from the data sets. The remaining 10 subjects are recalculated using the paired t-test to obtain new sets of p-value.

The p-values for the subjects excluding subject 9 and 10 is shown in the table below. The p-value of slightly more than 0.05 is also considered in this case since it is still marginally significant. Note that the only significant alpha band power is at channel Fp1 (p=0.054551). On the other hand, there is significance in the relative beta power at channels Fp1 (p=0.044262), Fp2 (p=0.040923), F7 (p=0.053205) and F8 (p=0.016962). It is also interesting to note that the channels Fp1, Fp2, F7 and F8 are located at the foremost part of the skull and that Fp1 are positioned with respect to Fp2 on opposite sides of the skull and same goes for F7 and F8.

Table 2. P-value for 7 channels excluding Subject 9 and 10

	Fp1	F3	F7	Fz	Fp2	F4	F8
Delta	0.145594	0.562335	0.010961	0.523223	0.236256	0.344926	0.016932
Theta	0.029971	0.59846	0.198761	0.215472	0.040312	0.570727	0.023345
Alpha	0.054551	0.928564	0.078773	0.304257	0.334198	0.947073	0.195192
Beta	0.601866	0.369758	0.611552	0.570874	0.498622	0.986072	0.761327
Relative Delta	0.054967	0.671843	0.009012	0.841808	0.232543	0.109278	0.002333
Relative Theta	0.275548	0.869634	0.329819	0.822513	0.266071	0.333348	0.437577
Relative Alpha	0.089843	0.453214	0.229854	0.996582	0.457802	0.622669	0.280142
Relative Beta	0.044262	0.710214	0.053205	0.702343	0.040923	0.515126	0.016962

Figure 19 shows the absolute alpha power at channel Fp1. It is noted that in majority of the sessions, the graphs shows a higher power magnitude in the absolute alpha power during the stress session compared to the control session. Some of the sessions have very close values in terms of magnitude power between the control and stress session. Only a few showed a decrease in the alpha power during the stress sessions as in Subject 1's Session 3, Subject 5's Session 2, Subject 7's Session 3 and Subject 12's Session 1. This contradicts the bulk of the past researches made whereby the alpha power is expected to be lowered during the stress session when compared to the control session.

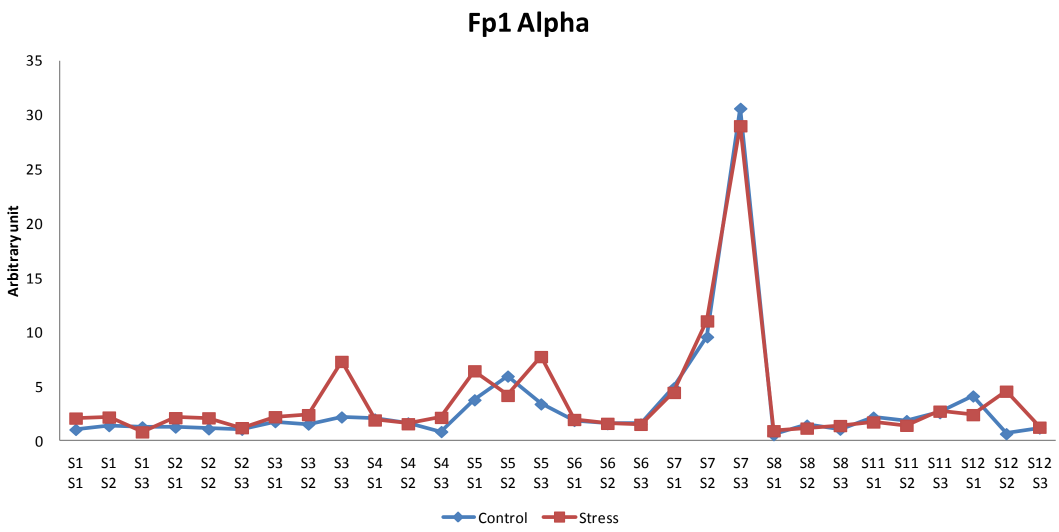

Figure 19. Absolute alpha power at channel Fp1 excluding subject 9 and 10

Figure 20, 21, 22 and Figure 23 shows the relative power of beta band at channels Fp1, Fp2, F7 and F8 respectively. In general, the behaviour of the results of the subjects during control and during stress is very erratic and showed no particular pattern.

