# CHARACTERIZATION OF BRAIN SIGNALS USING THE ELECTROENCEPHALOGRAM DURING THE STROOP TEST


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# Abstract


## Characterization of brain signals using the electroencephalogram during the stroop test

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The study of mental stress is essential to elevate our understanding of the designer's cognitive approach during a creative design process. As the first step in this effort, this thesis focuses on the analysis of the electroencephalogram (EEG) signals of the subject during the stroop test. Computer based stroop test, consisting of six difficulty levels, was developed and used as a stressor. The EEG data was recorded on Fz, Cz, Pz and Oz channel locations. Average absolute power of alpha, beta, delta and theta bands at all the channel locations was calculated. The subject's average performance on the Stroop test was calculated based on his/her reaction time and incorrectness.

It was observed that the power of theta band is more dominant in the Fz channel. Since the theta band corresponds to the subject's mental/emotional stress, the present study suggests using the theta band in Fz location for further analysis during the design process. It was also observed that Alpha and beta powers, corresponding to the subject's vision, are more dominant in the Oz channel. A simultaneous comparison of the performances and of the theta power of different subjects suggested a direct relationship between the performance and the theta power. The present study demonstrates the potential use of theta power, after being quantified in terms of mental/emotional stress, in obtaining a correlation between the subject's performance and mental/emotional stress.

The present thesis laid a foundation for on-going analysis of designer's mental stresses during design related tasks, in Dr. Zeng's research group.

# Acknowledgements

I would like to express my sincere gratitude to my supervisor Dr. Yong Zeng, for his invaluable support and guidance throughout the course of this research and in writing this thesis. Timely help provided by the library and IT help-desk personnel is appreciated. I am grateful to all my colleagues in the Design Lab for their co-operation during the course of this work. I would like to thank Mr. Rajeev Yadav for his guidance in the analysis of EEG data. I would also like to thank Ms. Thanh An Nguyen for her help in designing the stroop test.

**Dedicated To,**

My Husband Samir.

and

My Family

# Contents

# List of Figures

# 1. Introduction

Mental/emotional stress is a normal physical response to both internal and external events that make people feel fatigued or threatened. Mental/emotional stress affects every-day human life and it also affects human work performance. After a certain point, it may also cause major damage to the nervous system and may severely affect a person's productivity in work and his/her quality of life. The cognitive signs and symptoms of the stress are memory problems, inability to concentrate, poor judgment, negative thinking, constant worrying, to name a few.

### 1.1 Purpose and Motivation

The study of mental/emotional stress is of great importance in design. Design is nothing but a logical and sequential process intended to solve a problem. Various design methodologies have been suggested to assist designers in generating quality designs in an effective and timely fashion. It is very important for every designer to develop a good, structured and logical design methodology. According to the Yerkes-Dodson law, there exists an inverted U-shaped curve that correlates a designer's performance and mental/emotional stress during the design task, as shown in Figure 1 [1]. It can be observed that the best performance is achieved at an optimal stress level for a given task and the performance goes down in low or high level of arousal. Hence a good design methodology should aim to keep the designer's stress in the optimal range of stress [2-5], so as to achieve the best performance. Developing such a design methodology is crucially and primarily dependant on the quantification of the designer's metal/emotional stress and on modeling the relationship between the designer's stress and performance.

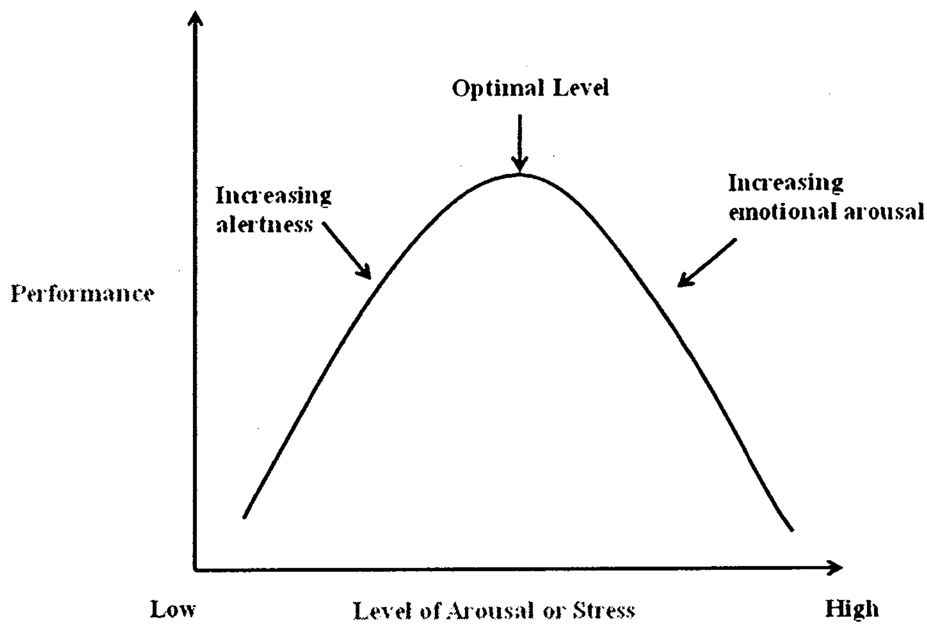



**Figure 1: Stress Vs Performance, according to the Yerkes-Dodson law [1].**

The physiological measurement of workload, stress or fatigue is an outcome of the central nervous system. Though it is not possible to measure mental activities directly, they can be detected through neural responses. The autonomic nervous system in the human body is a closed-loop automatic control system, which balances action and re-action processes within the body, as shown in Figure 2. Mental/emotional stress causes disturbances in the equilibrium of this control system. An elevated and prolonged stress level is a silent killer and cannot be noticed without the help of advance neurophysiological monitoring tools.

The stress can be assessed or quantified by the measurement of the physiological variables. These physiological variables can be broadly classified into the following three categories: [6]

1) Brain-related activity

2) Eye-related activity

3) Heart rate variability

The present thesis is focused on only one physiological variable, i.e. the brain related activity. The following sub-section introduces some of the measurable physiological variables (electric signals) related to brain and their measurement technique. The necessary details of the anatomy of human brain and its functioning are also provided.

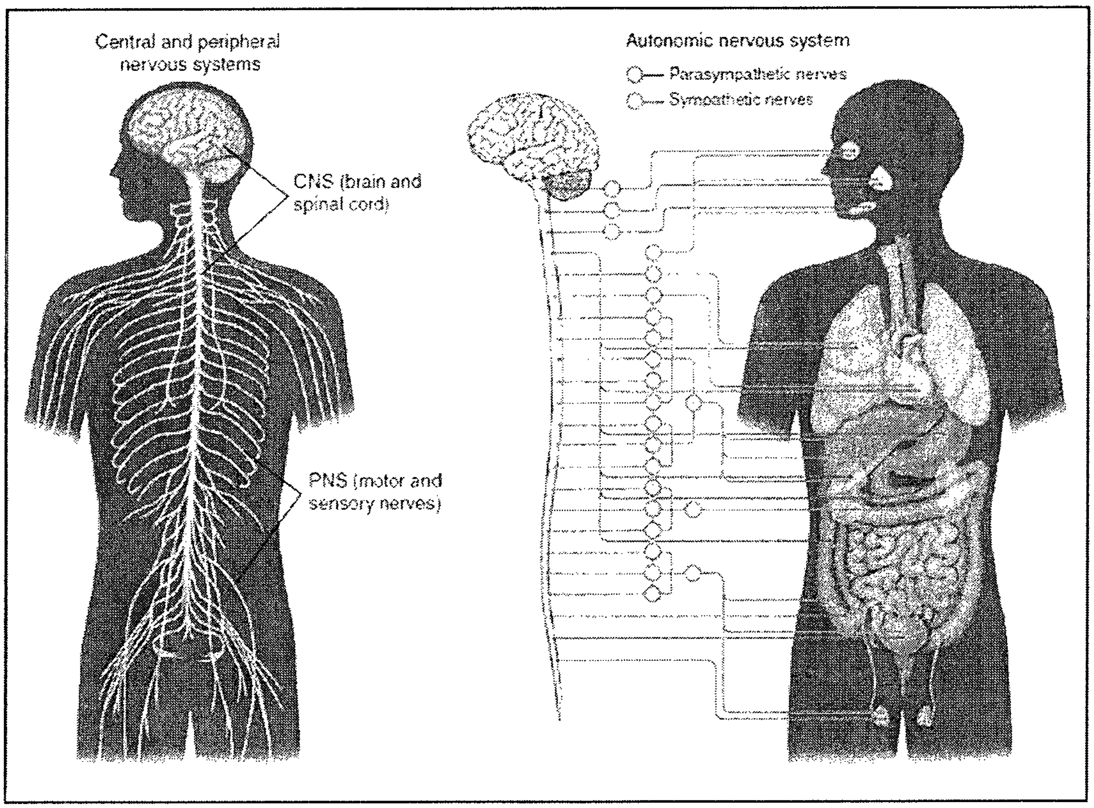



**Figure 2: Autonomic nervous system [7].**

## 1.2 Human Brain and Electroencephalogram (EEG)

The anatomy of human brain is shown in Figure 3. Medulla Oblongata and cerebellum consist of the posterior part of the brain and the cerebrum consists of the anterior and frontal part. The cerebrum consists of four lobes, viz. frontal, parietal, temporal and occipital. The locations (cf. Figure 3) and functions of these four different lobes in human brain are as follows [8]:

- Frontal lobe: The frontal lobe is located in front of the parietal lobe and above and anterior to the temporal lobe. The functions associated with the frontal lobe are planning, problem solving and emotions.
- Parietal lobe: It is located above the occipital lobe and behind the frontal lobe. The functions associated with this lobe are recognition, perception of stimuli and movement.
- Temporal lobe: It is located beneath the Sylvain fissure on both left and right side of the hemisphere. The functioning of occipital lobe is related to memory, recognition of stimuli and speech.
- Occipital lobe: The occipital lobe mainly contains visual cortex. Its functioning is associated with visual processing.

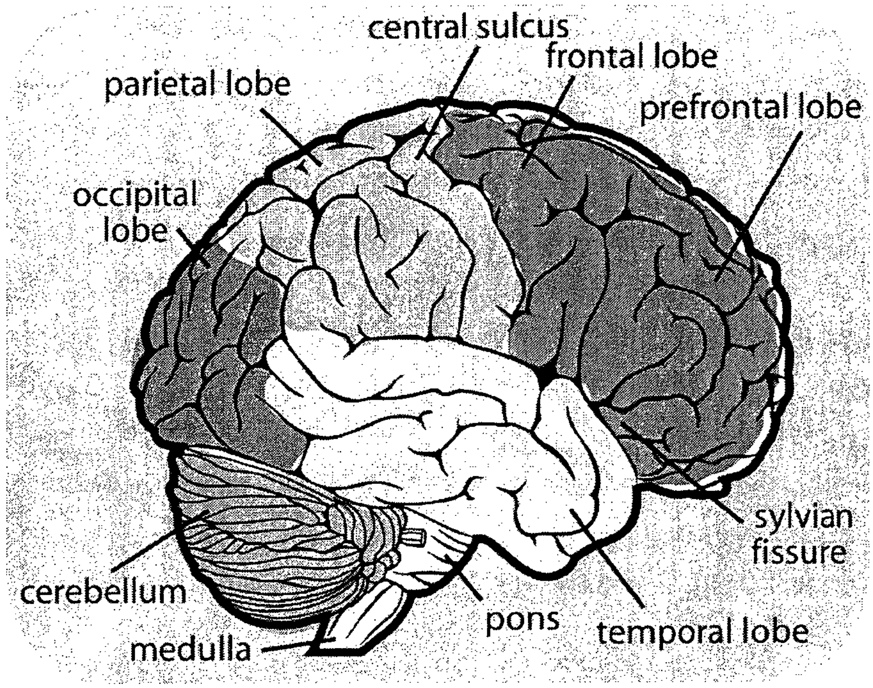



**Figure 3: Anatomy of human brain [9].**

The recording of brain's electrical activity by placing electrodes over the scalp is called as Electroencephalography, and the equipment used to do electroencephalography is called as electroencephalogram (EEG). The nerve cells in the brain, often called as *neurons*, are responsible for the electrical activity. EEG can be used to measure the changes in the neural electrical activity, which can be caused due to changes in the overall mental state or due to excessive workload or mental fatigue. In EEG, the electrical signal is recorded as a time-varying difference between one scalp electrode and one reference electrode placed on the scalp or earlobe or anywhere on the body. The electrical activity of the brain can simultaneously be measured at different positions of the brain using many electrodes. These electrodes are placed over the frontal, the parietal, the occipital and the temporal lobes of the brain.

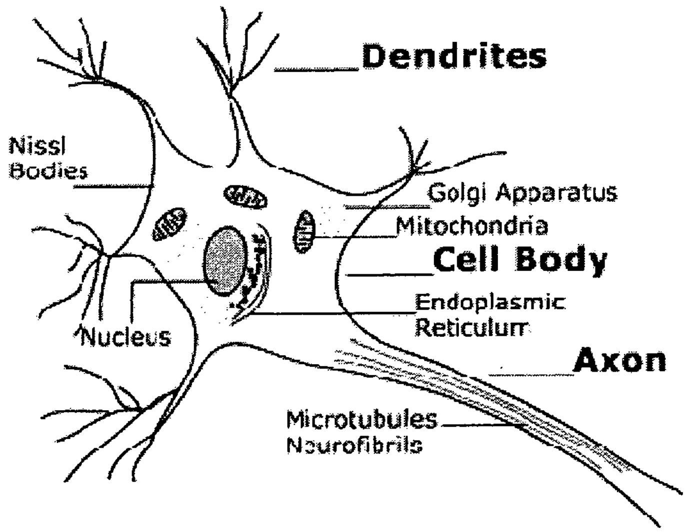



**Figure 4: Structure of a single neuron [10].**

As mentioned before, electrical activity in the brain is produced by the neuron, which is a very important part of the nervous system. Neuron, as shown in Figure 4, is an excitable cell in the brain which transmits an electrochemical signal. Neurons are able to send such signals for long distances and can pass messages, through these signals, to other neurons. Neurons are the most basic functional and structural units of nervous system. A neuron contains three main parts:

1) Cell body – the cell body contain nucleus and cell bodies of neurons vary in size.
2) Dendrites – are small-diameter, short extensions of protoplasm of the perikaryon.
3) Axon – is a protoplasmic continuation of the perikaryon. Axon diameters range from 1 or 2 micrometer up to 16 or 18 micrometer.

An electrical impulse, generated in the cell body, goes down from the axon to the synaptic terminal. There is a small gap between two neurons, combined with the endings is called Synapse. A synapse consists of 3 parts.

1) Presynaptic ending

2) Postsynaptic ending

3) Synaptic cleft

The synaptic vesicles contain neurotransmitter which fuses with the presynaptic membrane and allows the release of neurotransmitters into the gap. The neurotransmitters diffuse across the synaptic cleft where they can bind with the receptor sites on the postsynaptic ending. Once neurotransmitters are attached to postsynaptic receptors, they allow signals to continue through the next neuron and are called excitatory or they stop them and are then called inhibitory. In this way the electric potential is generated and is transferred to other neuron [8, 11]. It has to be noted that the EEG signal recorded from the scalp reflects the post-synaptic potential rather than the action potential. It is practically impossible get the potential from one neuron and EEG recorded signal is from a large neuron population.

When electrodes are attached on scalp locations (on different lobes), the potential in millions of neurons is changing synchronously and this will create various types of rhythms. There are four major different types of frequencies that are generated and are shown in Figure 5.

- <u>Delta</u> (0 to 3 Hz): Delta waves lie within the range of 0 to 3 Hz, with variable amplitude. Delta waves are primarily associated with deep sleep.
- <u>Theta</u> (3 to 7 Hz): Theta waves lie within the range of 3 to 7 Hz, with an amplitude usually greater than 20 μV. Theta waves are believed to be associated with emotional stress, creative inspiration and deep meditation.
- <u>Alpha</u> (8 to 13 Hz): Alpha waves lie within 8-13 Hz with 30-50 μV amplitude. Alpha is the most active type of wave and possibly spans a wide range. Alpha

waves are strongest over the occipital region of the brain and also over the frontal cortex.

- Beta (13 to 30 Hz): Beta waves lie within 13-30 Hz and usually have a low voltage, anywhere between 5-30 μV. Beta is the brain wave, which is usually associated with active thinking, active attention and problem solving [12-14].