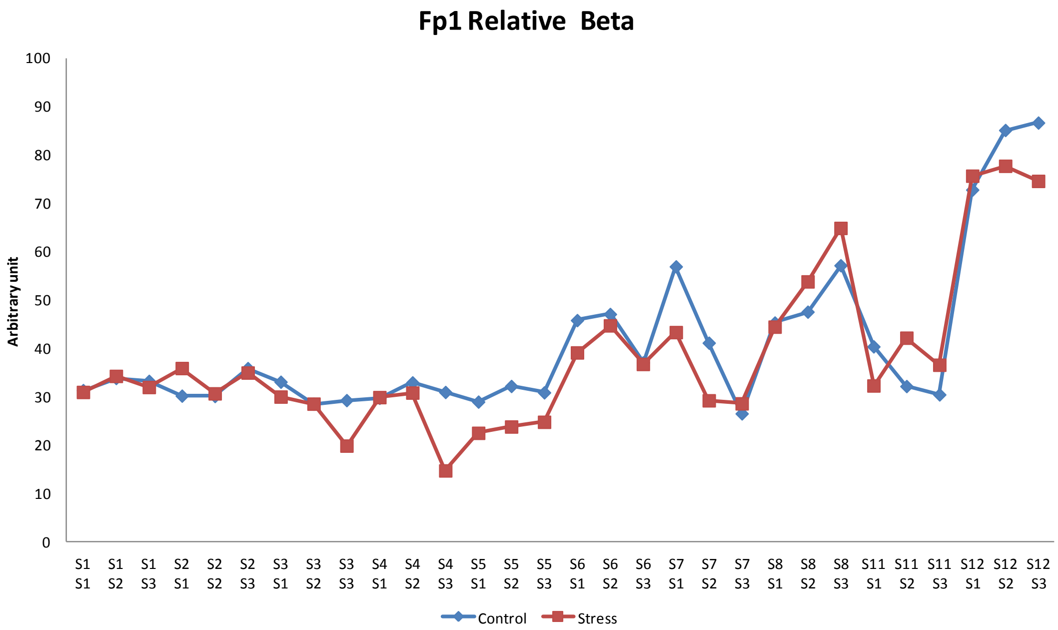

Figure 20. Relative beta power at channel Fp1 excluding subject 9 and 10

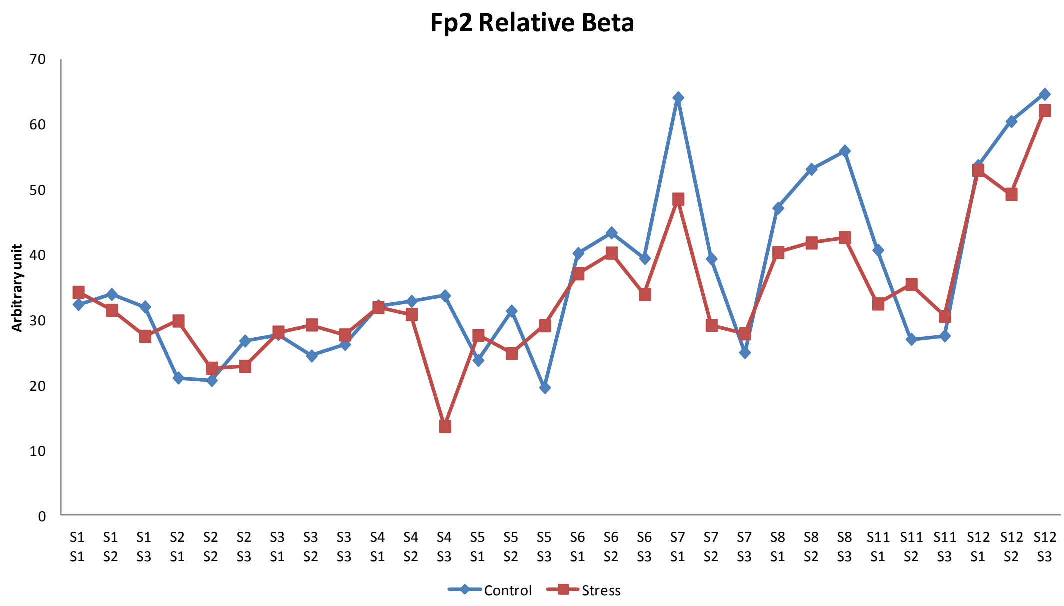

Figure 21. Relative beta power at channel Fp2 excluding subject 9 and 10

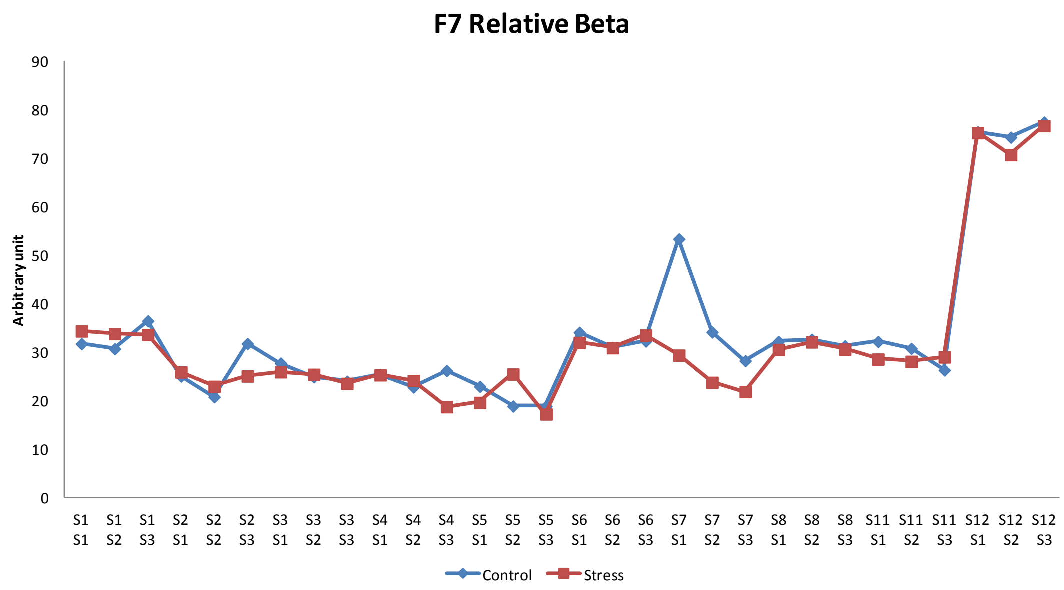

Figure 22. Relative beta power at channel F7 excluding subject 9 and 10

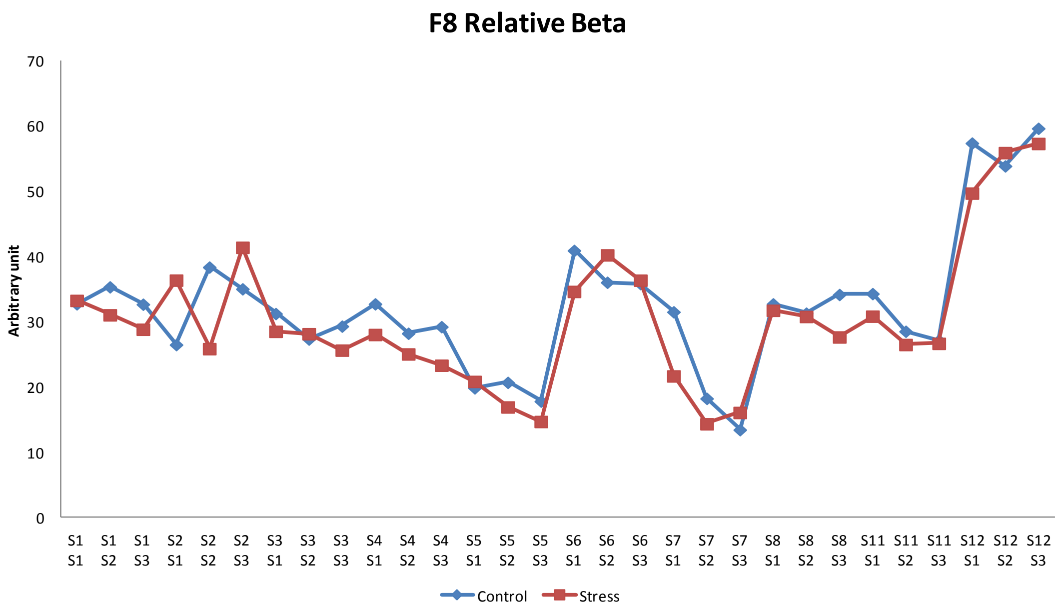

Figure 23. Relative beta power at channel F8 excluding subject 9 and 10

To further analyse the behaviour of the power spectrum bands of the subjects, comparison is done by comparing only between the same levels of difficulty for the mental arithmetic tasks assigned. Table 3 shows the p-value for Session 1 (Level 1 difficulty arithmetic questions) for the 10 subjects while Table 4 shows the p-value for Session 2 (Level 2 difficulty arithmetic questions) and Table 5 for Session 3 (Level 3 difficulty arithmetic questions). Only the p-value for the absolute and relative alpha and beta power spectrum are shown because these are the power spectrum bands that relates directly to the relaxation state and stressed state.

From Table 3, when only evaluating the power spectrum for Session 1, there is significance in the absolute power of alpha band at channel Fz (p=0.008289) and in the relative power of alpha at channel F3 (p=0.017629).

Table 3. P-value for Session 1 only excluding Subject 9 and 10

	Fp1	F3	F7	Fz	Fp2	F4	F8
Alpha	0.460316	0.26268	0.210867	0.008289	0.490047	0.700932	0.620746
Beta	0.30758	0.379587	0.455621	0.493776	0.374279	0.363386	0.556763
Relative Alpha	0.151758	0.017629	0.989202	0.130447	0.214146	0.620222	0.633518
Relative Beta	0.127648	0.224408	0.194898	0.894541	0.384031	0.50918	0.200514

From Figure 24 and Figure 25, it is noted that the magnitude of the alpha power band is larger during the stress session when compared to the control session. This results contradict the past literature reviews that have shown that the alpha power should be decreased when in the stressed state. This is because the alpha waves are most prominent during the relaxation state and therefore, it should be expected that when in control condition, the alpha power is higher than that of the stress session.

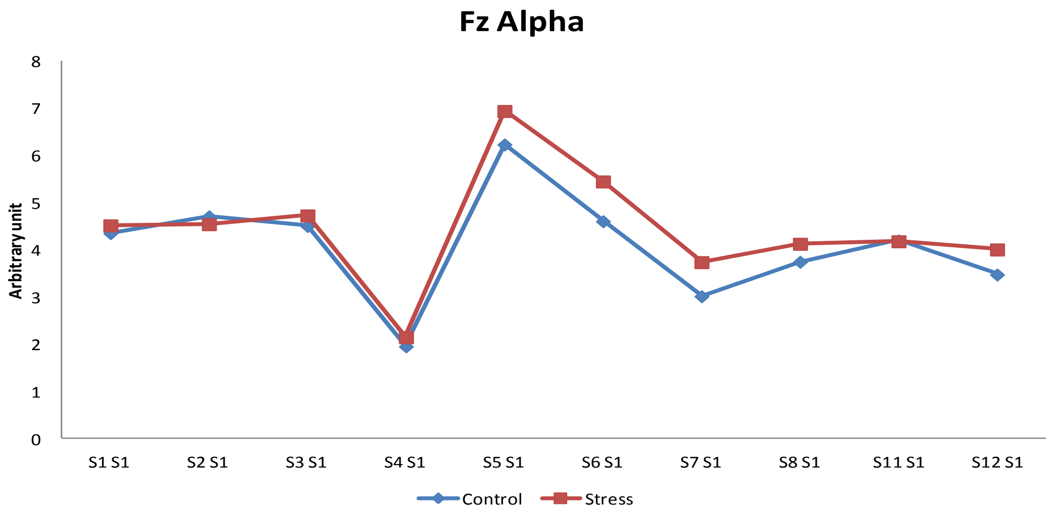

Figure 24. Absolute alpha power at channel Fz for Session 1 only

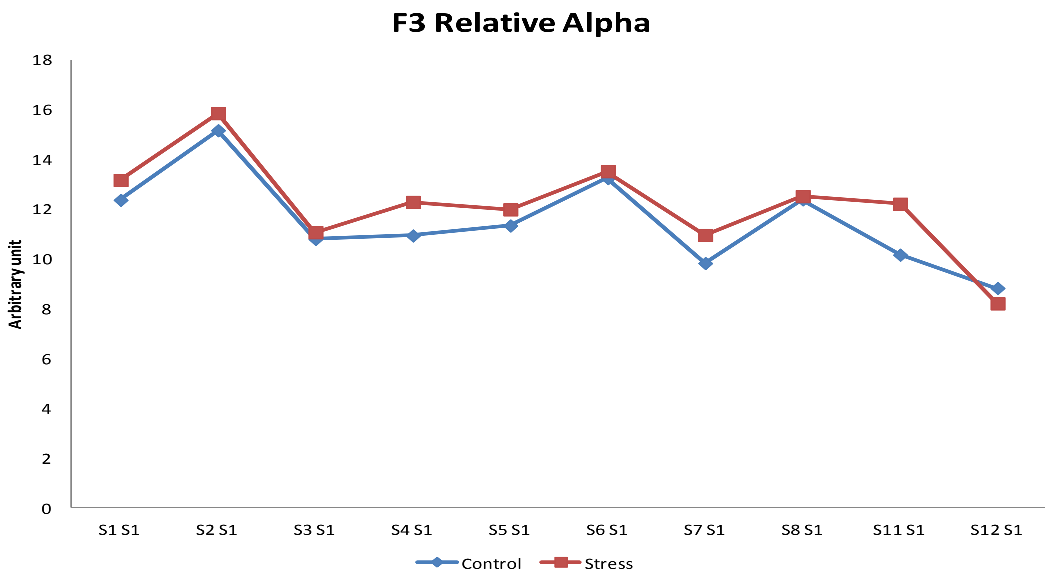

Figure 25. Relative alpha power at channel F3 for Session 1 only

However, when evaluating the power spectrum for Session 2, there is a difference in the channel and power band of significance. Table 4 shows that for Session 2, there is significance in the absolute alpha power band at channel F3 (p=0.022524) and in the relative alpha power band at channel F8 (p=0.039802). At channel Fz, the relative alpha power band is also taken into consideration since the p-value is only slightly than 0.05, at p=0.072962.

Table 4. P-value for Session 2 only excluding Subject 9 and 10

	Fp1	F3	F7	Fz	Fp2	F4	F8
Alpha	0.274933	0.022524	0.280473	0.586211	0.981485	0.986045	0.999269
Beta	0.532457	0.292887	0.262156	0.535621	0.238961	0.803748	0.413935
Relative Alpha	0.208056	0.19372	0.406538	0.072962	0.680034	0.907818	0.039802
Relative Beta	0.494063	0.163242	0.810827	0.288611	0.175254	0.739592	0.143976

From Figure 26, Figure 27 and Figure 28, it is noted that the magnitude of the alpha power band is smaller during the stress session when compared to the control session. Thus, when comparing only session 2, more than half of the subjects showed results that are in agreement of past researches' results.

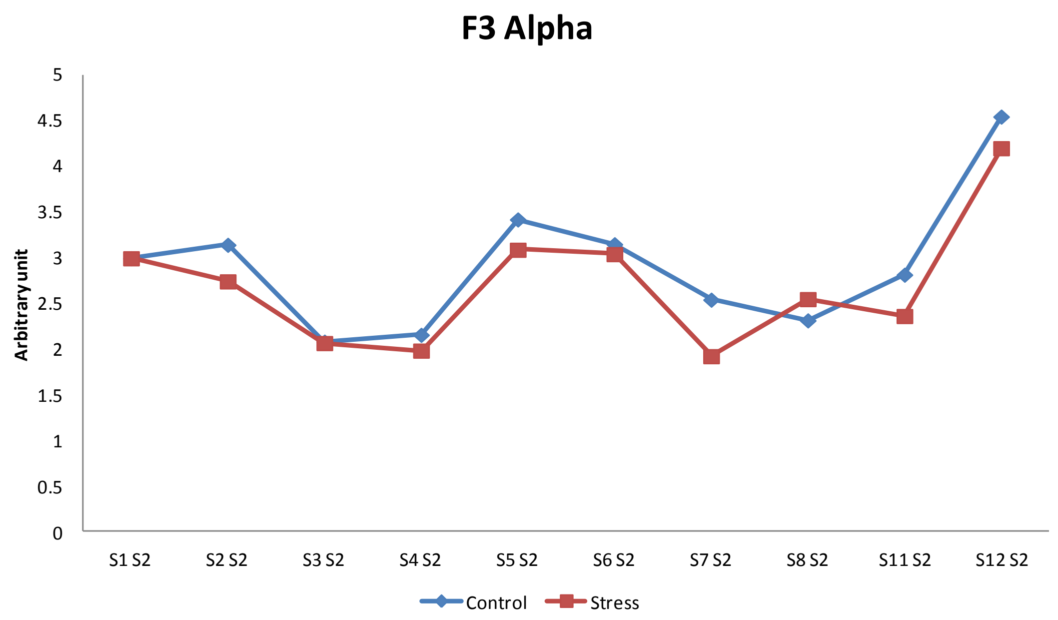

Figure 26. Absolute alpha power at channel F3 for Session 2 only

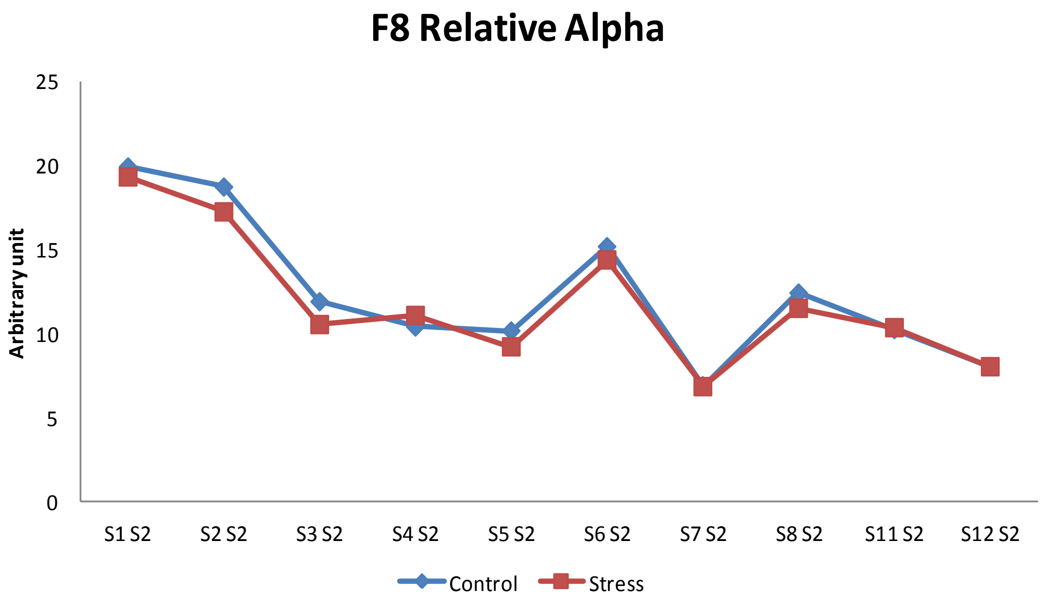

Figure 27. Relative alpha power at channel F8 for Session 2 only

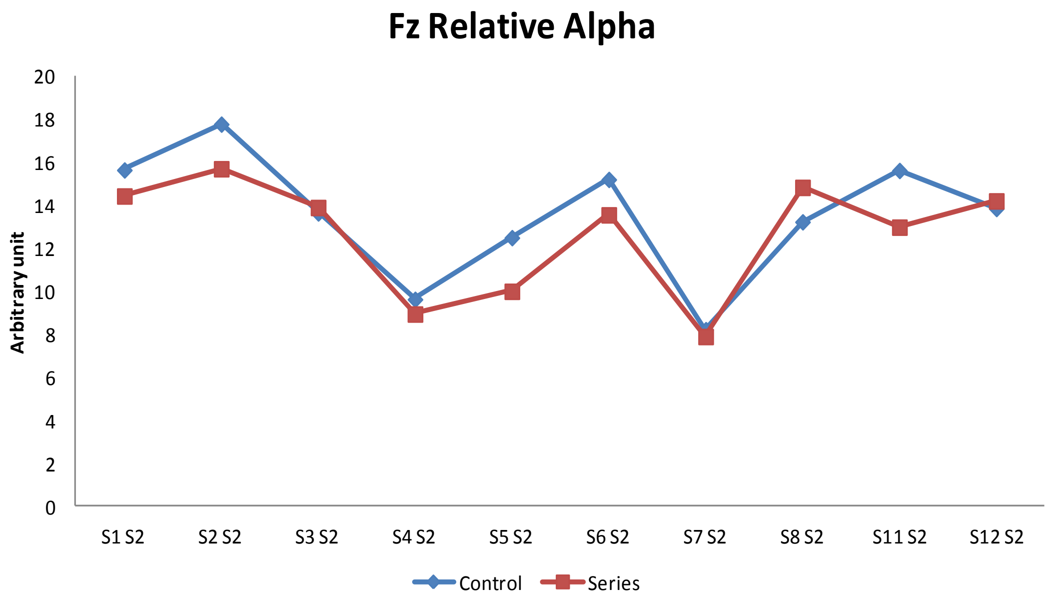

Figure 28. Relative alpha power at channel Fz for Session 2 only

Finally, the power spectrum for Session 3 is evaluated as shown in Table 5. There is significance in the absolute alpha power band at channel Fp2 (p=0.017503) and in the relative beta power band at channel F7 (p=0.067184).