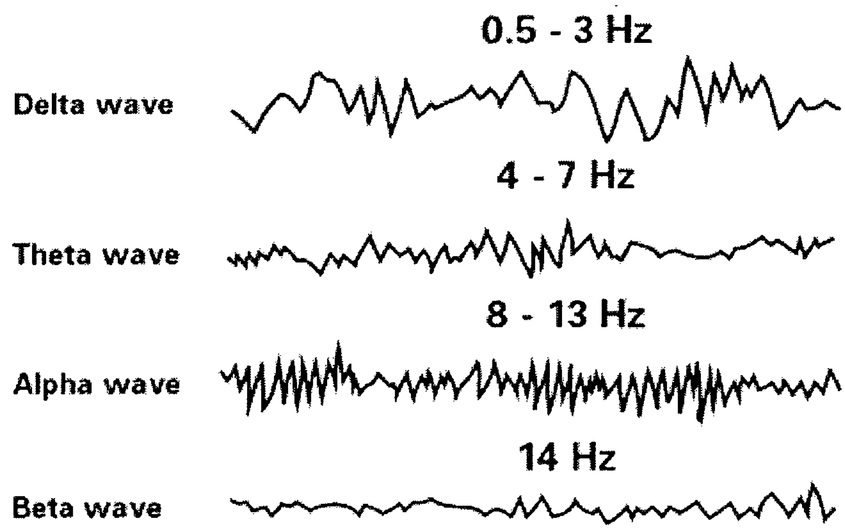



**Figure 5: EEG Wavegroup, as described in section 1.2 [15].**

Though EEG is mainly used to measure the electrical activity of the brain, it has to be noted that it can also be used to measure the eye-relate activity. The potential difference generated by the movement of an eye is captured by the EEG and this activity of eye-movement tracking by EEG instrument is called as electro-occulography (EOG). An EEG electrode is usually placed near the eye to measure this activity. The EOG can be used to measure the blinking rate and the inter-blink interval.

## 1.3 Stroop Test

A person's mental stress depends on his/her knowledge and experience related to the problem and many other cognitive parameters. With the same design problem, different designers will have different mental/emotional stress. If the brain-related activity is used to assess or quantify the metal stress (which is the motivation for the present thesis), then different mental/emotional stresses will result in different brain activities, leading to different EEG wave patterns. The ultimate aim is to quantify the mental stress of the designer, while doing a design task, using the EEG data. However, the first step in achieving this long term objective is to characterize the EEG data and to develop a methodology to quantify a subject's mental stress using this data. In order to achieve reliability and confidence in the characterization and quantification methodologies, it is extremely important to remove the artifact that could possibly be introduced due to the subject's background knowledge and experience in design. Therefore, it is necessary to define a non-subjective baseline to analyze the EEG data from different designers. To achieve this goal Stroop test can be used. Stroop test was invented by psychologist John Ridley Stroop in 1935 [16]. Stroop test, a color naming task, is a classical paradigm in neurophysiologic assessment of mental fitness [17]. The Stroop test is presentation of interference in the reaction of the task. This test is controversial about the exact mechanism responsible for this test, however, this tool is widely used for various cognitive-perceptual processes [18].

## 1.4 Objectives and Scope

Motivated by

(i) the fact that variation in mental/emotional stress results in variation in the electrical activities of the brain and different electrical activities result in different EEG wave patterns and,

(ii) the Yerkes-Dodson law which relates the designer's stress to his/her performance

and keeping in mind the long-term target of quantifying the mental stress, using EEG data, to validate Yerkes-Dodson law, the principle goals of this thesis are to characterize the EEG data obtained during the stroop test and to qualitatively demonstrate a relation between the designer's stress and his/her performance during the stroop test. The specific objectives and the scope of the project are as follows:

1. Develop a stroop test and a methodology to calculate the performance.
2. Develop an experimental protocol to record the EEG of a subject during the stroop test.
3. Record the EEG data on different scalp locations during the stroop test.
4. Develop an algorithm to filter raw EEG data, to segment it and to calculate absolute and average powers of different frequencies of brain activity for each difficulty level of the stroop test.
5. Develop a methodology to calculate the subject's performance from the stroop test, for each difficulty level.
6. Study changes in different powers for each difficulty level and identify the dominant power for each scalp location.
7. Observe the trend in the variation of different powers and performances simultaneously for each difficulty level of the stroop test and identify, if

possible, a qualitative correlation between the EEG band powers and the performance.

## 1.5 Thesis Outline

The literature review (i) summarizing the key findings in the field of analysis of various human responses using EEG and (ii) explaining in detail background knowledge of EEG, EOG and Stroop test is in chapter two. Experimental methods and protocol and EEG data analysis methods are covered in chapter three. Chapter 4 contains the results and their discussions and the conclusions are summarized in chapter five. Figure 6 shows the thesis overview and organization in a pictorial format.

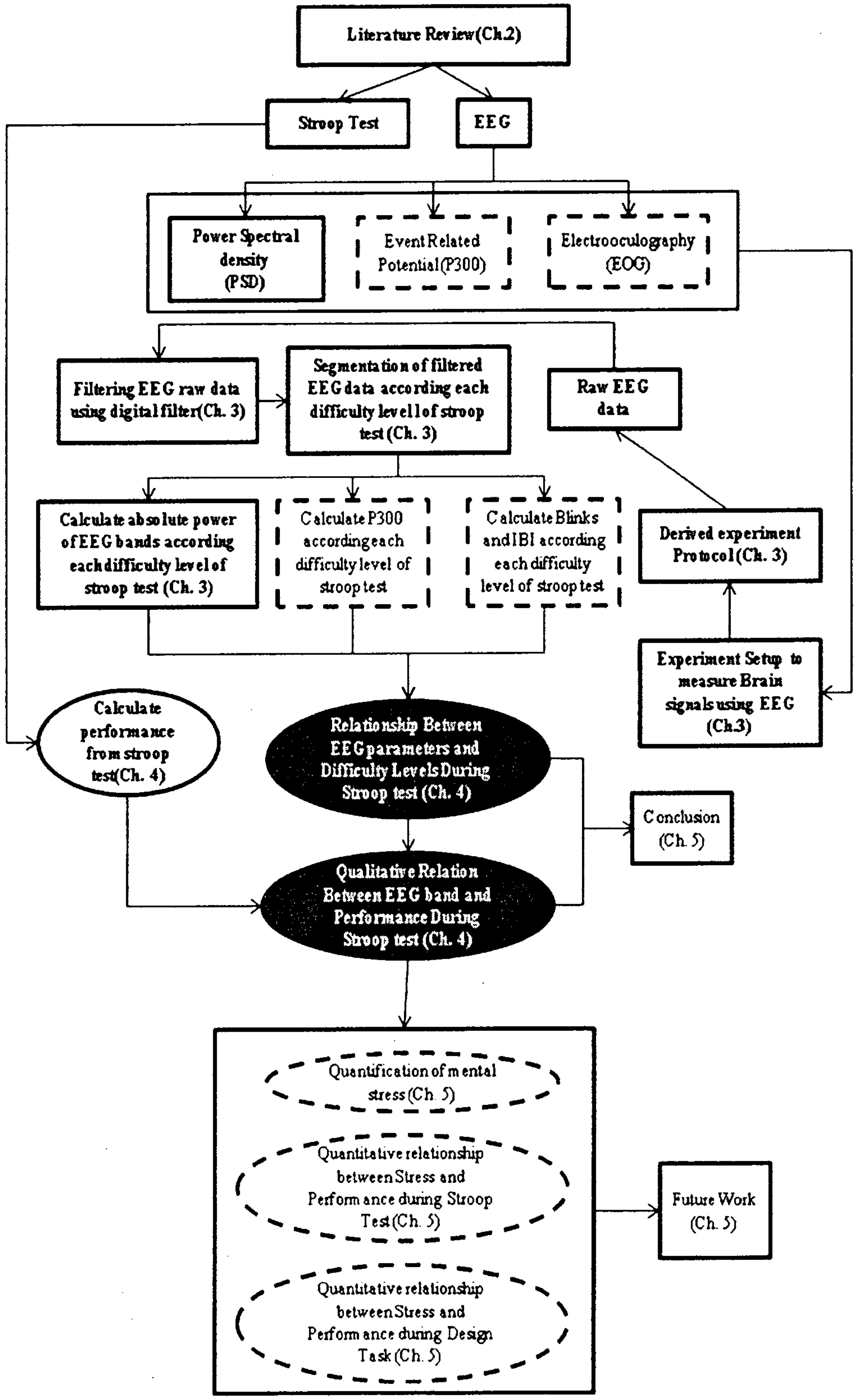



**Figure 6: Thesis Overview and Organization.**

# 2. Literature Survey

## 2.1 Introduction

A detailed study and survey, to get familiar with and to understand the intricacies of the functioning and operation of and accurate data recording from the EEG, was performed. The study of various signal processing techniques that are needed to apply to the raw EEG data to obtain meaningful results was also done. A systematic literature survey of the studies involving the analysis of different mental responses, like fatigue or workload, based on the EEG and EOG data was undertaken. The key and necessary details of the above mentioned studies are described in this section.

A brief review of Stroop test is also included in this chapter.

## 2.2 EEG and data recording

### 2.2.1 EEG electrodes

EEG records the cortical spontaneous electrical activity at the scalp. Different types of electrodes can be used to measure the electrical activity of brain using EEG. The electrodes are instrumental in data recording since they form a link between the electrical generators in the brain and the EEG instrument. EEG electrodes are nothing but metal cups that are held against the scalp and are connected to the EEG amplifiers using conducting wires. A conductive gel is applied to hold the electrodes on the scalp. The electrodes can be made up of various metals and their compounds like gold (Au), silver (Ag), platinum (Pt), silver chloride (AgCl), to name a few. Different metals develop different kinds of voltages with the same electrolyte [12].

### 2.2.2 Montages

The pairs of electrodes connected to each amplifier of the EEG machine are called a montage. The three types of montages are as follows [12]:

1) Bipolar montage: Each channel represents the difference between two electrodes. For example, if channel 1 represents "Fp1-F3" then it means that it represents the difference in voltage between the Fp1 electrode and the F3 electrode.

2) Referential montage: Each channel represents difference between one scalp electrode and one reference electrode. The reference electrode is same for every channel. The reference electrodes are attached to the earlobes.

3) Average reference montage: Activities from all electrodes are measured, summed together and are then averaged. This averaged signal is used as a common reference for each channel.

### 2.2.3 EEG data locations and Artifacts

As mentioned in section 1.2, different brain areas are related to different functionalities. Though it is not very obvious to distinguish, one may think that the EEG data measured from different scalp locations may correspond to different functionalities. The four different locations in the brain, as previously discussed, are Fz (Frontal lobe), Cz (Central lobe), Pz (Parietal lobe), Oz (Occipital lobe). Fz location represents emotional control, Cz represents sensory and motor functions, Pz represents perception and differentiation and Oz represents visual areas [19].

However, it has to be noted that all the electrical activities recorded by the EEG instrument are not necessarily originated by the subject's brain, though those originated from the subject's brain are only of interest. The other activities recorded by the instrument are called as noise or artifacts. There are two main types of artifacts, physiological and non-physiological. Physiological artifacts include the electrical signals generated by the subject but other than those in the brain. Non-physiological artifacts originate from different sources like radiation from light, electronic devices in the room, power cables etc.

## 2.3 Physiological responses and EEG

### 2.3.1 Common usage of EEG in medicine

EEG is used extensively in clinical applications due its following benefits.

1) EEG can continuously monitor the brain function for a long period.
2) The associated cost is lower than that of other techniques.
3) EEG gives higher temporal resolution.

EEG is also used in the following clinical research purposes:

1) It monitors epilepsy, alertness and brain death.
2) EEG detects epileptic seizures
3) It also monitors animal and human brain development.

### 2.3.2 EEG spectral power

Engineers and designers are mostly in heavy mental activities all the work places. Hence a tool to measure or quantify the mental activity becomes very important. During any mental activity the physiological variables also change. Parameters of the autonomic nervous system such as pupil diameter, galvanic skin response and heart rate change because of excessive mental workload, mental stress or fatigue. But it is intuitive that the bioelectrical activity of the brain is more closely related to the mental activity than any of the above mentioned parameters. In the past, some research has been directed towards measuring this bioelectrical activity of brain using the EEG during some type of cognitive workload and analyzing it using power spectral analysis. The key findings are summarized below.

The spectral power of EEG recorded signals contains information of the electrical activity discharges synchronously by many neurons. Kiroy et al. found out that the EEG spectral power changed after a prolonged mental activity consisting of attention and calculating tasks. All the frequency bands (including slow and fast EEG waves) increased during 6-hours of non-stopped prolonged activity of attention and calculating task and the effect remained same even in the resting period after the session [20]. The EEG power analysis also shows the capacity or performance of cortical information. Klimesch (1999) suggested that the EEG alpha and theta oscillations were related to cognitive and memory performance. They also suggested that, during any event related task, an increase in the theta power and a large decrease in the alpha power indicate a good cognitive and memory performance. The other finding was that small theta power and larger alpha power showed good task related performance [21]. The short-lasting activity in the brain is detected by the alpha band of the EEG and hence visual perception could possibly be detected by this band because it is short-lasting activity [22].

It has been observed by Boksem et al. that, during any mental task, when the alertness of the subject drops, the EEG waves shift from fast, low amplitude to slow, high amplitude (indicative of mental fatigue since the attention drop could be due to the fatigue). Boksem et al. specifically showed that the theta and lower-alpha EEG band power increased with the decrease in the subject's attention. They also observed that reaction times, misses and false alarms increased during the lack of attention and this indicated a decreasing performance [23]. Uetake and Murata found out that the alpha-band power decreases after the completion of a task (post-task). They suggested that the activity of central nervous system slows down due to mental and physical fatigue [24]. Murata et al. evaluated mental workload using wavelet transform. They calculated theta, alpha and beta frequency bands and the time at which the maximum power appeared for these three frequency bands. As the cognitive task difficulty level increased, the time for which the brain works actively also increased. They concluded that these findings were sensitive indicators of mental workload [25].

### 2.3.3 Event related potentials

Event related potentials (ERP) are the reflections of the neural activity of the brain to specific cognitive events. ERPs are estimated by recording EEG from the scalp of the subjects during any cognitive task and then averaging epoch's time-locked to a particular event. The time locking event is the external stimulus and the response is elicited by the subject. As the EEG reflects millions of simultaneous ongoing brain processes, the response of the brain to a single event or stimulus is not usually visible. To see the brain response to a particular event or stimulus, many trials (100 or more) are conducted and the results are averaged, causing random brain activity to be averaged out and the relevant ERP to remain. The measurement of ERPs is a tool for mental chronometry. There are various applications of ERPs related to human factors including assessment of mental workload, mental fatigue and evaluation of mechanism of vigilance.

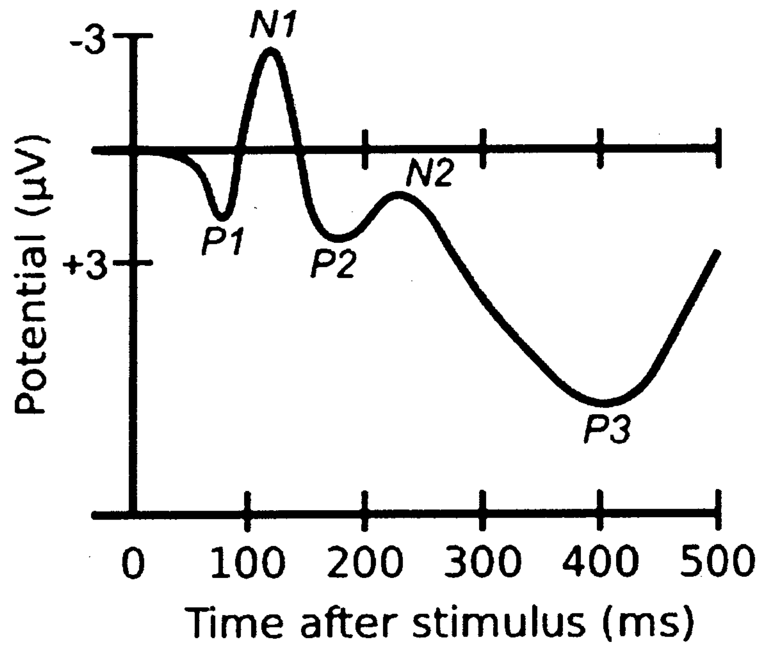



**Figure 7: P300 event related potential.**

A large number of studies of ERP in human factor were associated with the assessment of mental workload. In the ERP study of mental workload, many researchers studied the P300 component, which was discovered by Samuel Sutton, Margery Braren, Joseph Zubin and E. R. John in 1965 [26]. The P300 signal is measured usually from the parietal lobe of the brain. The P300 is a slow positive wave with the mean latency at around 300ms, as shown in Figure 7. The P300 components are useful in identifying the depth of cognitive information process. The P300 (also referred as P3 sometimes) can be recorded as a positive deflection in the voltage at a latency of roughly 300 ms in the EEG (cf. Figure 7) [27]. P300 amplitude reflects the amount of attention associated with the stimulus when some mental activities are employed [28]. Kutas et al. found that increase in the difficulty level of the identifying target stimuli would affect the P300 latency. P300 latency got prolonged with increasing difficulty level of the identifying target stimuli.

Uetake and Murata also reported the same observation but, additionally, they also found out that the P300 amplitude decreased after the experimental task (Post task) with increase in the difficulty level of the target. This finding is an effective measure of mental fatigue [24]. Parasuraman et al. also reported that as the difficulty level increases the P300 amplitude decreases [29].

### 2.3.4 Electrooculography (EOG)

As mentioned before, EOG measures the change in electrical activity due to the eye movement. It has to be noted that the subject's eye blink is an indication of the information related to the task that subject is performing. It has been suggested that the eye blinking rate increase with the increase in subject's attention and alertness and hence could possibly be used as an indication of the mental stress. Inter-blink-interval (IBI) refers to the time interval between two blinks. It has been reported that as the difficulty level of the task increases, the IBI of the subject also increases [6]. Blinking rate is also a parameter that can be obtained from EOG and is believed to be related to the cognitive state of the subject and is believed to be a potential candidate for assessing stress [30]. The reduced blinking rate indicates an increase in the visual demands on the task [31]. Increase in blinking rate is also believed to be an indicator of fatigue [32, 33]. Veltman et al. measured mental workload with eye blinks and they observed that as the visual demand of the task increased, the IBI also increased. They emphasized that this physiological measure is very closely related to the subject's mental stress [34].

## 2.4 Stroop Test

### 2.4.1 Stroop Test and EEG

In cognitive physiology studies, the stroop test is the most widely used task. The effect of any stroop test on the subject can be best investigated using the P300 ERP because it provides independent measures of stimulus evaluation time and attentional requirements [35]. Rebai et al. also found out that ERPs were similar for reading concordant and discordant stimuli. They found similar results for mental naming of a color associated to the written name of the same color. Another important finding is related to the mental naming of the color associated to the written name of a different color and it is demonstrated that the N400 wave in the Cz location is more significant in this case [36]. Liotti et al. suggested that the anterior cingulated cortex is initially activated by the stroop test, followed by the activation of the left temporal-parietal cortex [37]. Schack et al. studied the instantaneous EEG coherence analysis during the stroop test and they found out that the 13-20 Hz frequency band is sensitive to the discrimination between the congruent ("red" written in red color) and the incongruent task ("red" written in any other color). They also found higher coherence in left frontal and left parietal areas during the incongruent task than during the congruent task [38]. Xu et al. studied the effects of tobacco smoking on topographic EEG during the stroop test. They found that tobacco smoking significantly depressed delta and increased alpha and beta activity and it also slightly increased the effect of the stroop. Smoking did not improve the subject's performance in the stroop test [39].

### 2.4.2 Stroop Test and other physiological signals

Other than EEG, many other physiological signals are also studied during the stroop test, such as Heart Rate Variability (HRV), skin conductance, pupil diameter etc. Hoshikawa et al. studied the effect of the stroop test on the autonomic nervous system by analyzing the heart rate variability [40]. They found out that, during the stroop test, the RR interval decreased and the parasympathetic and sympathetic nervous system indicators remained unchanged. Salahuddin and Kim also detected the mental stress (as the ratio of low frequency to high frequency components) by HRV. They also measured the galvanic skin resistance and finger temperature. It was observed that the skin conductance increased during stroop test and finger temperature decreased. In their work, RR intervals and heart rate results remained unchanged between the baseline and the stroop test. From these results they concluded that stroop test possesses the capacity to produce cognitive stress [41]. Siegle et al. found out that the pupil dilation was larger in an incongruent task than in the congruent task. It showed that pupil dilation reflected cognitive load of the task [42].

# 3. Experimental Methods and EEG data Analysis

## 3.1 Introduction

This chapter includes (i) a detailed explanation of the stroop test used in this work and its different difficulty levels, (ii) description of the experimental setup and experimental procedure, (iii) mathematical and physical details of the processing of the raw EEG data and its analysis, (iv) description about the EEG instrument used in this work, procedure for electrode placement, data acquisition and safety and other precautions and, (v) relevant details of the subjects employed in this work.

## 3.2 Stroop test

Stroop test was used in the present work as a stressor/stimulus for the subject. Stroop test, a designed computer game, presented a color name (referred as stimulus word) on the subject's computer screen and this color name was displayed in a color that was same as or different from that the stimulus word refers to. The subject had to select the answer corresponding to the color of the word. For example, with a GREEN word in BLUE color, the subject had to select the word BLUE in the answer list. Our Stroop test contained six colors: RED, BLUE, YELLOW, PURPLE, GREEN and BLACK, and six difficulty levels as listed and described below:

1) Difficulty level 1 (DL1): A stimulus word is displayed in the color referred by itself and each word in the answer list was displayed in the color referred by itself. For example, the stimulus word 'RED' was written in red color and the word 'RED' in response list was also written in red color (cf. Figure 8).

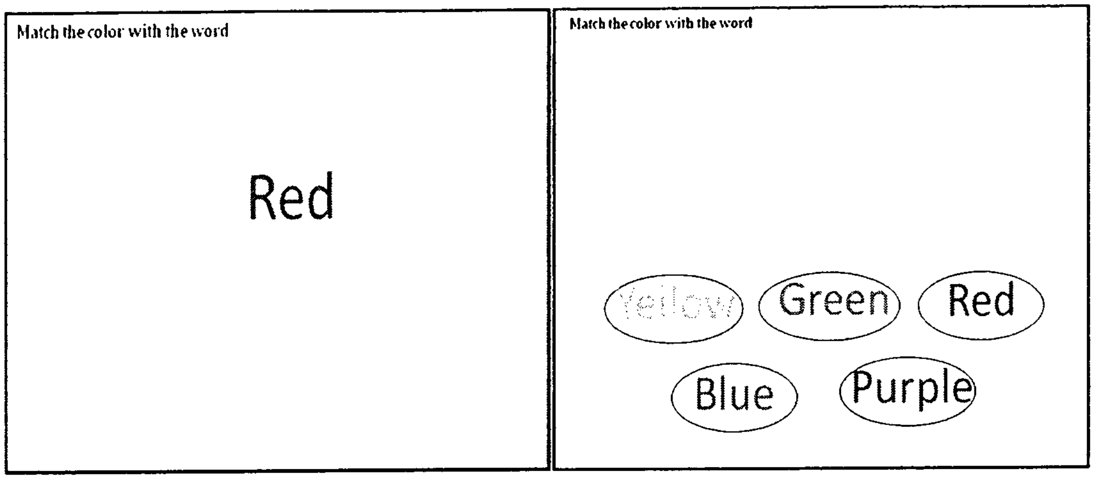



**Figure 8: Difficulty Level 1 (DL2), also referred in the thesis as "Congruent-Congruent".**

2) Difficulty level 2 (DL2): A stimulus word was displayed in the color referred by itself and each word in the answer list was displayed in black color. For example, the stimulus word 'RED' was written in red color and the word 'RED' in response list was written in black color.

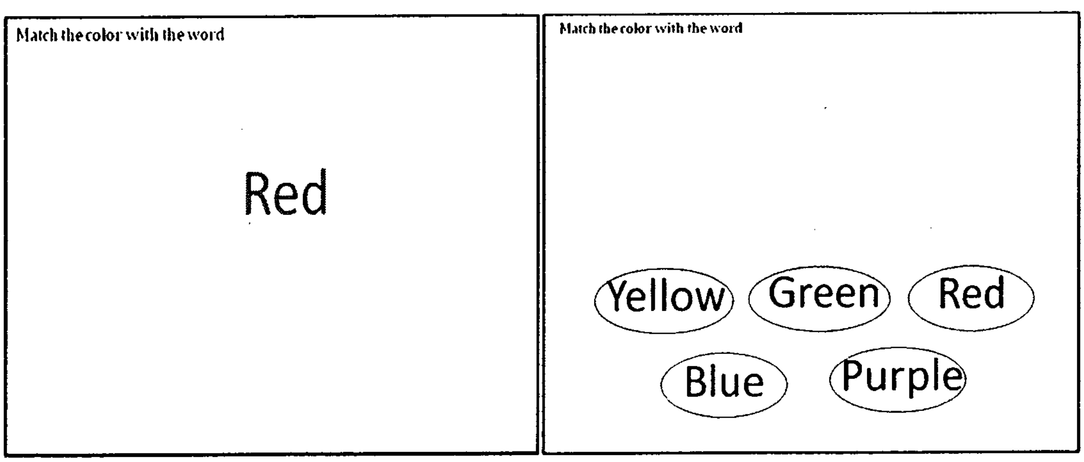



**Figure 9: Difficulty Level 2 (DL2), also referred in the thesis as "Congruent-Black".**

3) Difficulty level 3 (DL3): A stimulus word was displayed in a color different from that it refers to and each word in the answer list was displayed in black color. For

example, the stimulus word 'RED' was written in blue color and the word 'RED' in response list was written in black color.

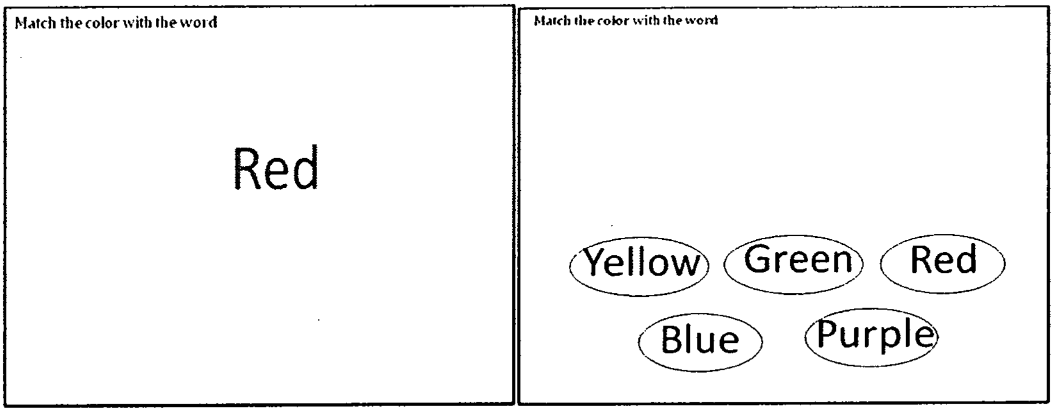



**Figure 10: Difficulty Level 3 (DL3), also referred in the thesis as "Incongruent-Black".**

4) Difficulty level 4 (DL4): A stimulus word was displayed in a color different from that it refers to and each word in the answer list was displayed in the color referred by itself. For example, the stimulus word 'RED' was written in blue color and the word 'RED' in response list was written in red color.

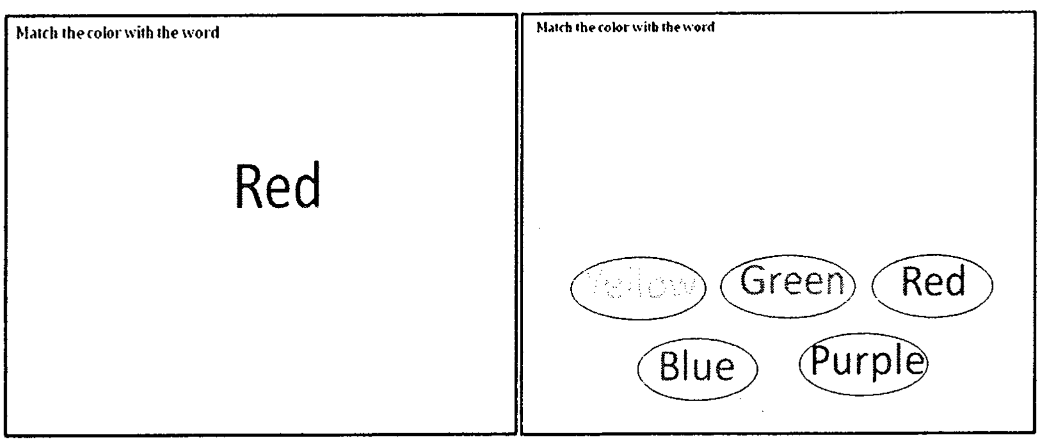



**Figure 11: Difficulty Level 4 (DL4), also referred in the thesis as "Incongruent-Congruent".**

5) Difficulty level 5 (DL5): A stimulus word was displayed in the color referred by itself and each word in the answer list was displayed in a different color that it refers to. For example, the stimulus word 'RED' was written in red color and the word 'RED' in response list was written in yellow.

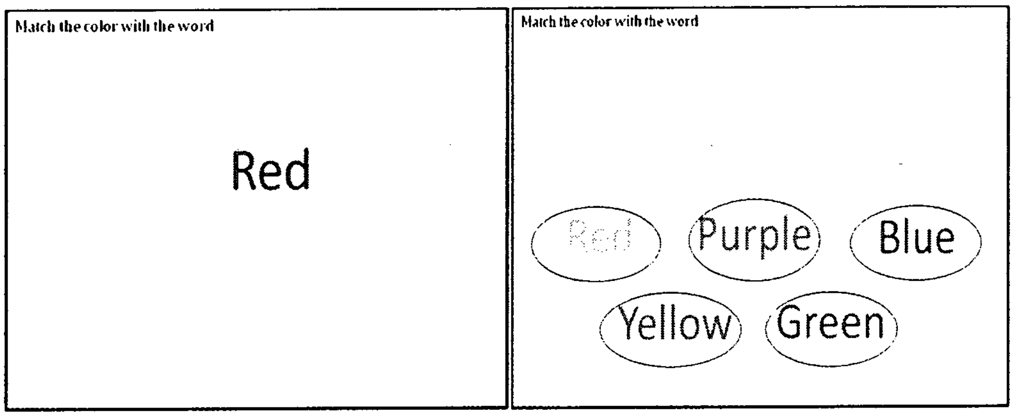



**Figure 12: Difficulty Level 5 (DL5), also referred in the thesis as "Congruent-Incongruent".**

6) Difficulty level 6 (DL6): A stimulus word was displayed in a color different from that it refers to and each word in the answer list was displayed in a different color that it refers to. For example, the stimulus word 'RED' was written in green color and the word 'RED' in response list was written in yellow.

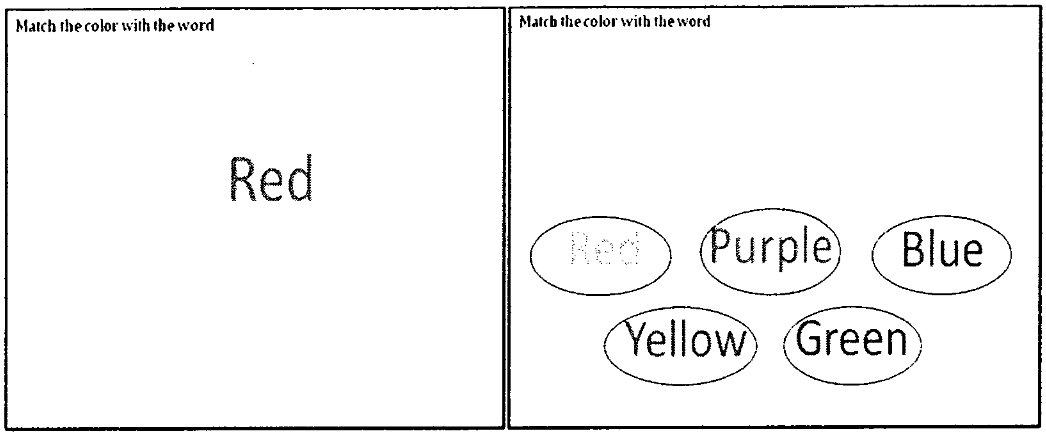



**Figure 13: Difficulty Level 6 (DL6), also referred in the thesis as "Incongruent-Incongruent".**

During all the above difficulty levels of the stroop test, the subject was presented the stimulus word for 500 milliseconds. Then the response screen was displayed for 1500 milliseconds maximum in which the subject had to click on the answer. This process of observing the test screen for 500 milliseconds and responding in less than 1500 milliseconds is referred as a Stroop task. The time interval between two stroop tasks was kept as 1000 milliseconds. The EEG data sampling frequency was taken as 200 (per second).

### 3.2.1 Design of Stroop Experiment

The complete stroop test, comprising of the above described difficulty levels, was divided into three profiles described below.