Table 5. P-value for Session 3 only excluding Subject 9 and 10

	Fp1	F3	F7	Fz	Fp2	F4	F8
Alpha	0.19857	0.41605	0.580973	0.653619	0.017503	0.761902	0.168426
Beta	0.432368	0.480228	0.389435	0.956165	0.101239	0.185251	0.418127
Relative Alpha	0.619897	0.307356	0.290774	0.546441	0.794667	0.650857	0.658179
Relative Beta	0.249004	0.579831	0.067184	0.495819	0.253299	0.948539	0.226188

From Figure 29, it is noted that the magnitude of the alpha power band is now higher during the stress session when compared to the control session. This is the behaviour that was seen when analysing the subjects in Session 1 as well. Furthermore, from Figure 30, the relative power of the beta band is actually lower during the stress session than that of the control session. Beta is usually associated to the state of the brain when it is being active, alert and having intense focus and problem solving. As such, beta power band should be higher in magnitude during stress as according to some past researches done. In this case, the relative beta power band is in the opposite of the results expected.

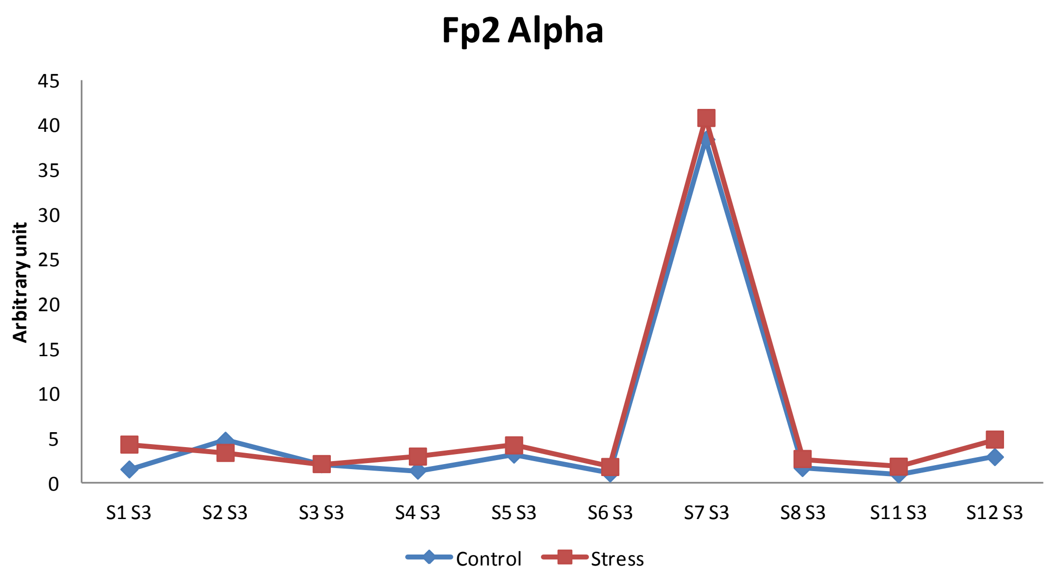

Figure 29. Absolute alpha power at channel Fp2 for Session 3 only

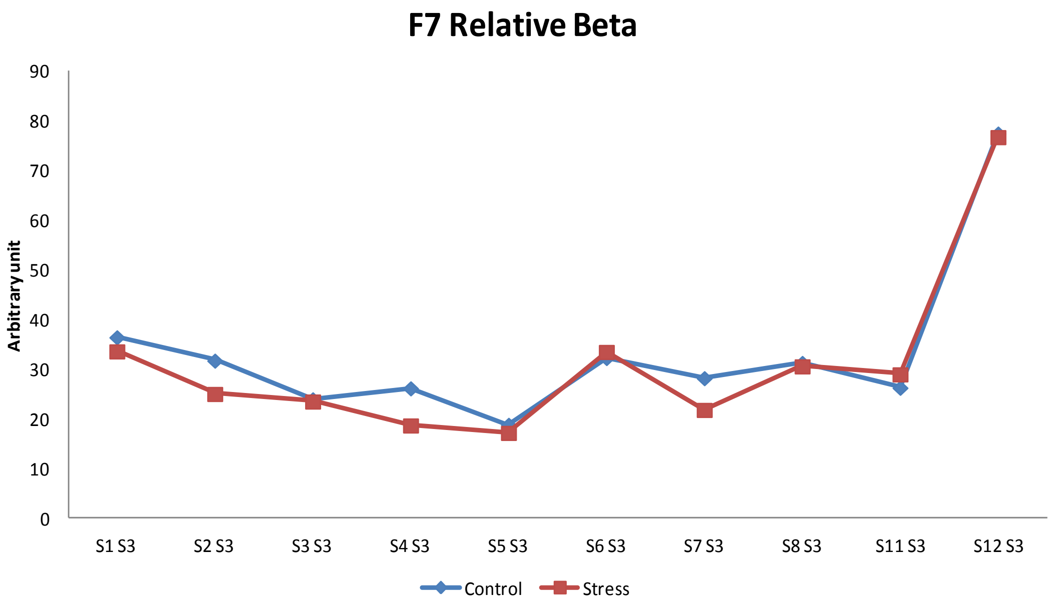

Figure 30. Relative beta power at channel F7 for Session 3 only

4.9 Analysis of the EEG results

Even though the overall trend of the EEG results showed that the alpha power band during the stress is higher than that during the control session, it is still possible to correlate it with the OT results by looking at each subject on its own. By comparing the subject's EEG and OT result in each session, a correlation may be found.

During a stressful condition such as performing mental arithmetic calculations, certain area of the brain will undergo changes in the haemodynamic response. Through neurovascular coupling, it is expected that when under stressful condition, the neuronal activity changes with the cerebral blood flow. From the EEG, neuronal activity during stressful condition is indicated from reduced alpha power band. A qualitative study is then done for the OT results to compare with either an increased or decreased value of the EEG signal during the stress session.

4.10 Plotting oxyhaemoglobin and deoxyhaemoglobin level for OT

Figure 31 shows the changes in the haemodynamic responses for Subject 1 during the first control session across the OT channels. The channels that showed fuzzy lines are channels that are unattached to the scalp of the head. The changes in the oxyhaemoglobin is observed and compared for both the control and stress sessions. Comparing Figure 31 and Figure 32, it is noted that the oxyhaemoglobin level is higher during the first control session.

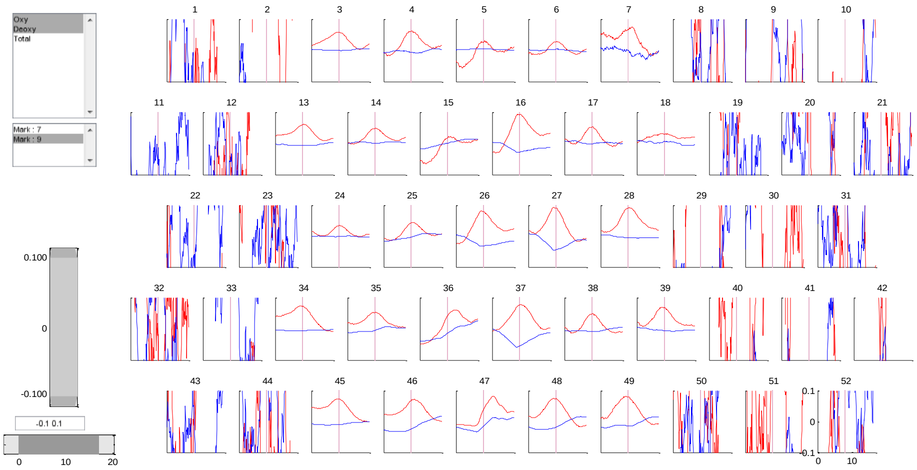

Figure 31. OT result for Subject 1 during Control Session 1

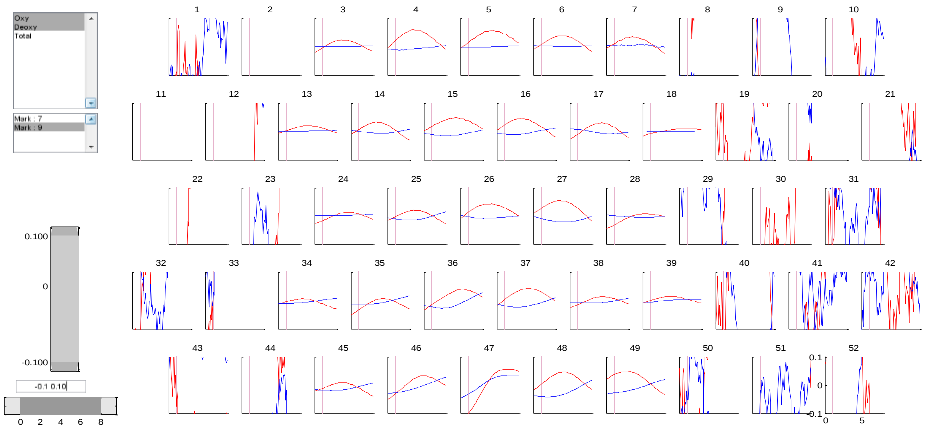

Figure 32. OT result for Subject 1 during Stress Session 1

Channels 26, 36, 37 and 47 are chosen to be analysed because they are located at the center of the head and would give a more balanced haemodynamic response reading. Figure 29, 30, 31 and 32 shows the peak oxyhaemoglobin level at channel 26, 36, 37 and 47 respectively. The plots show the comparison of the peak level of the oxyhaemoglobin during each session, comparing between the control and stress session.