**Profile 1** – The profile 1 consisted of 60 screens. Each difficulty level had 10 screens on the computer. In this profile the sequence of the difficulty levels was kept as follows:

*Difficulty level 1 ➔ Difficulty level 2 ➔ Difficulty level 3 ➔ Difficulty level 4 ➔ Difficulty level 5 ➔ Difficulty level 6*

**Profile 2** – The profile 2 consisted of 60 screens. Each difficulty level had 10 screens on the computer. In this profile the sequence of the difficulty levels was kept as follows:

*Difficulty level 6 ➔ Difficulty level 5 ➔ Difficulty level 4 ➔ Difficulty level 3 ➔ Difficulty level 2 ➔ Difficulty level 1*

**Profile 3** – The profile 3 consisted of 60 screens. Each difficulty level had 10 screens on the computer. In this profile the sequence of the difficulty levels was kept as follows:

*Difficulty level 4 ➔ Difficulty level 3 ➔ Difficulty level 1 ➔ Difficulty level 6 ➔ Difficulty level 2 ➔ Difficulty level 5*

## 3.3 Experimental setup and procedure

### 3.3.1 Subjects

Experiments were conducted on eight different subjects of different ethnic backgrounds. All the subjects belonged to the age-group of 20-35 years and were with or without glasses. English was the native or working language for them. All the subjects were male. Female subjects were purposely not taken for the present study because the EEG electrodes had to be attached to the subject's scalp directly (without EEG cap) and log hair in females used to cause a lot of problem in fixing the electrodes on the scalp (cleaning the hair to remove the EEG conductive gel after the experiment was also an issue).

### 3.3.2 EEG instrument

The GrassLab instrument was used in this work for the EEG experiments. To be specific, the 15LT model of the GrassLab instrument was used. The instrument had two 15A94 QUAD amplifiers. The 15A94 has high frequency response to 100 Hz, suitable for clinical applications in EEG, and Polysomnography (PSG). 15LT model provided a bipolar electrode board; model F-15EB/B1 electrode board. Each differential amplifier channel has two active inputs; G1 and G2, which are accessible via the electrode board. Each differential amplifiers two active inputs are connected to the electrode board via the bipolar electrode interface module. G1 and G2 are grouped by channel number. This arrangement is the most flexible, but requires external electrode linkers to allow common-reference derivations. Electrode linkers, model F-EL2, are provided with al bipolar systems to allow common reference derivations.

### 3.3.3 EEG recording technique

The 10-20 system is an internationally recognized method for placement of electrodes on the subject's scalp, and is shown in Figure 14 [43]. The numbers 10 and 20 indicate that the actual distances between adjacent electrodes are either 10% or 20% of the total front-back or right-left distance of the skull. To identify each lobe, each site has a letter and to identify hemisphere location, each site has a number. Frontal- F, Temporal-T, Central- C, Parietal- P, and Occipital- O. Z refers to an electrode placed on the midline. Even numbers (2, 4, 6, 8) refer to the right hemisphere and odd numbers (1, 3, 5, 7) refer to the left hemisphere. Nasion is point between the forehead and nose. The Inion is the bump at the back of skull [44].

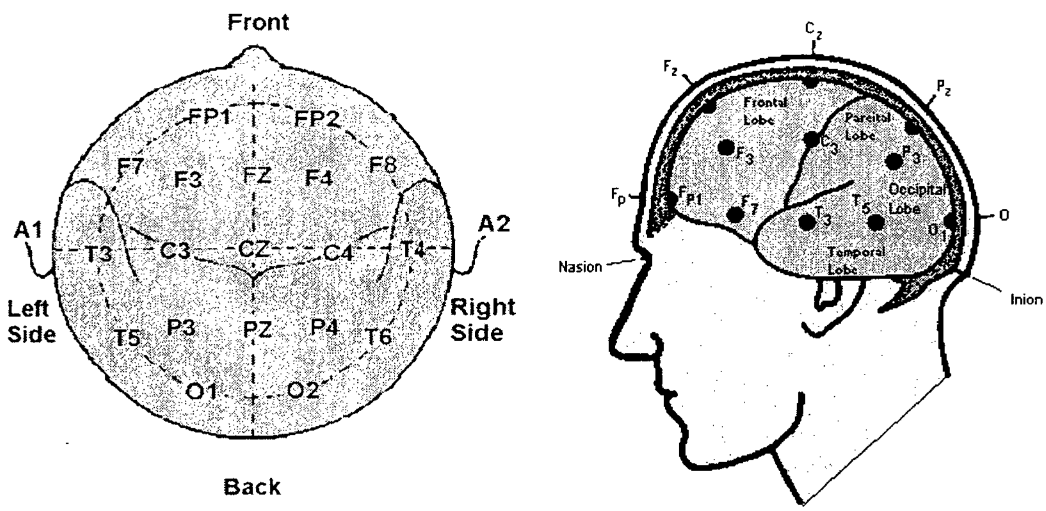



**Figure 14: 10-20 Electrode placement, top view and profile view [43].**

Following the 10-20 system, EEG signals were recorded from four different scalp locations (Fz, Cz, Pz, Oz) during the stroop test. It provides generalized activity of a particular lobe. As briefed before, Fz location is for emotional control, Cz location is for sensory and motor functions, Pz is for perception and differentiation, Oz is for visual areas [19]. EOG was also recorded to observe the blink rate and inter-blink-interval from eye.

### 3.3.4 Electrode placement procedure

- Take measurement of the head of the subject and mark locations on the scalp following the 10-20 scalp location manual.
- Locations to be marked for electrode placement are
  1) Fz-reference electrode left ear lobe
  2) Cz- reference electrode left ear lobe
  3) Pz- reference electrode left ear lobe
  4) Oz- reference electrode left ear lobe

5) Heart rate (on left hand)-reference right hand

6) Left Eye-reference electrode left earlobe

- After marking the locations, scrub that location with alcoholic pads and Nuprep gel.
- Apply the EEG paste on every location.
- Fill the cup of the electrode with a glob of EEG paste and then fix that electrode on that the marked location.
- Once the electrode is fixed on the scalp, apply EEG paste over the electrode and around the edge.
- Put a 2×2 cm gauze pad on the electrode after applying the paste on the top of the electrode. This is to make sure that the electrode is secured and chances of loosing the contact with the scalp are less.
- Before starting the EEG equipment, turn off the lights and disconnect the phone and internet in the lab.
- Start the EEG equipment for recording brain signals and do filter and amplitude setting in the instrument itself.
- It is very important to observe the raw data for 10 mins or so to make sure that the electrodes are securely connected to the scalp and that you are not loosing any data due to loose connections.

### 3.3.5 Experimental setup

In order to get accurate data, external stimuli like room lighting and environmental temperature were kept constant. The experimental setting is shown in Figure 15. Consent form was given to subject before his arrival in the lab. The consent form contained all the information about the experiment. Subject was asked to sign the consent form and after signing the consent form experiment setup would start. Subjects were also explicitly informed about not moving and sitting straight in front of the desktop during the experiment. Subjects were also asked to sit in front of the computer at ease for the first 6 minutes in a pre-Stroop test stage, followed by the Stroop test (which lasted for another 9 minutes), and finally the subjects were again asked to sit in the relaxed state for an extra 5 minutes, which is called the post-stroop test stage.

Before starting the experiment, the subject was allowed to play a few trials to get the knowledge as well as to get acquainted with the stroop test. In general, it took the subjects around eight to ten minutes in the trial stage before the experiment started. EEG amplifier settings were kept at 200 Hz frequency and 10 second time constant. The low frequency filter (LFF) was at 0.1 Hz and the high frequency filter (HFF) was at 30 Hz setting in the GrassLab instrument to filter the noise in the raw EEG data. A 60 Hz notch filter, available in the instrument must also be used to remove the noise resulting from the power cables present in the room. Each EEG measurement session lasted approximately 20 minutes. After the recordings were completed, the subject was asked to wash his hair. The EEG paste provided by GrassLab was used and can easily be removed with water only.

**Figure 15: Experiment Setup for the EEG data recording.**

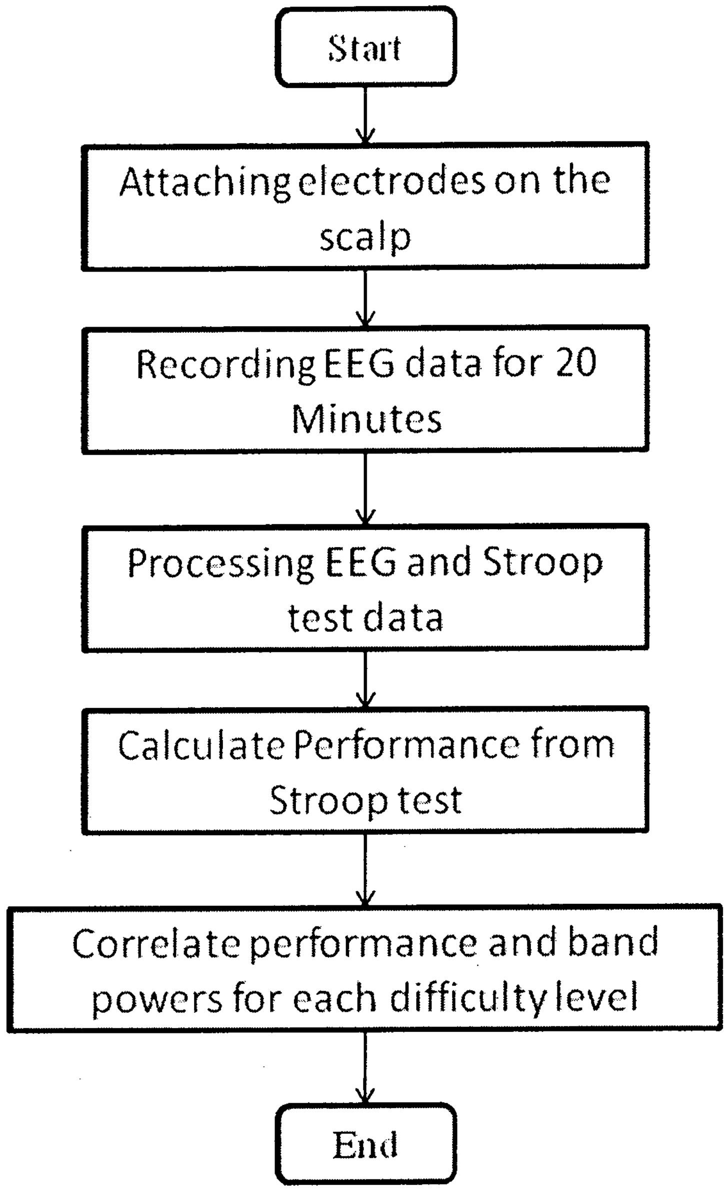



**Figure 16: Experimental and Analysis procedure.**

## 3.4 Data Processing: Filtering and Segmentation

### 3.4.1 Data Filtering

Data filtering is a treatment method for the raw EEG data in which some attributes of the data are selected to preserve and some data to filter out. Scalp EEG data is susceptible to various non-physiological signals that could interfere with the recording electrodes. These interfering noises can cause a major problem in reliable analysis of the subject's EEG data during the stroop test. Also, many physiological signals of the subject himself can interfere with his own EEG. In filtering, both, the spectral components and noise, are significantly important issues. The filters are designed in such way where the desired spectral components are only selected or are passed and the noise gets rejected. There are two main kinds of filters:

1) *Analog filter* - An analog filter is a hardware based filter that uses electronic circuits. to reduce noise, video-signal enhancements etc. Analog filters were not used in this thesis.

2) *Digital filter*- A digital filter uses digital processor which performs mathematical calculations on sampled values of the signal. Digital filters for EEG data processing are implemented as software programs and they computer power. There are basically two types of filters. Finite impulse response (FIR) and Infinite impulse response (IIR) filter.

- *FIR filter* - In the FIR filter, the impulse response is finite because its response settles back zero in a finite number of samples. The equation defining the output of this filter is as follows:

$$\{h(n)\} = \{h_0\delta(n) + h_1\delta(n-1) + \cdots + h_q\delta(n-q)\} \tag{1}$$

The transfer function of a $q^{th}$ order FIR filter is given by the $z$-transform of its impulse response.

$$H(z) = \sum_{k=0}^{q} h(k)z^{-k} = \frac{h(0)z^q + h(1)z^{q-1} + h(q)}{z^q} \tag{2}$$

- *IIR filter* – The IIR filter has an impulse function that is non zero over infinite length of time. Examples of IIR filter are Chebyshev filter, Butterworth filter and the Bessel filter.

$$\{h(n)\} = \{h(0)\delta(n) + h(1)\delta(n-1) + \cdots\} \tag{3}$$

In the $z$-domain the IIR filter can be analyzed in terms of its transfer function as:

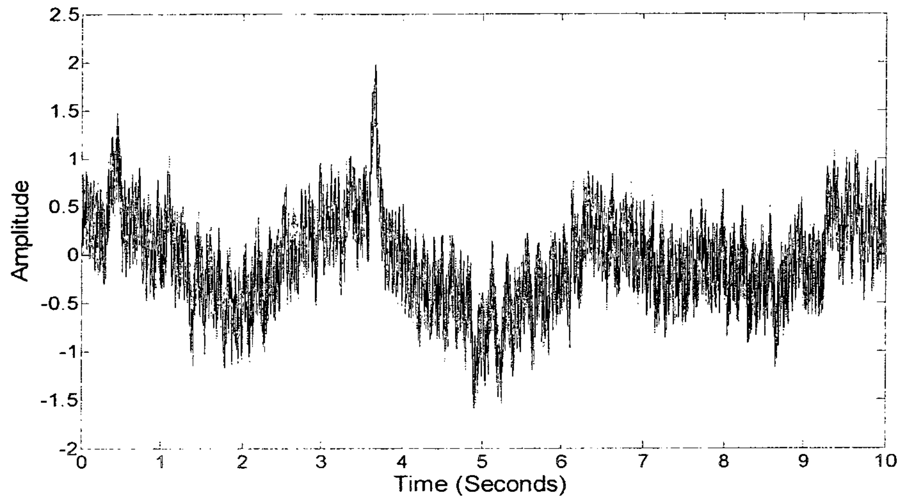
$$H(z) = \sum_{k=0}^{+\infty} h(k)\, z^{-k} \tag{4}$$

$$H(z) = \frac{N(z)}{D(z)} = \frac{\sum_{k=0}^{M} \alpha(k) z^{-k}}{1+\sum_{k=1}^{N} \beta(k) z^{-k}} \tag{5}$$

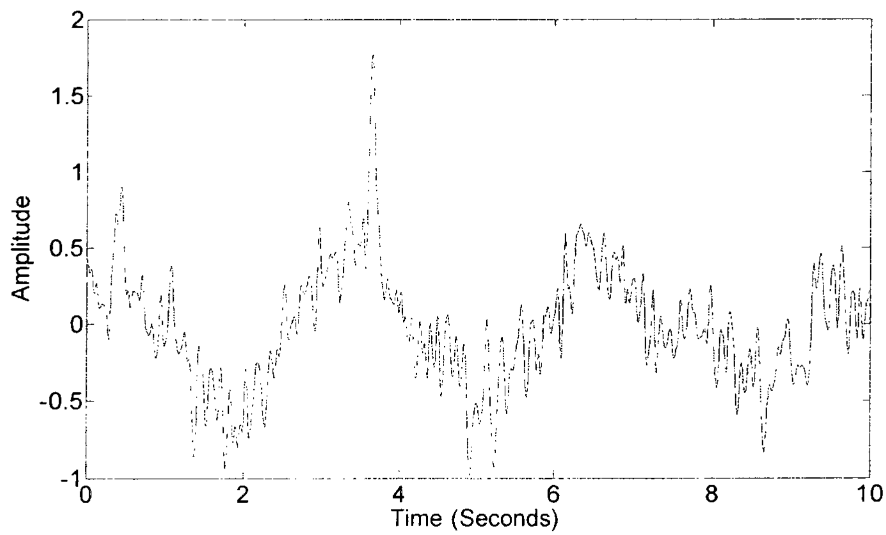
In this thesis, the digital IIR low-pass digital Butterworth filter was used to filter the noisy data from raw EEG signal. The digital filter was implemented using the MATLAB's signal processing toolbox. MATLAB function "butter" allows the design of lowpass, bandpass, highpass and bandstop Butterworth filters. In the digital domain, *(b, a)=butter (n, $W_n$)* designs an order $n$ lowpass digital Butterworth filter with normalized cut-off frequency $W_n$. It returns the filter coefficients in length $n+1$ row vectors $b$ and $a$, with coefficients in descending powers of $z$. Cut-off frequency is that frequency where the magnitude response of the filter is $\sqrt{1/2}$. For butter, the normalized cut-off frequency must be a number between 0 and 1, where 1 corresponds to the Nyquist frequency, $\pi$-radians per sample.

After using the 5$^{th}$ order Butterworth filter, zero-phase digital filtering was used. It processes the input data in forward and reverse directions. After filtering in the forward direction, it reverses the filtered sequence and runs it back through the filter. The advantage of zero-phase digital filtering is that it eliminates non-linear phase distortion.

Figure 17(a) and (b) show a 10 second raw data and the corresponding filtered data for a Fz channel recording of two consecutive stroop tasks, respectively. In some cases this signal processing is not enough, so in that case additional processing is necessary for analysis.