Figure 33 shows that at channel 26, the oxyhaemoglobin peak level is higher for the control session in 19 out of the 30 sessions.

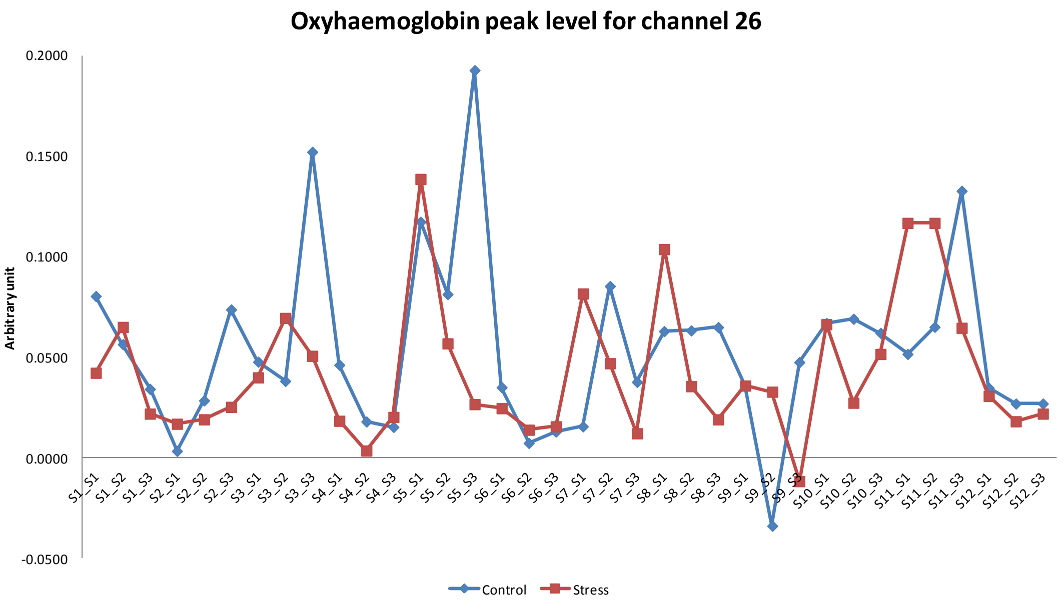

Figure 33. Oxyhaemoglobin peak level for channel 26

Figure 34 on the other hand, shows that at channel 36, the oxyhaemoglobin peak level is higher for the control session in 15 out of the 30 sessions.

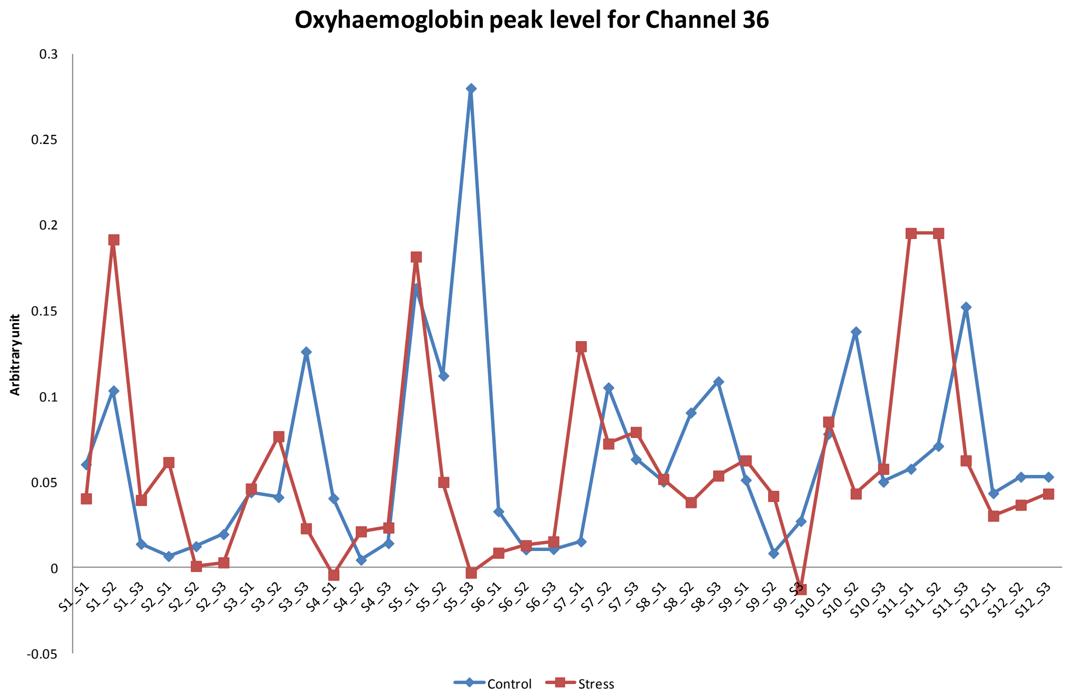

Figure 34. Oxyhaemoglobin peak level for channel 36

Figure 35 shows that at channel 37, the oxyhaemoglobin peak level is higher for the control session in 17 out of the 30 sessions.

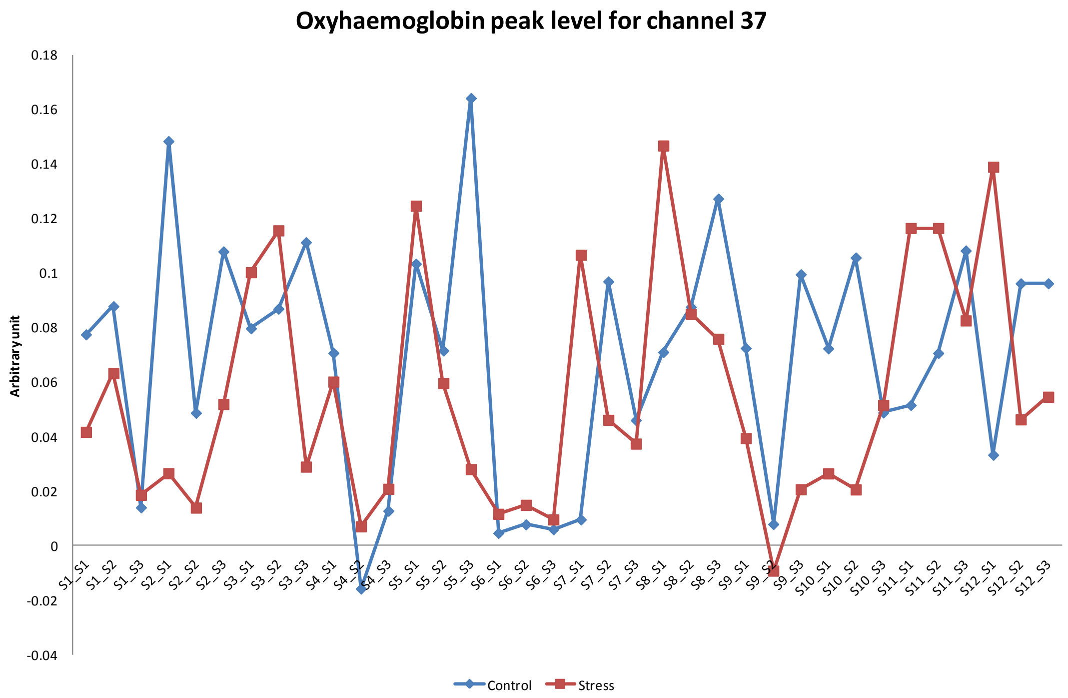

Figure 35. Oxyhaemoglobin peak level for channel 37

Figure 36 shows that at channel 47, the oxyhaemoglobin peak level is higher for the control session in 16 out of the 30 sessions.