**(a)**




**(b)**

**Figure 17: A sample (a) Raw EEG data, (b) Filtered EEG data.**

To attenuate the signal at 60 Hz, a special notch filter was used with the EEG instrument. It is to remove artifact produced by electrical power lines. It is also known as band-stop filter. A notch filter passes all the frequencies except those in stop band centered on a center frequency.

### 3.4. 2 Data segmentation

The filtered EEG data was then segmented according to the stroop tasks' timings. In the stroop test, three profiles with six difficulty levels were used. Each profile had 60 screens. Each difficulty level in each profile had 10 screens. Time duration for the Stroop test is nine minutes (3 minutes for each profile and 3 seconds per screen, as described in section 3.2). Therefore, the EEG data was segmented into 3 second fragments. Data segmentation was done in MATLAB. To segment the filtered EEG data "mat2cell" function in MATLAB was used. The syntax is

c = mat2cell (x, m, n)

where x ➔ row × column matrix

m ➔ number of rows

n ➔ number of columns

In this work, the data segmentation was done in five steps for the analysis of EEG data for each difficulty level and the segmentation scheme is illustrated in Figure 18.

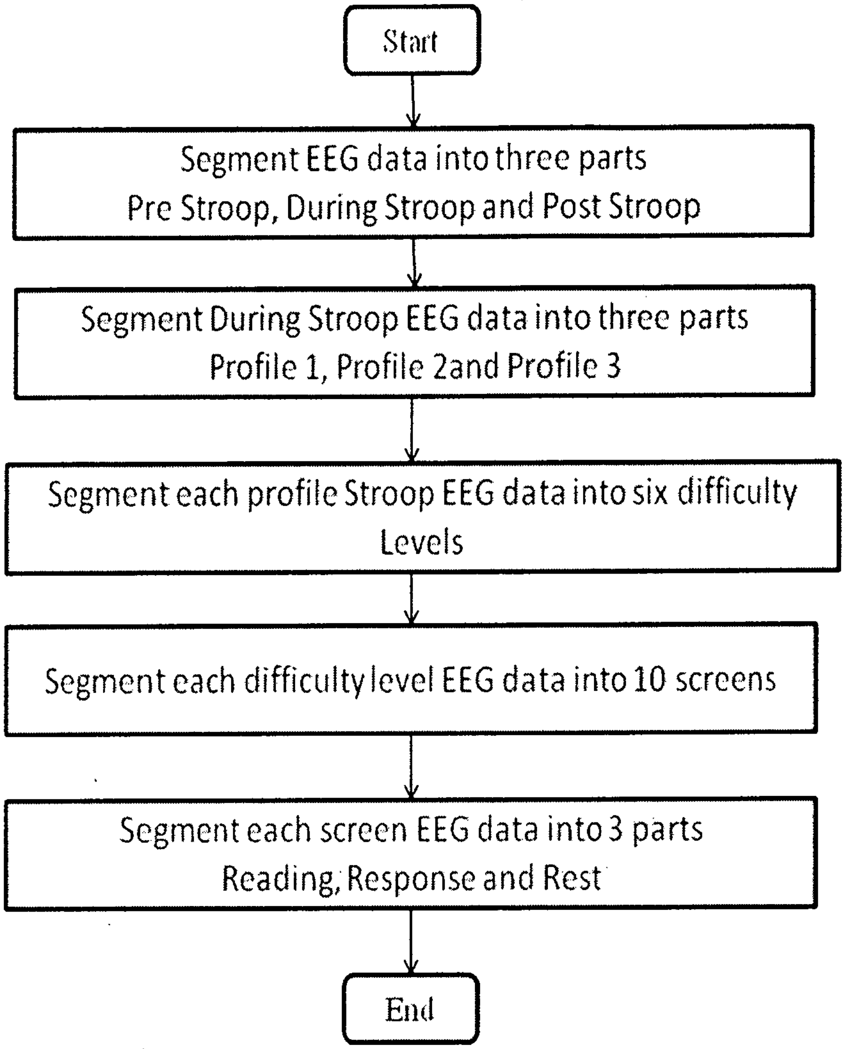



**Figure 18: Segmentation scheme for the EEG data collected during the stroop test.**

- In step 1, the whole EEG data was segmented into three parts, pre-stroop, stroop and post-stroop because analysis had to be performed only on the stroop data. Figure 19 shows the segmentation of a sample EEG data (data-points) for one channel into three parts as follows.

  Pre stroop –72400 = 362sec×200 (sampling frequency = 200 per second)

  During stroop –108000 = 540sec×200

Post stroop –59600 = 298sec×200

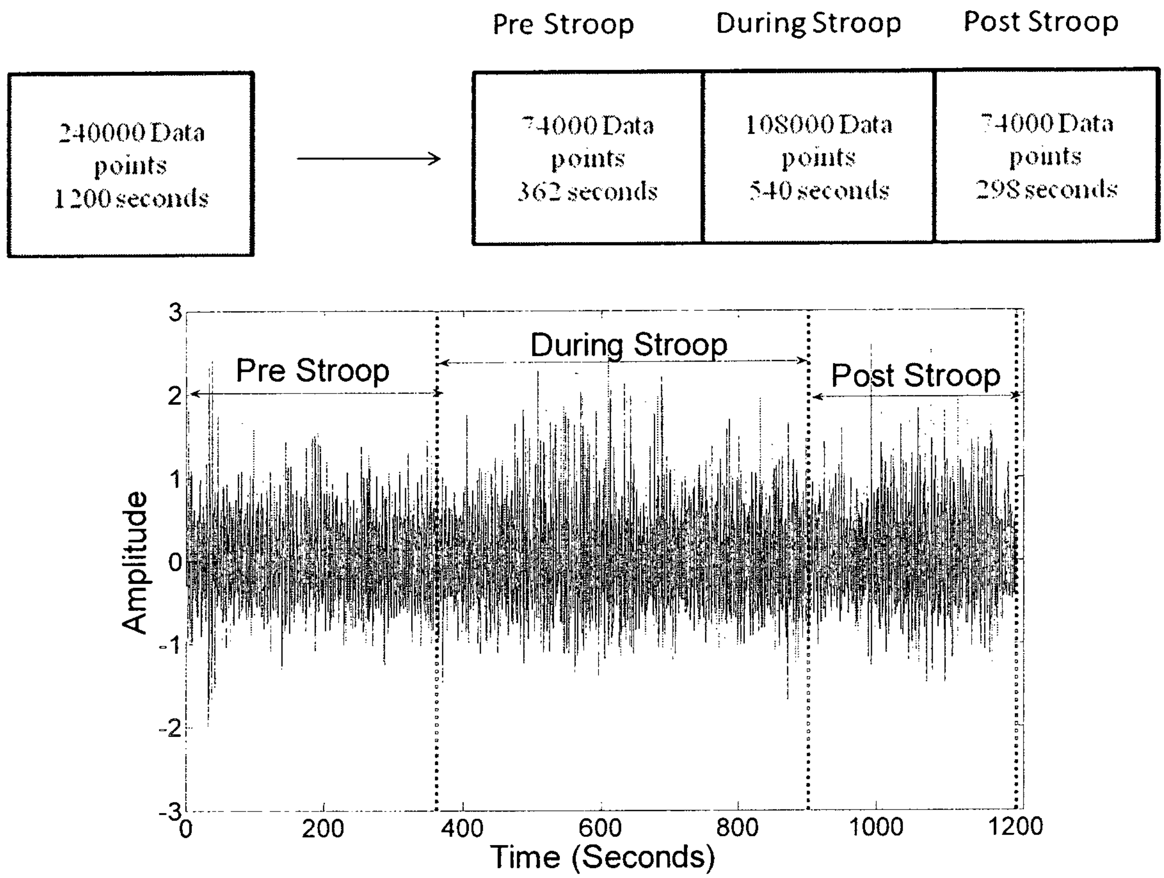



**Figure 19: Segmentation of the filtered EEG 20 min (1200 seconds) data.**

- In the second step, the during-stroop data was again segmented for further analysis because the stroop-test consisted of three profiles. The during-stroop test EEG data segmented into 3 parts (36000×3) is shown in Figure 20:

  1) Profile 1 – 36000 = 180sec×200
  2) Profile 2 – 36000 = 180sec×200
  3) Profile 3 – 36000 = 180sec×200

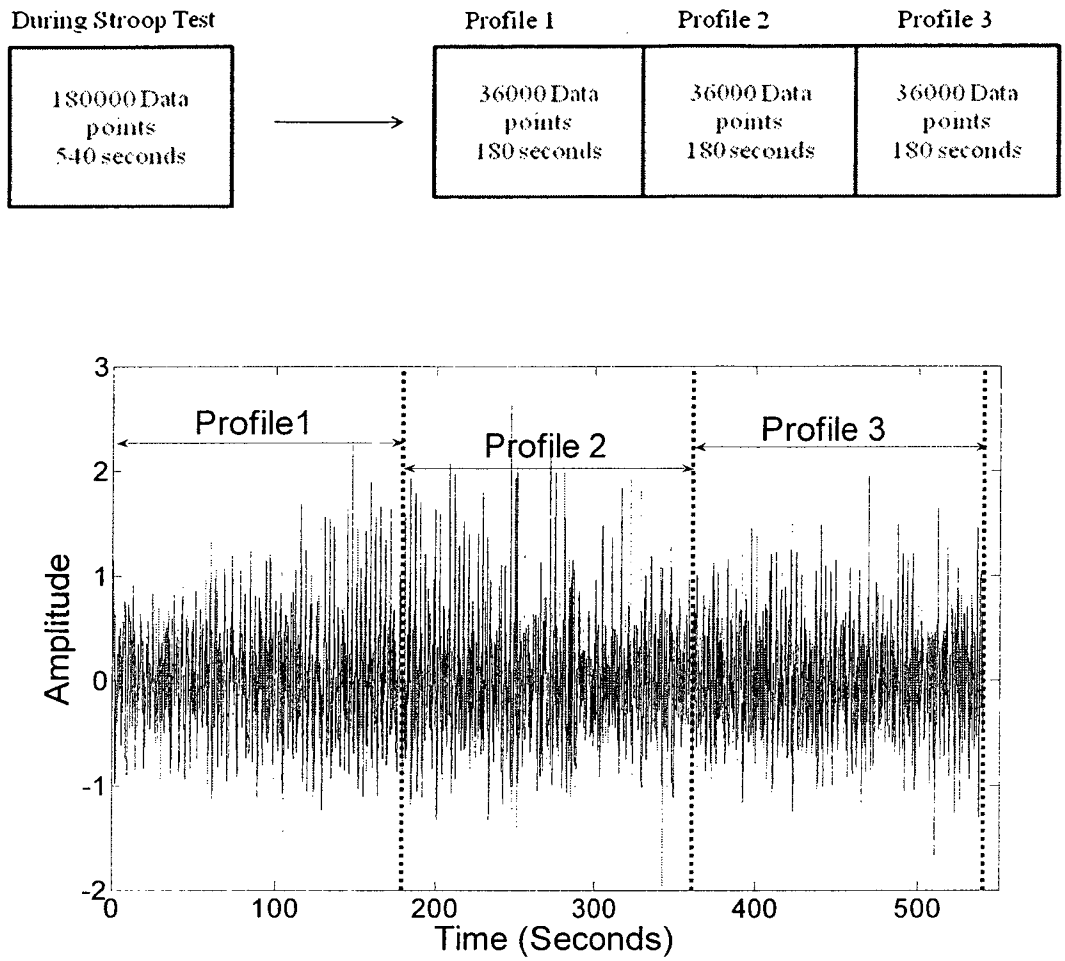



**Figure 20: Segmentation of During EEG 9 min (540 sec) data corresponding to Stroop test for one channel.**

- Since each profile in the stroop test had six difficulty levels, the segmented data for each profile was further segmented as follows.

  Difficulty Level $i$ – 6000 = 30sec×200; $i$ = 1 ... 6.

Figure 21 shows the segmentation of a sample profile into six difficulty levels.

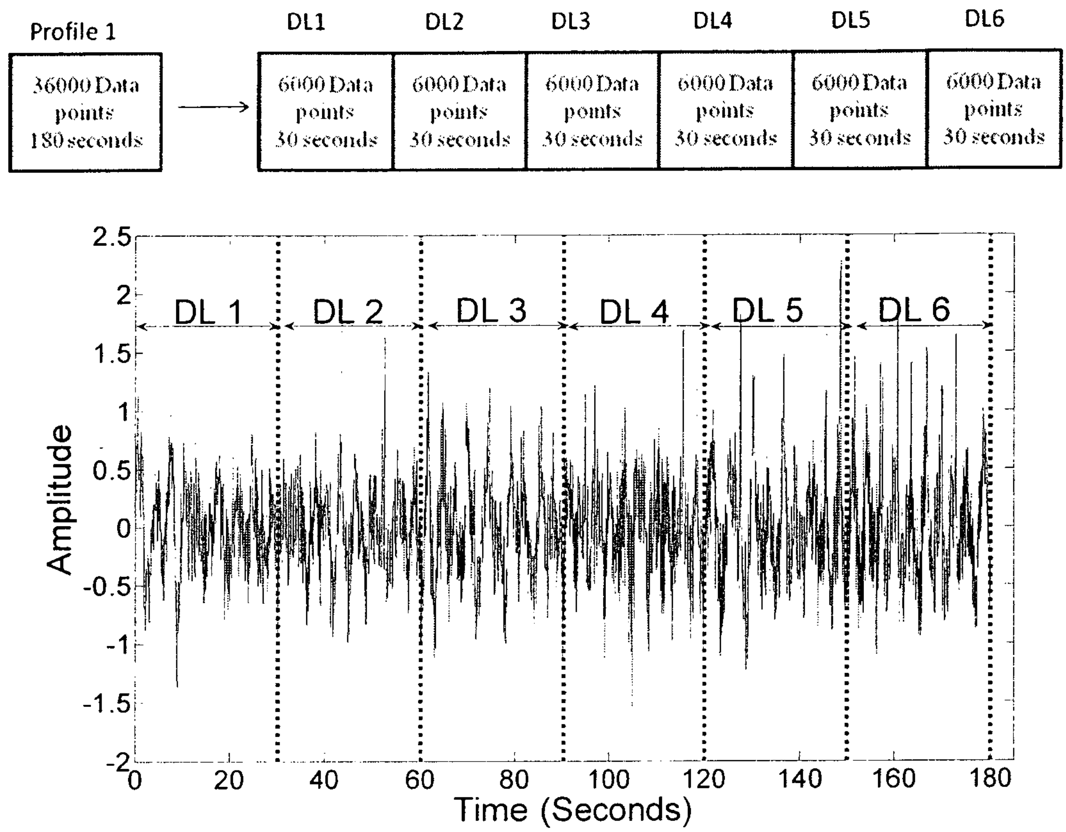



**Figure 21: Segmentation of Profile 1 EEG data corresponding to Stroop test for one channel.**

- In the fourth step, each difficulty level was segmented in ten screens (600×10). Figure 22 shows the segmentation of difficulty level 1 into 10 screens of profile 1 for channel Fz.

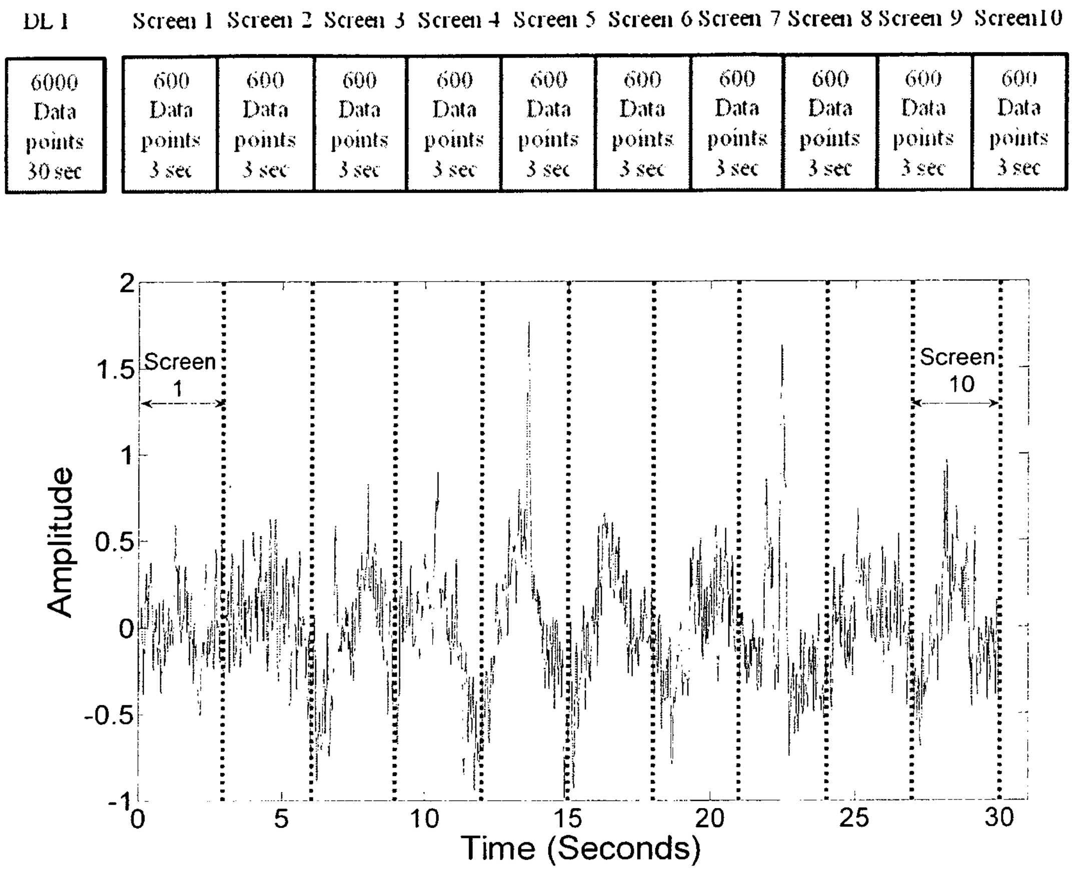



**Figure 22: Segmentation of each difficulty level EEG data corresponding to each screen of Stroop test for channel.**

- In fifth step, each screen was segmented into three different parts as follows:

  Reading part – 100 = 500msec×200

  Response part – 300 = 1.5sec×200

  Rest part – 200 = 1sec×200

Figure 23 shows segmentation of screen 1 in the EEG data for difficulty level 1 of profile 1 during the stroop test. It can be observed from this figure the amplitude is higher in the response part of the screen.

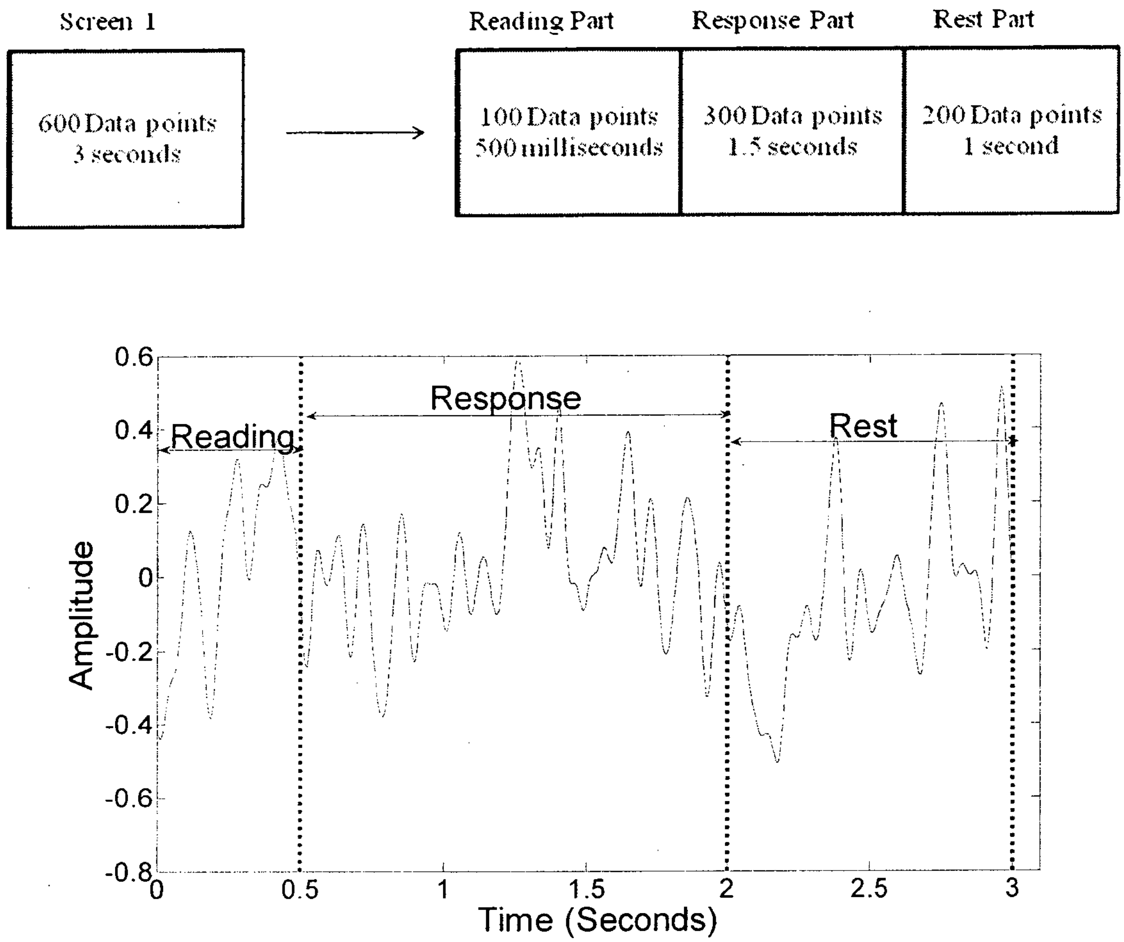



**Figure 23: Segmentation of each screen EEG data into three different parts.**

## 3.5 Data analysis

### 3.5.1 Power Spectral density

The power spectral density (PSD) is the average distribution of power of a signal with respect to frequency. If the power is concentrated in the low frequency region, it means that the signal varies very slowly; if the power is concentrated at a fundamental frequency of rhythm, it means the signal tends to be rhythmic; if the power of the signal is distributed in different frequencies, then the signal lacks its rhythmicity [45].

There are two types of power spectra estimation methods and they are as follows:

1) Non-Parametric method

2) Parametric method

The main advantage of the parametric method over the non-parametric method is that it gives better results than non-parametric method when the data length of the signal is relatively short [46-50].

**3.5.1.1 Non-parametric methods**

In these methods, PSD is estimated directly from the signal itself. The periodogram is the simplest non parametric method and the modified version of the periodogram is the Welch's method. The discrete Fourier transform (DFT) is one of the popular methods of Fourier transform, which is used in Fourier series. Fourier transform transforms original function into its reciprocal space. It transforms the time domain analysis into the frequency domain analysis. The Fourier transform can be expresses as

$$X(f) = \int_{-\infty}^{\infty} x(t) e^{-i2\pi ft} dt \tag{6}$$

DFT requires discrete input function and whose non-zero values have limited duration. The DFT can be efficiently calculated using the Fast Fourier Transform (FFT) method [46].

$$X_k = \sum_{n=0}^{N-1} x_n \, e^{-i2\pi k\frac{n}{N}} \tag{7}$$

where

$X_k$ – represents the amplitude and phase of the sinusoidal components of signal $x_n$

$x_n$ – input signal

N – total number of samples

The power spectral estimation by the FFT is given as

$$P(k) = ||X(k)||^2 \tag{8}$$

### 3.5.1.2 Parametric methods

In these methods, PSD is calculated from a signal that is assumed to be created with equations, with unknown coefficients to approximate. There are various regression methods to estimate the parameters, such as least squares, Yule-Walker and Burg methods are the common parametric methods.

In this work, autoregressive model was used for the spectral analysis. In parametric methods, autoregressive (AR) method is the more frequently used method because of the ease in estimation of autoregressive parameters. The AR model is defined as:

$$x_n = -\sum_{k=1}^{p} a(k)x(n-k) + w(n) \tag{9}$$

where$w(n)$ is the white noise and $a(k)$ are the AR coefficients. AR model can be characterized by AR parameters $\{a[1], a[2], \ldots, a[p]\}$. The PSD is then given as

$$P_{AR}(f) = \frac{\sigma^2}{|A(f)|^2} \tag{10}$$

where

$$A(f) = 1 + \varphi_1 e^{-j2\pi f} + \cdots + \varphi_p e^{-j2\pi f} \tag{11}$$

**AR spectral estimation by Burg method**

For the PSD calculation, the parametric Burg method was used in this thesis. Burg method is considered as the most reliable method, which provides reliable parameter estimates as well as guaranteed stable estimated model (This is why Yule-walker should not be used for autoregressive modeling). The Burg AR method is based on the minimization of the forward and backward prediction errors and estimation of the reflection coefficient [51, 52].

$$\hat{P}_{BURG}(f) = \frac{\hat{e}_p}{\left|1+\sum_{k=1}^{p} \hat{a}_p(k) e^{-j2\pi fk}\right|^2} \tag{12}$$

where

$$\hat{e}_p = \hat{e}_{f,p} + \hat{e}_{b,p} \tag{13}$$

A separate computer code was not written in this thesis for the Burg method and standard MATLB tools were used. There exist several syntaxes for the Burg method, however, the following syntax was used in this thesis.

*[Pxx, f] = pburg (x, p, nfft, fs)*

The above command returns *Pxx*, an estimate of the power spectral density of the vector *x*. *x* is the discrete filtered EEG data (time signal), *p* is the integer specifying the order of an autoregressive prediction model for the signal. In normal awaken state, EEG rhythms can be easily modeled using the 8$^{th}$ order model. This uses the sampling frequency as an integer in hertz to compute the PSD vector and the corresponding vector of frequencies. The unit of PSD is in power per Hz. The range of frequency depends on *nfft*, *fs* and the input value of *x*. Figure 24 shows the PSD values during a sample profile of the stroop data (9 min data when subject was doing the stroop test) for all four channels.

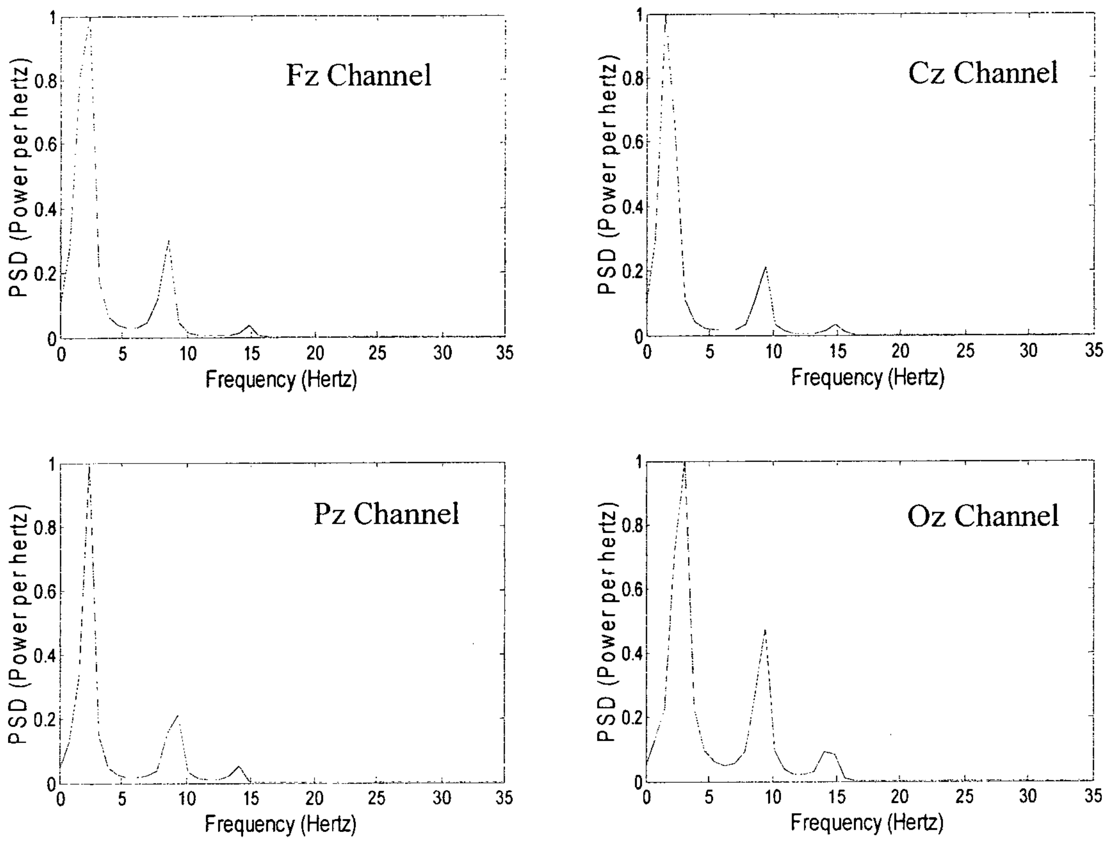



**Figure 24: PSD for all four channels for profile 1.**

After calculating the PSD, the absolute band power within each frequency band was calculated during each difficulty level of stroop test.

# 4. Results and Discussion

## 4.1 Introduction

The stroop test was conducted on all the subjects and the EEG data was recorded. The data was then filtered and the power in each frequency band was calculated. The performance of all the subjects in the stroop test was also calculated. This chapter describes the method of calculating the performance based on the stroop test. The variation of theta, alpha and beta power during all the six difficulty levels of the stroop test for all the subjects was studied and are reported in this chapter. Their variation in different channels was also studied and is discussed here. This chapter also discusses the inter-relationship between the theta power and the performance of the subjects.

## 4.2 Performance from the stroop test

The performance of a subject during the stroop test is calculated by considering the average response time of the subject and the percentage of incorrectness. With increase in the difficulty level, subjects tend to slow down and are prone to make more mistakes, thus deteriorating the performance. The formula used to calculate the performance is

$$Performance = (2 - \beta - t/T)$$

where $\beta$ is the incorrectness rate, $t$ is the average response time over one stroop segment and $T$ is the maximum response time.

The performance of each subject was calculated at each difficulty level in each profile. The average performance of all the subjects at each difficulty level can be calculated by taking an average over all the three profiles. Such an average performance is shows in Figure 25.

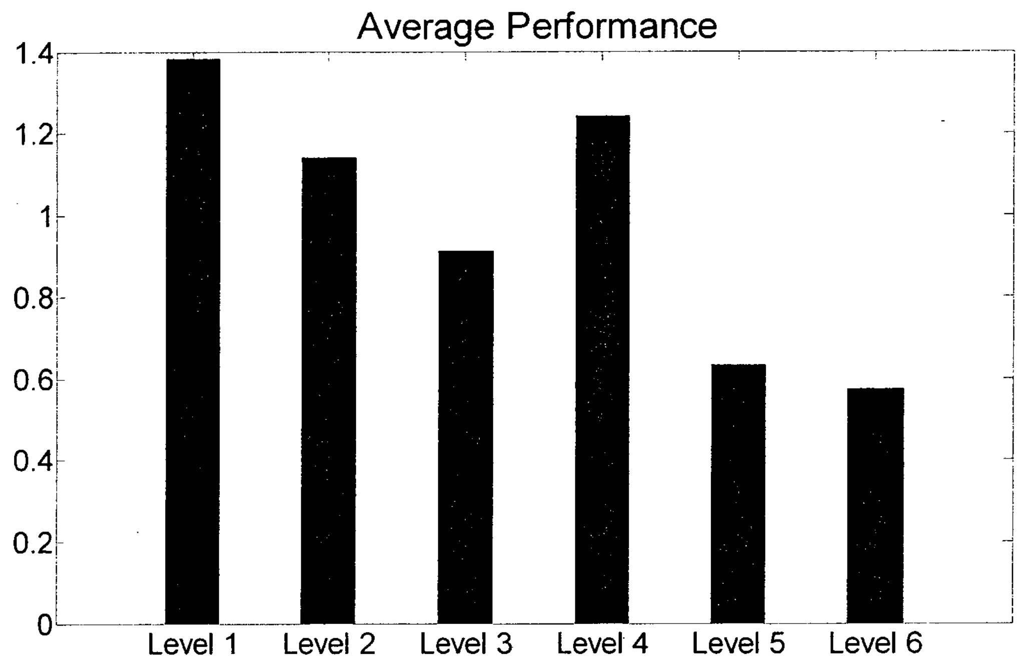



**Figure 25: The average performance of all the subjects during different difficulty levels (also averaged over all the three profiles of the stroop test).**

It can be seen from Figure 25 that as the difficulty level increases the subjects' performance goes down, as expected. However, the difficulty level 4 is an exception. It is difficult to precisely cite a reason behind it, however, it has to be noted that the difficulty levels 1 through 6 were defined intuitively and there was no quantitative evidence demonstrating this ranking. For example, it is intuitive that "congruent-congruent" will be easy to identify than "congruent-black" or "congruent-incongruent". However, such type of intuitive ranking might be difficult when "congruent-incongruent" is compared with "incongruent-congruent". Hence, from this point onwards, the difficulty levels are mentioned using their names and not their numbers (e.g. writing congruent-congruent instead of writing difficulty level 1). A detailed statistical analysis is required on a large number of subjects to confidently rank these six cases in terms of their difficulty levels. Such type of analysis was not performed in this thesis but is recommended.