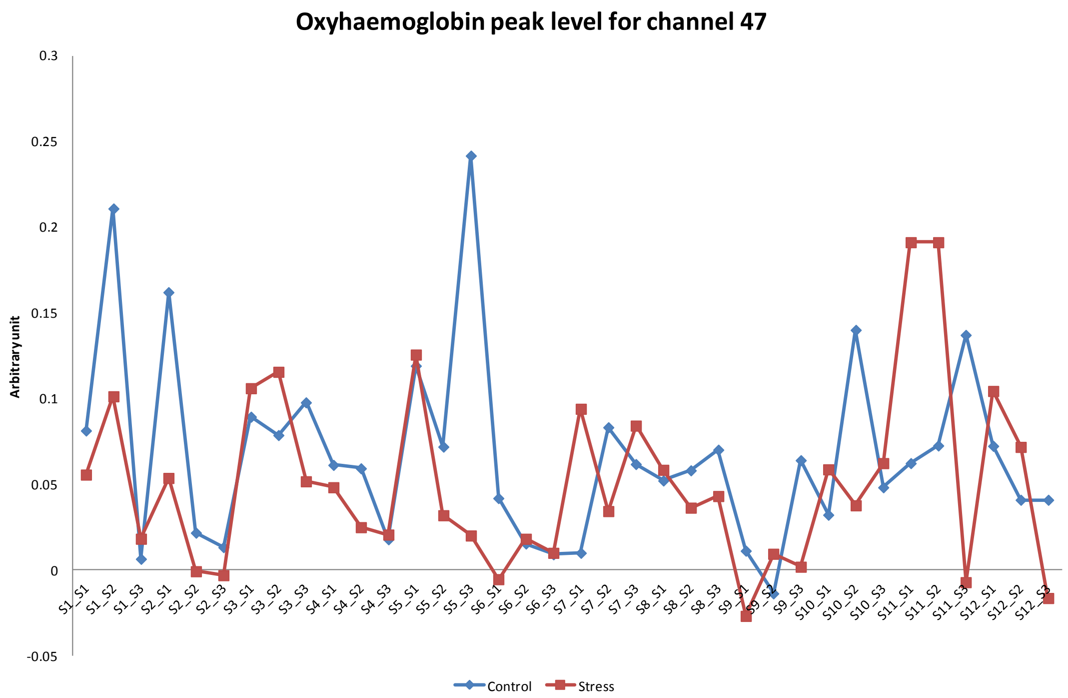

Figure 36. Oxyhaemoglobin peak level for channel 47

From the plots of the oxyhaemoglobin peak levels above, it is noted that during the control session, the oxyhaemoglobin level is generally higher than that of during the stress sessions. Table 6 shows the summary of the delta peak of the oxyhaemoglobin level at the 4 channels of interest whereby the negative values indicate that the oxyhaemoglobin level is higher during control sessions compared to stress sessions.

$$\begin{aligned} Delta\ peak = {} & Peak\ oxyhaemoglobin\ level\ \ during\ stress \\ & - peak\ oxyhaemoglobin\ level\ during\ control \end{aligned}$$

Table 6. Delta peak at channels 26, 36, 37 and 47

Delta peak at Channel 26	Delta peak at Channel 36	Delta peak at Channel 37	Delta peak at Channel 47
-0.0381	-0.0199	-0.0357	-0.0257
0.0086	0.0883	-0.0246	-0.1096
-0.0123	0.0256	0.0046	0.0117
0.0135	0.0549	-0.1218	-0.1084
-0.0094	-0.0115	-0.0348	-0.0225
-0.0484	-0.0165	-0.0560	-0.0164
-0.0078	0.0022	0.0206	0.0166
0.0313	0.0356	0.0287	0.0369
-0.1013	-0.1032	-0.0823	-0.0461
-0.0278	-0.0447	-0.0105	-0.0130
-0.0144	0.0166	0.0228	-0.0344
0.0049	0.0091	0.0081	0.0028
0.0212	0.0184	0.0213	0.0065
-0.0245	-0.0621	-0.0119	-0.0400
-0.1659	-0.2830	-0.1361	-0.2217
-0.0104	-0.0242	0.0070	-0.0473
0.0066	0.0024	0.0072	0.0028
0.0026	0.0045	0.0036	0.0009
0.0660	0.1140	0.0971	0.0841
-0.0384	-0.0328	-0.0508	-0.0489
-0.0255	0.0159	-0.0086	0.0224
0.0407	0.0016	0.0758	0.0062
-0.0277	-0.0523	-0.0026	-0.0218
-0.0458	-0.0550	-0.0514	-0.0270
0.0651	0.1377	0.0649	0.1289
0.0516	0.1243	0.0459	0.1186
-0.0681	-0.0897	-0.0256	-0.1443
-0.0040	-0.0132	0.1057	0.0321
-0.0088	-0.0164	-0.0499	0.0309
-0.0050	-0.0099	-0.0416	-0.0573

The higher peak values of the oxyhaemoglobin level during control sessions indicate that the subjects are concentrated in trying to solve the mental arithmetic questions assigned. Performing mental arithmetic tasks has been known to be associated to an increase in the concentration of the oxyhaemoglobin and a decrease in the deoxyhaemoglobin [25]. During the stress sessions, there may be factors contributing to loss of concentration, indirectly contributing a lower level of oxyhaemoglobin across the cerebral.

4.11 Correlation test between the EEG and the OT

From the previous EEG results obtained, the absolute alpha power at channel Fp1 is chosen as the feature to be correlated with the OT results. The absolute power at channel Fp1 is chosen because it has a significant p-value of 0.054551. This is used to be correlated with the oxyhaemoglobin level of the four channels of the OT. Table 7 shows the correlation results between the delta alpha power and the delta peak oxyhaemoglobin level for the 4 different channels. Figure 37, 38, 39 and 40 shows the plots of the correlation between the two parameters.

Table 7. Summary of correlation results

	R-square
Alpha power and oxyhaemoglobin (channel 26)	0.2295
Alpha power and oxyhaemoglobin (channel 36)	0.2148
Alpha power and oxyhaemoglobin (channel 37)	0.3255
Alpha power and oxyhaemoglobin (channel 47)	0.141

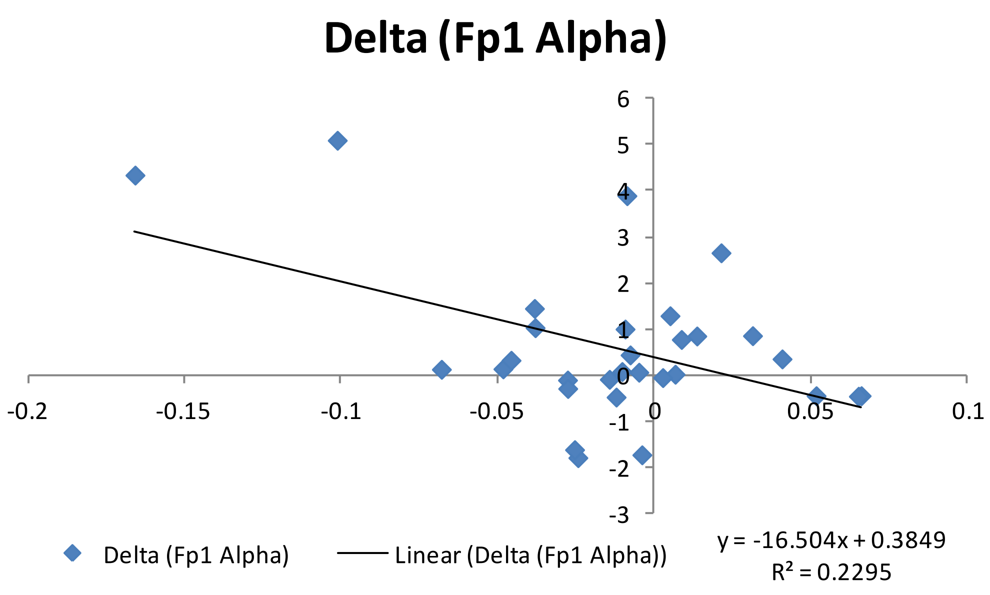

Figure 37. Correlation result between EEG and OT (channel 26)

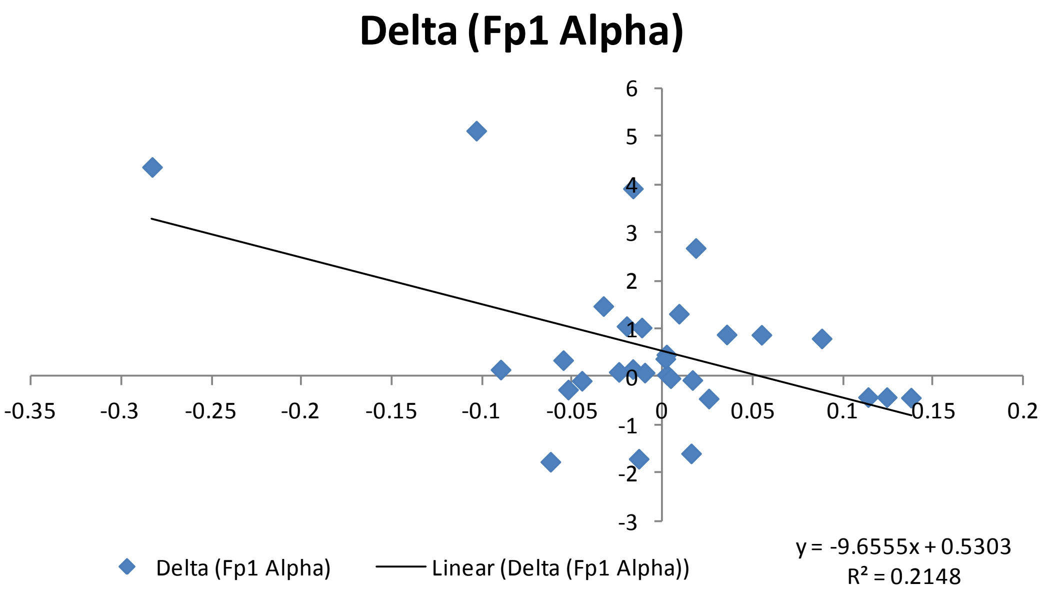

Figure 38. Correlation result between EEG and OT (channel 36)

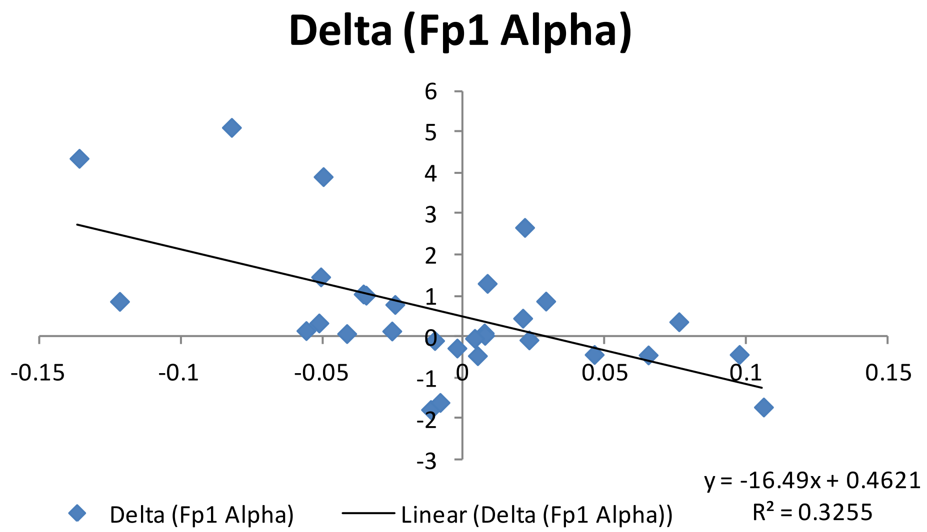

Figure 39. Correlation result between EEG and OT (channel 37)

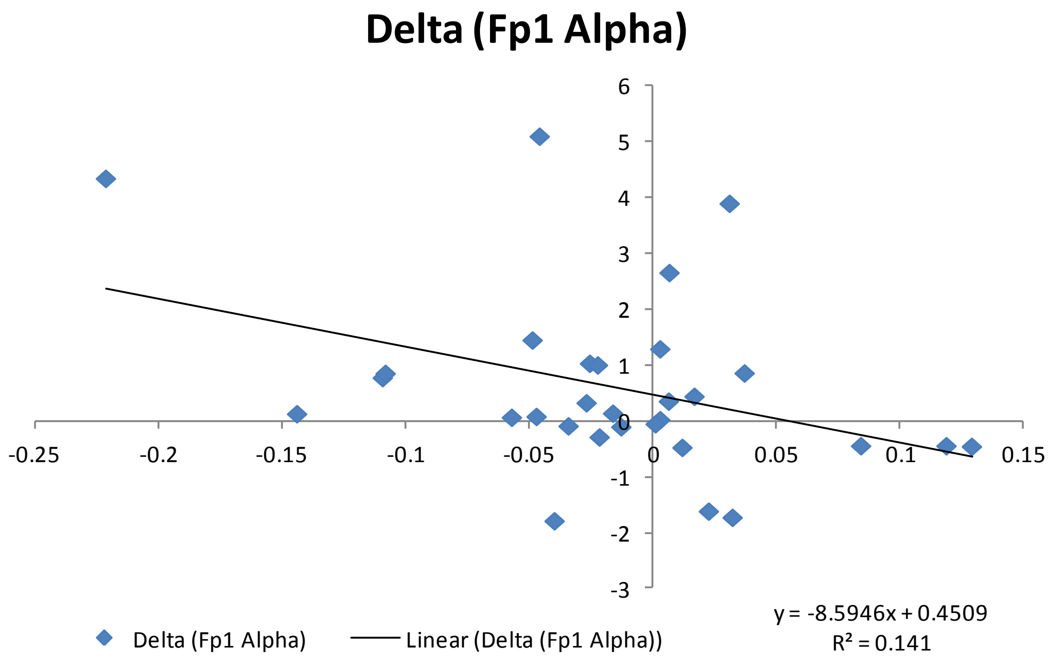

Figure 40. Correlation result between EEG and OT (channel 47)

From the correlation test done, it is noted that taking into account all the four channels, the highest R-square is still only 0.3255, which is at channel 37 of the OT. This shows that the two modalities do not actually have a significant relationship.

4.12 Discussion

From the previous EEG results showing the comparison of the alpha power band in the control and stress sessions, it has been established that the results obtained in this project does not conform to the results shown by previous researches. In this project, the results clearly shown that in 19 of the 30 sessions, the alpha power band is lower for the control session, rather than for the stress sessions. Literature reviews had shown that a lower alpha power band is associated to a stressed mental state. Thus, this could indicate that the control sessions are actually more stressful for the subjects undertaking the mental arithmetic questions.

The reason for this might be due to the experimental design for the data collection. Although the sessions are differentiated into control and stress sessions, both of them actually involve a certain concentration and also the use of the frontal lobe of the brain. In both the sessions, the subjects are required to solve mental arithmetic questions, with the difference being that the stress session has a shorter time duration allocated for each question. Given the condition for the stress sessions, the subjects may actually have a tougher time to really try to solve the questions, especially with such a short time constraint. As such, when the subject is given a difficult arithmetic question, they tend to give up while trying to solve the arithmetic questions. Furthermore, the questionnaires done by the subjects after the stress sessions revealed that they guessed most of the answers of for the arithmetic questions. Moreover, for both the sessions, the subjects indicated in the questionnaires that they had a difficult time trying to solve the questions. With the arithmetic questions being too difficult plus a short time allocated, these factors may have contributed to the reason why the subjects chose to guess when rather than actually try to solve the arithmetic questions.

However, when looking at the OT results by comparing the oxyhaemoglobin level of both the control and stress sessions, it was found that generally, the peak oxyhaemoglobin level is higher for the control session compared to the stress sessions. Oxyhaemoglobin level is expected to be higher for the control session because the when the subject is stressed, the concentration of the brain is affected and thus less neuronal activity, leading to a reduced cerebral blood flow. Thus, on the part of the OT, the results do conform to the previous researches. However, when the correlation is being done for both the modalities, the correlation result only showed R-square value of as high as 0.3255. This result showed that there is little correlation between the neuronal activities and haemodynamic response due to stress.

In analysing the correlation between the neuronal activities and the haemodynamic response of the brain, it has been assumed that in accordance to the theory of neurovascular coupling, the change in the oxyhaemoglobin level during tasks reflect the neuronal activity as they correlate with the evoked changes in regional cerebral blood flow [25]. However, it should be kept in mind that the OT does not in fact, directly measure the neuronal activity itself. While EEG measures the potential during the synaptic excitations of the dendrites of many pyramidal neurons in the cerebral cortex [26], the OT does not directly measure the same thing. Rather, what the OT measures is the haemodynamic response which comes as an effect of the changes in the cerebral blood flow, which is a physiological response that is related to postsynaptic neurons activity. However, there is no evidence showing that the synaptic excitations causing the neuronal activity are directly correlated to the postsynaptic neuronal activity [27]. Therefore, with the EEG and OT distinctly measuring different measurements, there need to be more researches done to prove that there is indeed a correlation between the neuronal and the haemodynamic response.

CHAPTER 6

CONCLUSION & FUTURE WORK

In this research, the neuronal and haemodynamic response due to stress had been recorded simultaneously using the EEG and the OT. The objective on processing and analysis of the EEG has been achieved. The EEG data had been cleaned through rejection and artifact and further processed to obtain the power spectrum of each band. Through the power spectrum, analysis of the EEG data showed that there is significance difference between the control and stress group. This is proven through the alpha and beta power band at channel Fp1 and Fp2. The results obtained indicated that the magnitude of the alpha power bands during the stress sessions are higher than that of the control sessions.

The objective of processing and analysis of OT had also been achieved. The raw OT data had been cleaned and processed to give the haemoglobin level. The oxyhaemoglobin level was analysed across different channels and the peak oxyhaemoglobin level. From the OT results, it was shown that the oxyhaemoglobin level for the stress session is lower than that of the control sessions. The peak oxyhaemglobin level is then used for correlation with the EEG results. From the correlation done, it was found that there is little correlation between the neuronal and haemodynamic response due to stress. Therefore, the objective on finding a correlation had been done, though result showed little significance relationship.