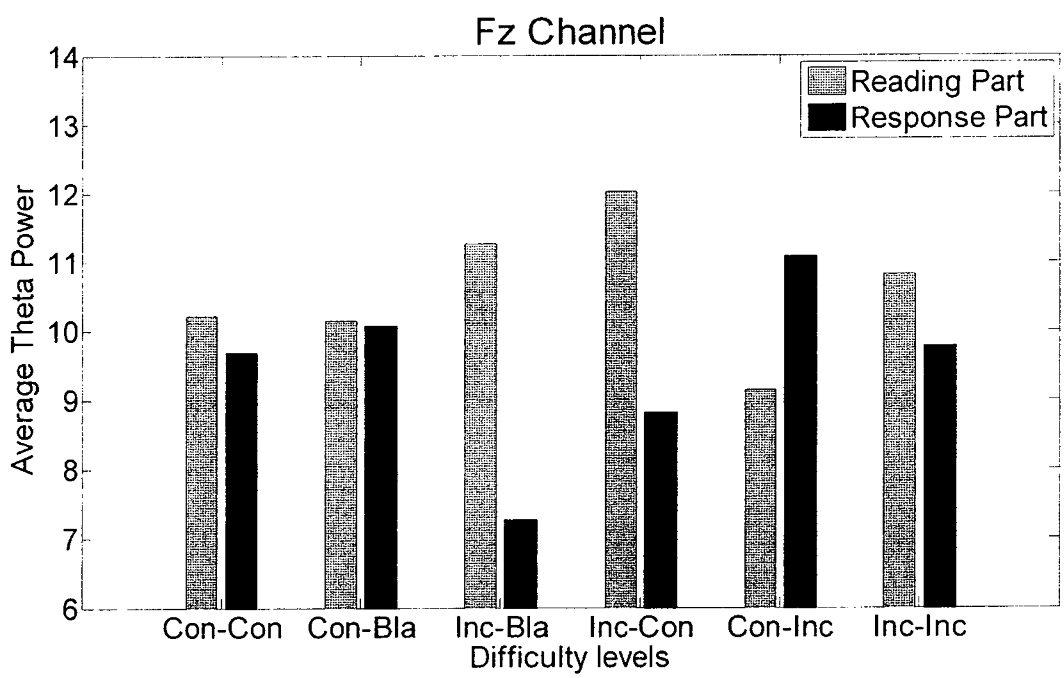
## 4.3 Band power analysis

This section reports the analysis of the powers calculated for all four bands (Delta, Theta, Alpha, and Beta) for all the four channels (Fz, Cz, Pz and Oz), arranged according to the difficulty levels. As mentioned in chapter 2, different channels and different bands are associated with different functionalities of the brain, however a clear demarkation is almost impossible. The four channels studied in this thesis, if associated with the type of functionality based on their locations, are:

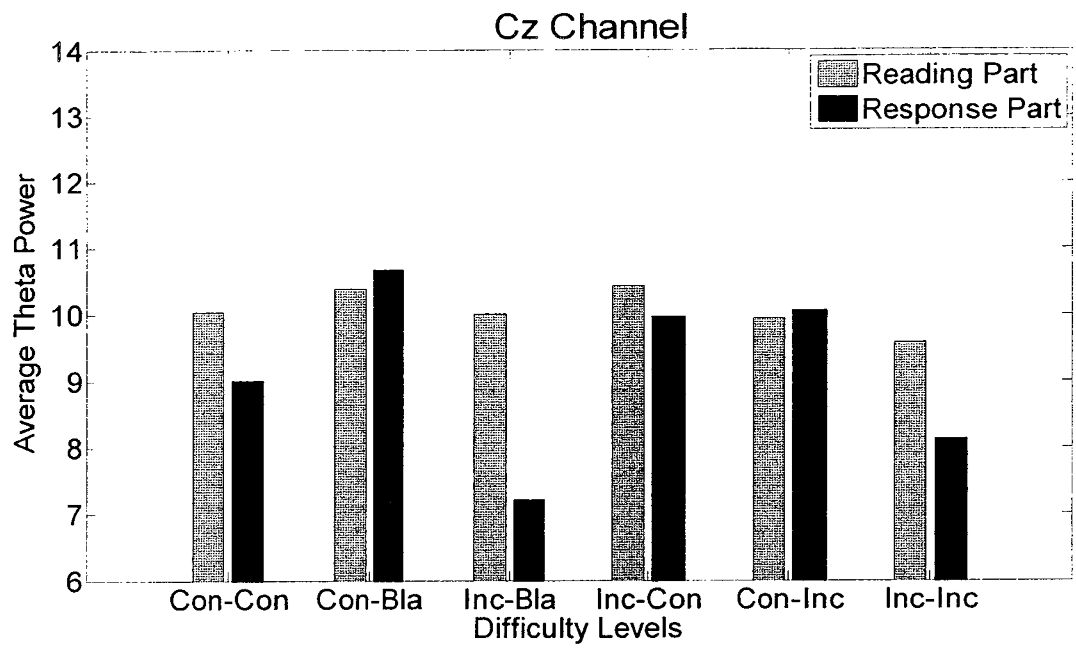
- Fz – emotional/mental control.
- Cz – sensory and motor function
- Pz – percpetion and differentiation
- Oz – vision.

Though each channel is located on a different part of the brain, since each channel in the EEG measures electrical activity of millions of neurons in the brain, there is bound to be an interference of different electrical activities associated with different functionalities in each channel of the EEG. This is also evident from the fact that all the four frequency bands powers (alpha, beta, theta and delta) are present in each of the channel. In order to simultaneously associate any particular band power and its channel location to a particular functionality of the brain, it is very important to calculate individual band powers in each of the channel and compare their activities during the task (stroop test). This is the reason that in this thesis, each band power is calculated seperately for each channel and each profile. The reading part and the response part of the power was separated and for each difficulty level, it was averaged over all the profiles of all the subjects.

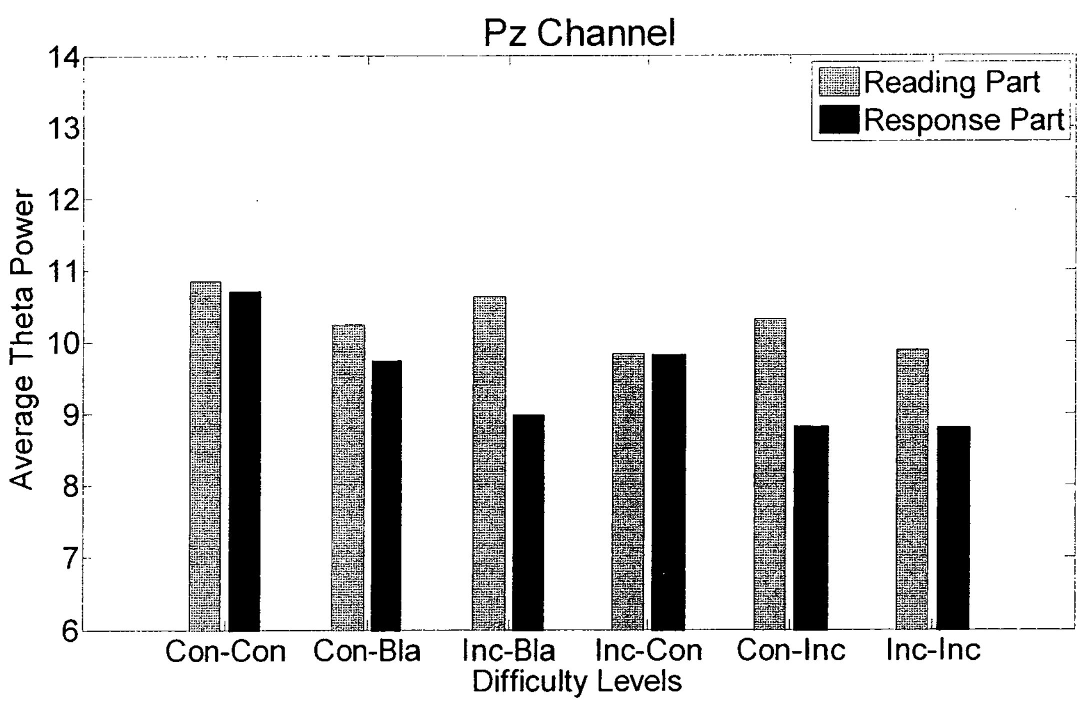
### 4.3.1 Theta Power



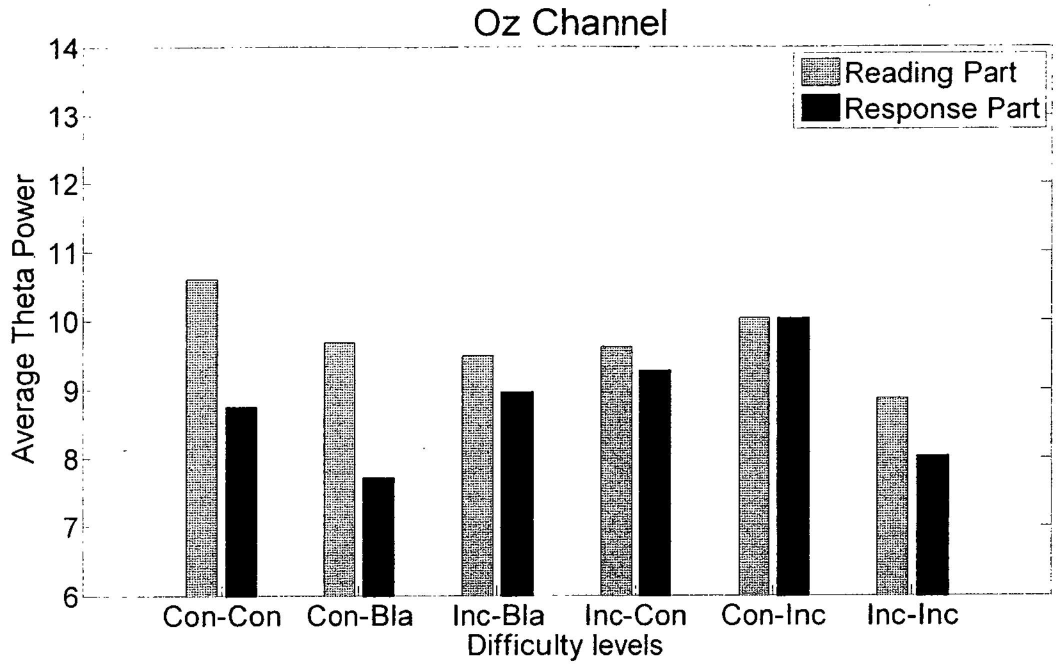

**(a)**


Cz Channel
Reading Part
Response Part
Average Theta Power
14
13
12
11
10
9
8
7
6
Con-Con
Con-Bla
Inc-Bla
Inc-Con
Con-Inc
Inc-Inc
Difficulty Levels

**(b)**


Pz Channel
Reading Part
Response Part
Average Theta Power
14
13
12
11
10
9
8
7
6
Con-Con
Con-Bla
Inc-Bla
Inc-Con
Con-Inc
Inc-Inc
Difficulty Levels

**(c)**



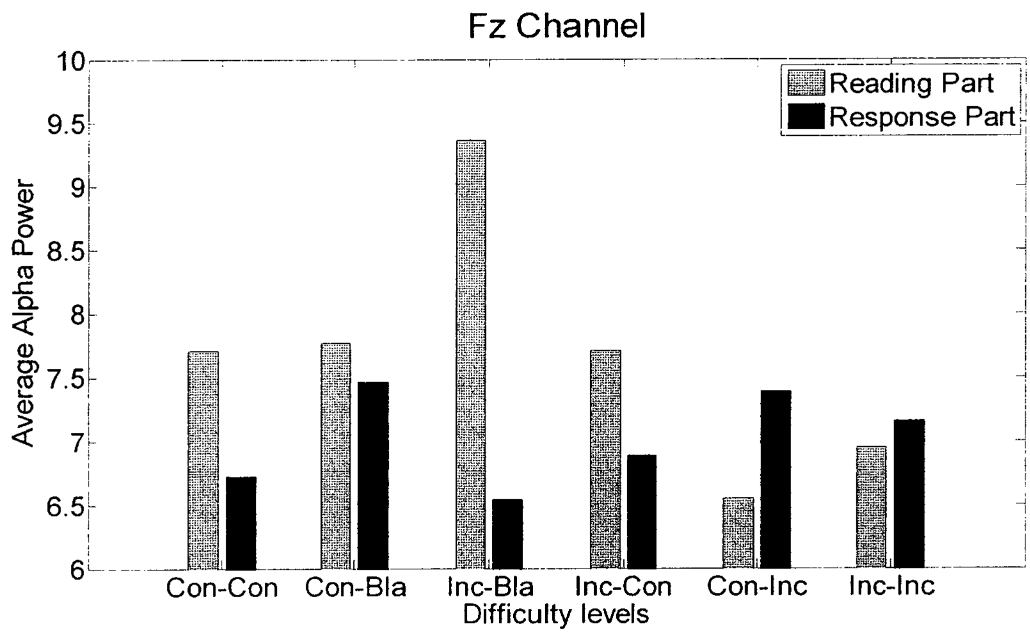

**(d)**

**Figure 26: Average theta power of all the subjects during the reading and response part of the stroop test in (a) Fz channel, (b) Cz channel, (c) Pz channel and (d) Oz channel.**

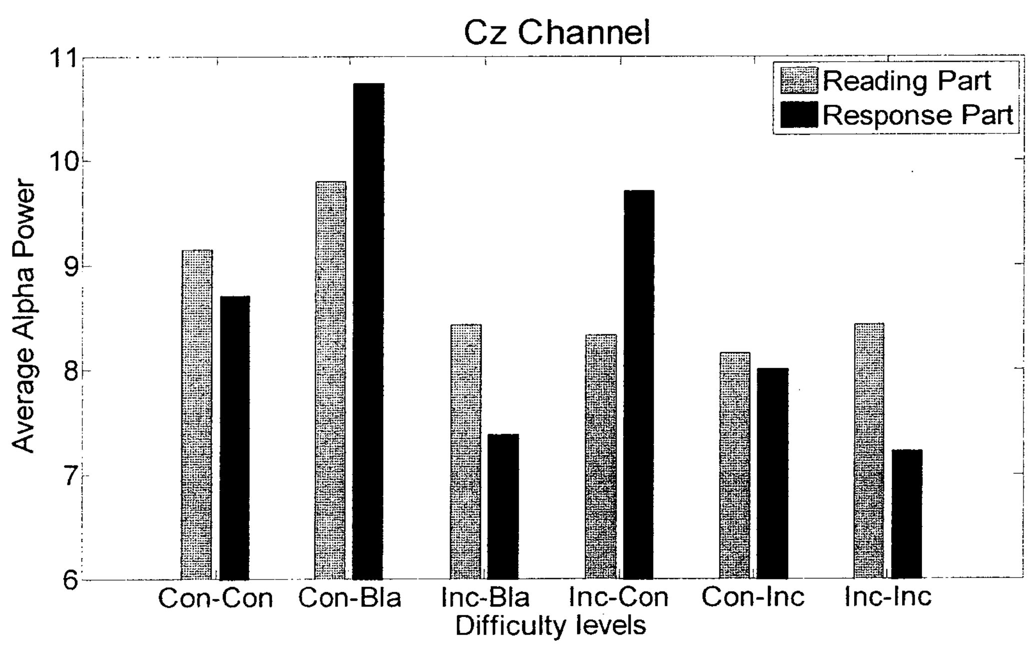
Figure 26 shows the variation in theta power during different difficulty levels of the stroop test in all the channels. The theta power was calculated separately for the reading and the response part, at each difficulty level. It can be observed from Figure 26 (a – d) that the average theta power, particularly in the reading part, is more in the Fz channel than in any other channel. This is consistent with the facts that Fz channel location corresponds to emotional and mental control and the theta frequency band is also believed to be associated with mental/emotional stress. Hence, it completely makes sense to observe a higher power for the theta band in channel Fz. This observation is also consistent with the previous literature, which suggests that the frontal midline (Fz) theta power is useful to assess mental/emotional stress during any mental task and is a good indication of the subject's concentration [53-55].

It can also be observed from Figure 26 (a) that when "Incongruent-Congruent" is compared with "Congruent-Incongruent", the theta power is significantly higher for the "incongruent" part, be it during the reading or during the response. Contrary to that, and rightly so, when the reading and response part are same (Congruent-Congruent and Incongruent-Incongruent), the difference in their theta powers is the least. The reading part of the theta power is always higher for the incongruent part than that for the congruent part, since, it is more difficult to perceive the incongruent part than the congruent part and the subjects probably get more stressed during the incongruent part, revealing a higher theta power. The above observations validate and are in agreement with the belief that the theta power in the Fz channel is a measure of the mental/emotional stress, since incongruent reading and response is definitely more stressful than the congruent reading and response respectively and there will not be a lot of difference in the person's mental stress when the reading and response part have the same difficulty level. It can also be observed that the difference between the reading and response parts of the theta power is maximum for the "Incongruent-Black" difficulty level and the theta power for the reading part of this difficulty level is the least. This slightly different behavior of the theta power in this difficulty level is synchronous with the average performance of the subjects since at this same difficulty level (level 4 in Fig. 25), the average performance also shows a deviation from the trend.