For future work, it would be recommended to redesign the experimental design for data collection. The control and stress sessions could have the subjects performing tasks that are able to be distinctly differentiated. In this research, the subjects were required to perform the same task which is solving mental arithmetic questions albeit being allocated different time constraint. Other than that, the subjects in the research are from the same vocation, that is, researchers. The scope for subjects could be broadened to include a wider variety of subjects from different field of work and wider range of age.

REFERENCES

[1] S. H. Seo and J. T. Lee, "Stress and EEG," in *Convergence and Hybrid Information Technologies*, ed: InTech, 2010, pp. 413-426.

[2] N. H. A. Hamid, N. Sulaiman, S. A. M. Aris, Z. H. Murat, and M. N. Taib, "Evaluation of human stress using EEG Power Spectrum," in *Signal Processing and Its Applications (CSPA), 2010 6th International Colloquium on*, 2010, pp. 1-4.

[3] N. Sharma and T. Gedeon, "Modeling a stress signal," *Applied Soft Computing*, vol. 14, Part A, pp. 53-61, 1// 2014.

[4] N. Sulaiman, M. N. Taib, S. Lias, Z. H. Murat, S. A. M. Aris, M. Mustafa, *et al.*, "Development of EEG-based stress index," in *Biomedical Engineering (ICoBE), 2012 International Conference on*, 2012, pp. 461-466.

[5] R. Khosrowabadi, Q. Chai, A. Kai Keng, T. Sau Wai, and M. Heijnen, "A Brain-Computer Interface for classifying EEG correlates of chronic mental stress," in *Neural Networks (IJCNN), The 2011 International Joint Conference on*, 2011, pp. 757-762.

[6] R. S. Lewis, N. Y. Weekes, and T. H. Wang, "The effect of a naturalistic stressor on frontal EEG asymmetry, stress, and health," *Biological Psychology*, vol. 75, pp. 239-247, 7// 2007.

[7] T. Hayashi, Y. Mizuno-Matsumoto, E. Okamoto, R. Ishii, S. Ukai, and K. Shinosaki, "Anterior brain activities related to emotional stress," in *Automation Congress, 2008. WAC 2008. World*, 2008, pp. 1-6.

[8] S. Reisman, "Measurement of physiological stress," in *Bioengineering Conference, 1997., Proceedings of the IEEE 1997 23rd Northeast*, 1997, pp. 21-23.

[9] H. Bin and L. Zhongming, "Multimodal Functional Neuroimaging: Integrating Functional MRI and EEG/MEG," *Biomedical Engineering, IEEE Reviews in*, vol. 1, pp. 23-40, 2008.

[10] S. A. Hosseini and M. A. Khalilzadeh, "Emotional Stress Recognition System Using EEG and Psychophysiological Signals: Using New Labelling Process of EEG Signals in Emotional Stress State," in *Biomedical Engineering and Computer Science (ICBECS), 2010 International Conference on*, 2010, pp. 1-6.

[11] H. Peng, B. Hu, F. Zheng, D. P. Fan, W. Zhao, X. B. Chen, *et al.*, "A method of identifying chronic stress by EEG," *Personal and Ubiquitous Computing*, vol. 17, pp. 1341-1347, Oct 2013.

[12] R. K. Sinha, "An approach to estimate EEG power spectrum as an index of heat stress using backpropagation artificial neural network," *Medical Engineering & Physics*, vol. 29, pp. 120-124, 1// 2007.

[13] F. Kawaguchi, N. Ichikawa, N. Fujiwara, Y. Yamashita, and S. Kawasaki, "Clinically available optical topography system," *Hitachi review*, vol. 50, p. 19, 2001.

[14] K. Dedovic, R. Renwick, N. K. Mahani, V. Engert, S. J. Lupien, and J. C. Pruessner, "The Montreal Imaging Stress Task: using functional imaging to investigate the effects of perceiving and processing psychosocial stress in the human brain," *Journal of Psychiatry & Neuroscience*, vol. 30, 2005.

[15] N. Sulaiman, N. H. A. Hamid, Z. H. Murat, and M. N. Taib, "Initial investigation of human physical stress level using brainwaves," in *Research and Development (SCOReD), 2009 IEEE Student Conference on*, 2009, pp. 230-233.

[16] A. Saidatul, M. P. Paulraj, S. Yaacob, and N. F. Mohamad Nasir, "Automated system for stress evaluation based on EEG signal: A prospective review," in *Signal Processing and its Applications (CSPA), 2011 IEEE 7th International Colloquium on*, 2011, pp. 167-171.

[17] R. N. Goodman, J. C. Rietschel, L.-C. Lo, M. E. Costanzo, and B. D. Hatfield, "Stress, emotion regulation and cognitive performance: The predictive contributions

of trait and state relative frontal EEG alpha asymmetry," *International Journal of Psychophysiology,* vol. 87, pp. 115-123, 2// 2013.

[18] N. Sulaiman, M. N. Taib, S. A. M. Aris, N. H. A. Hamid, S. Lias, and Z. H. Murat, "Stress features identification from EEG signals using EEG Asymmetry & Spectral Centroids techniques," in *Biomedical Engineering and Sciences (IECBES), 2010 IEEE EMBS Conference on*, 2010, pp. 417-421.

[19] H. Laufs, A. Kleinschmidt, A. Beyerle, E. Eger, A. Salek-Haddadi, C. Preibisch, *et al.*, "EEG-correlated fMRI of human alpha activity," *NeuroImage,* vol. 19, pp. 1463-1476, 8// 2003.

[20] N. Sulaiman, M. N. Taib, S. Lias, Z. H. Murat, S. A. M. Aris, M. Mustafa, *et al.*, "Intelligent System for Assessing Human Stress Using EEG Signals and Psychoanalysis Tests," in *Computational Intelligence, Communication Systems and Networks (CICSyN), 2011 Third International Conference on*, 2011, pp. 363-367.

[21] F. Lotte, M. Congedo, A. Lécuyer, F. Lamarche, and B. Arnaldi, "A review of classification algorithms for EEG-based brain–computer interfaces," *Journal of neural engineering,* vol. 4, 2007.

[22] S. Fazli, J. Mehnert, J. Steinbrink, G. Curio, A. Villringer, K.-R. Müller, *et al.*, "Enhanced performance by a hybrid NIRS–EEG brain computer interface," *NeuroImage,* vol. 59, pp. 519-529, 1/2/ 2012.

[23] Y. Juanhong, A. Kai Keng, G. Cuntai, and W. Chuanchu, "A multimodal fNIRS and EEG-based BCI study on motor imagery and passive movement," in *Neural Engineering (NER), 2013 6th International IEEE/EMBS Conference on*, 2013, pp. 5-8.

[24] T. C. Ferree, P. Luu, G. S. Russell, and D. M. Tucker, "Scalp electrode impedance, infection risk, and EEG data quality," *Clinical Neurophysiology,* vol. 112, pp. 536-544, 3// 2001.

[25] M. Tanida, M. Katsuyama, and K. Sakatani, "Relation between mental stress-induced prefrontal cortex activity and skin conditions: A near-infrared spectroscopy study," *Brain Research,* vol. 1184, pp. 210-216, 12/12/ 2007.

[26] M. Teplan, "Fundamentals of EEG measurement," *Measurement science review,* vol. 2, pp. 1-11, 2002.

[27] O. J. Arthurs and S. Boniface, "How well do we understand the neural origins of the fMRI BOLD signal?," *Trends in neurosciences,* vol. 25, pp. 27-31, 2002.

APPENDICES

	Subject 1		Subject 2		Subject 3		Subject 4		Subject 5		Subject 6		Subject 7		Subject 8		Subject 9		Subject 10		Subject 11		Subject 12	
	Ctrl	Stress	Ctrl	Stress	Ctrl	Stress	Ctrl	Stress	Ctrl	Stress	Ctrl	Stress	Ctrl	Stress	Ctrl	Stress	Ctrl	Stress	Ctrl	Stress	Ctrl	Stress	Ctrl	Stress
Relaxed?	O	X	O	O	O	O	X	O	O	O	X	X	X	X	O	O	X	O	O	O	X	X	X	X
Think?	O	O	O	O	O	O	O	O	O	O	O	O	O	X	O	O	O	O	O	O	X	X	O	X
Difficulties?	O	O	O	O	X	O	O	O	O	O	O	O	O	O	X	X	X	O	X	X	O	O	X	O
Guess?	X	O	X	O	X	O	X	O	O	O	O	X	O	O	X	X	X	O	X	X	X	O	O	O
Click wrongly?	O	O	O	O	X	X	X	O	X	X	O	O	X	X	X	O	O	O	X	X	O	O	X	X
Discomfort?	X	O	O	O	X	X	X	X	O	O	X	X	X	X	X	X	O	X	X	X	O	O	X	X
Sleepy?	O	O	O	X	X	X	X	X	O	O	X	X	O	X	X	X	X	X	O	O	X	X	X	X

Appendix 1: Summary of questionnaire by the subjects