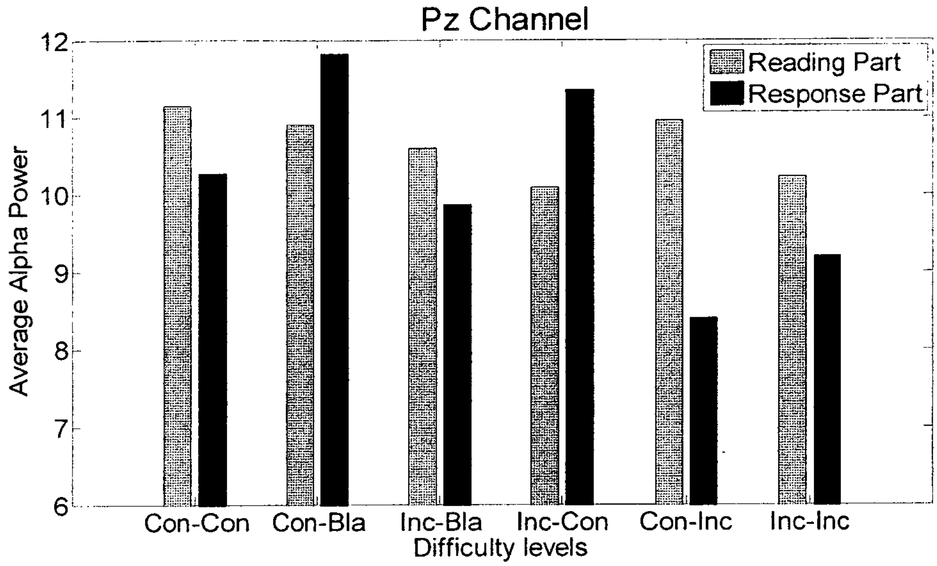
### 4.3.2 Alpha Power



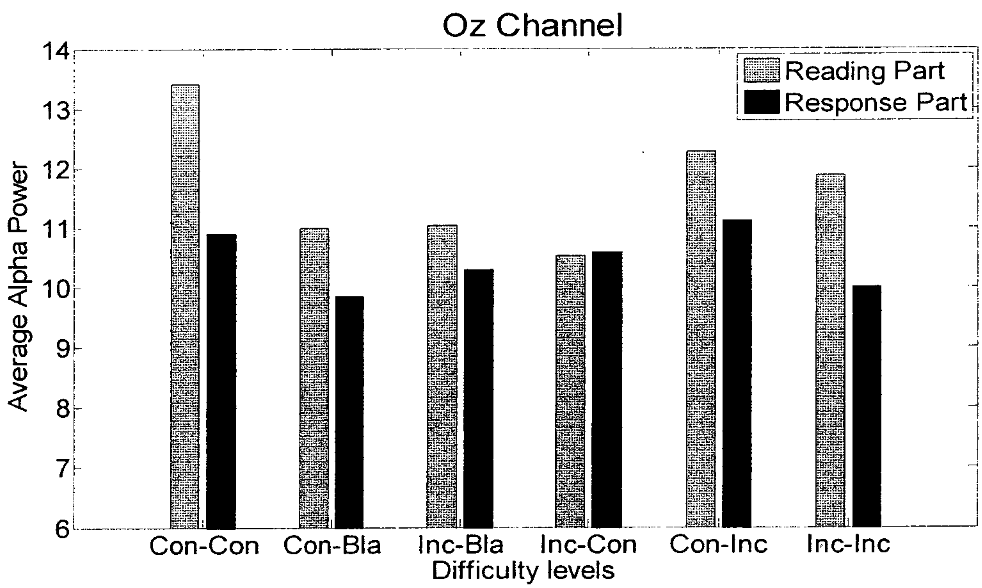

**(a)**




**(b)**




(c)



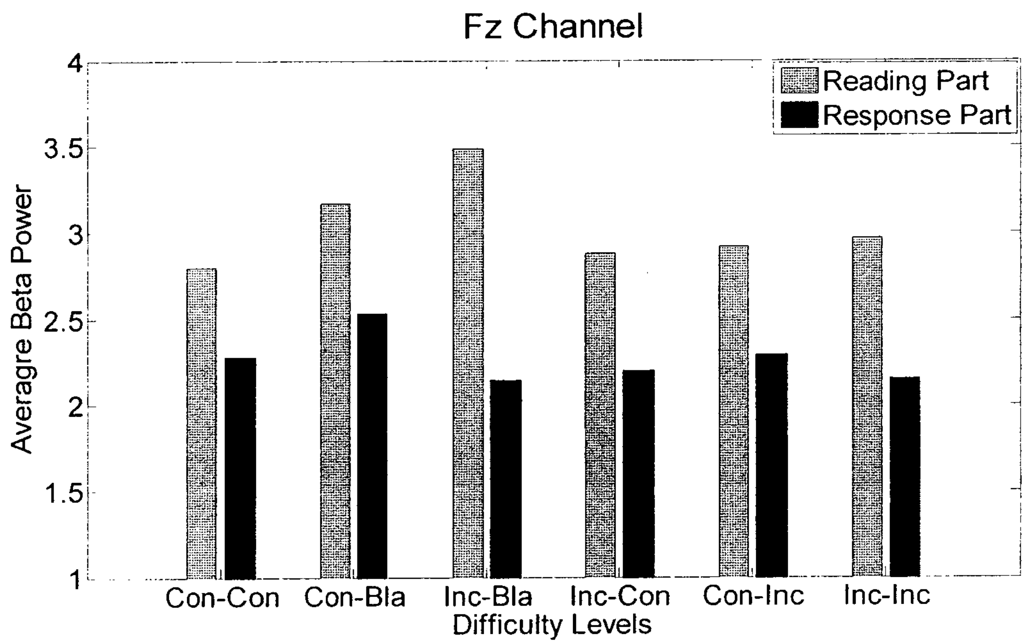

(d)

**Figure 27: Average alpha power of all the subjects during the reading and response part of the stroop test in (a) Fz channel, (b) Cz channel, (c) Pz channel and (d) Oz channel.**

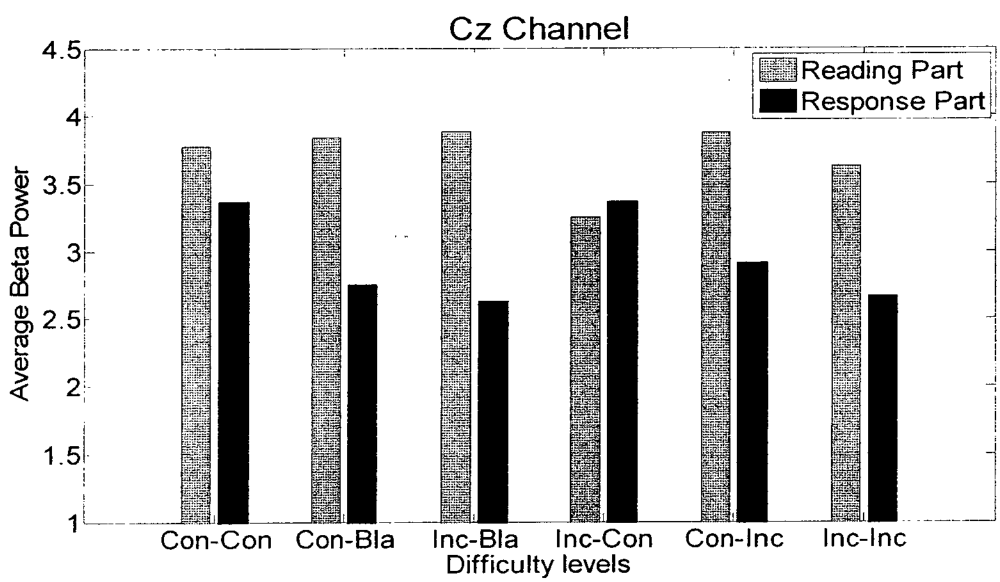
Figure 27 (a – d) shows the variation of the subjects' alpha power, in different channels, during the stroop test with respect to different difficulty levels. The alpha power was also calculated separately for reading part and response part separately. It can be observed from Figure 27 (a - d) that alpha power during the reading part is significantly higher in the Oz channel than in Fz, Cz and Pz channels. Not only it is in agreement with the reported literature suggesting that the alpha power is more active in the Oz region of brain during a vision related task [14, 22] but also validates the same since the stroop test used in this work is also a vision related task. It also needs to be noted that the alpha power in the Oz channel is always higher in the reading part than in the response part and even for the response part, the alpha power is more in the Oz channel.

The other important observation for the alpha power in the Oz channel is that the difference between the alpha powers in the reading and the response part is the maximum for Congruent-Congruent and Incongruent-Incongruent levels. The reason for this could be that the subjects find the (visual) transition easy since the reading and the response parts are the same. It can also be noted that the alpha power in the response part is slightly higher for congruent and incongruent parts than for black. If the alpha power in the Oz channel is believed to be for visual detection, it can be said that the subjects find it easy to identify the black (all color names written in black) than the congruent or incongruent parts. This could be due to the fact that all of us are used to reading the text, printed or on computer, written in black color.

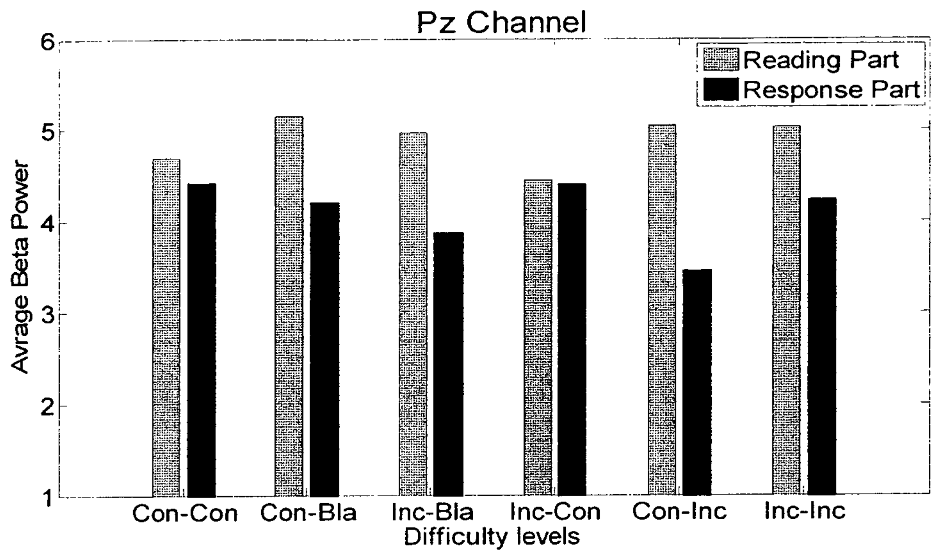
### 4.3.3 Beta Power



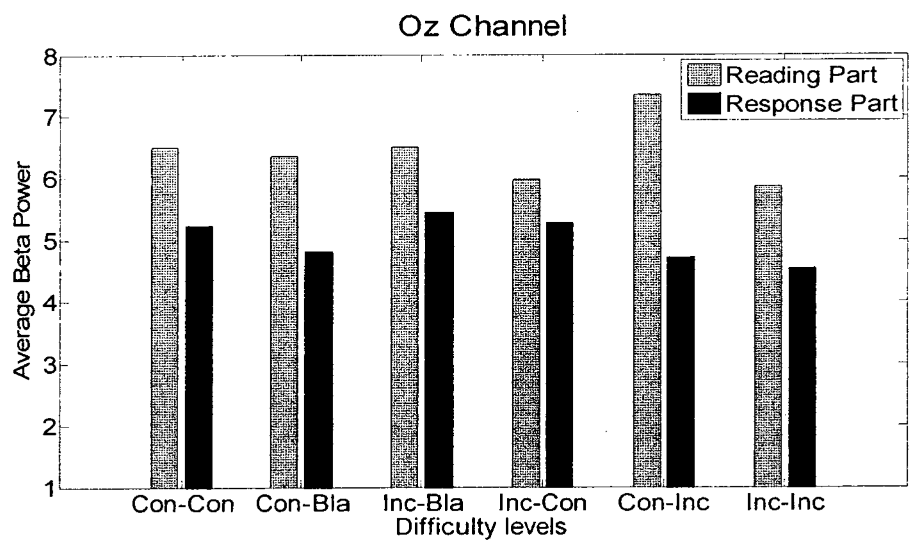

(a)




(b)




**(c)**



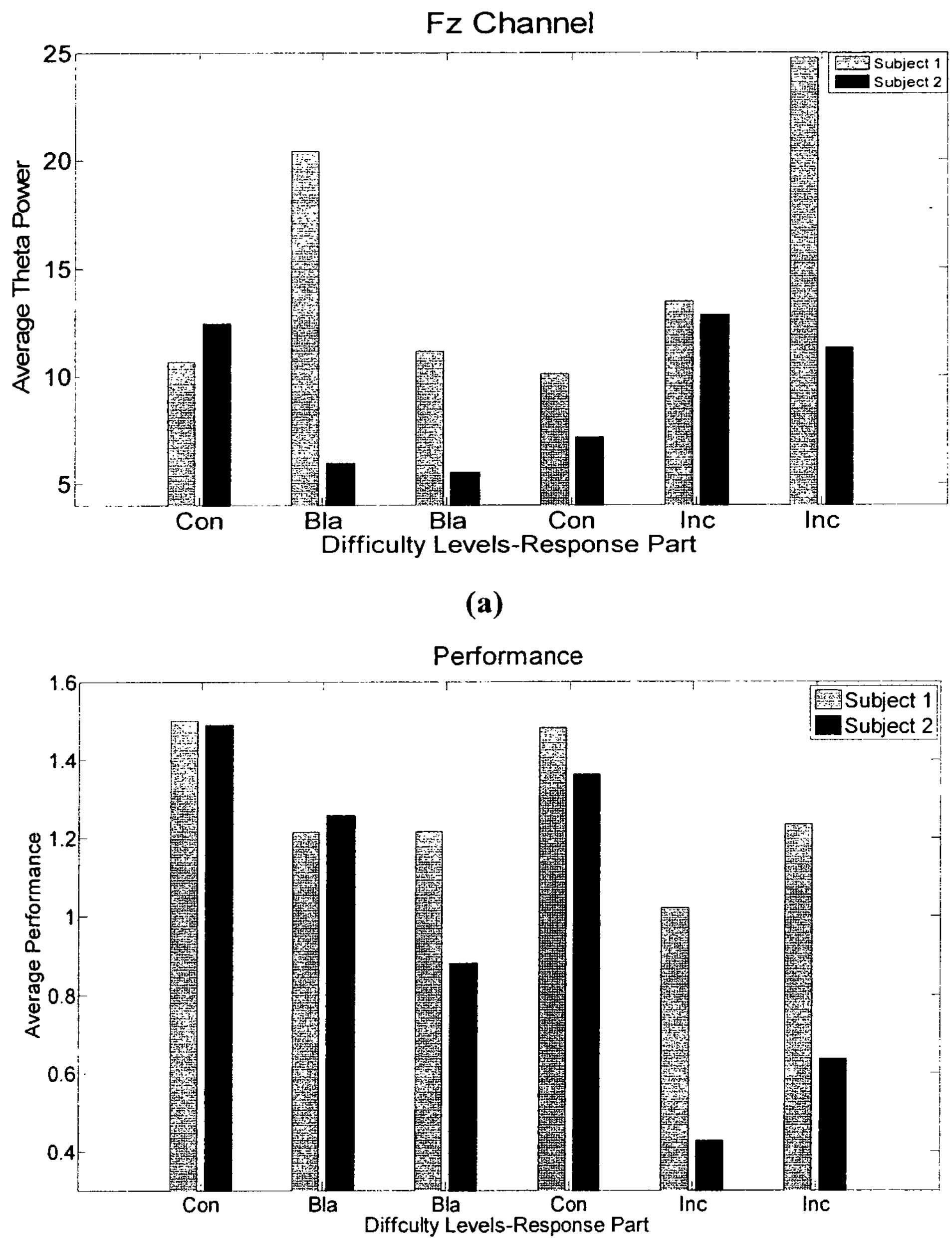

**(d)**

**Figure 28: Average beta power of all the subjects during the reading and response part of the stroop test in (a) Fz channel, (b) Cz channel, (c) Pz channel and (d) Oz channel.**

Figure 28 (a – d) shows the variation of average beta power at all the six difficulty levels in all four channels. As mentioned before, it has been reported in the literature that the beta is related to active concentration and thinking [12-14]. It can also be observed in Figure 28 (a – d) that the beta power for the reading part is always higher than for the response part, in all the channels and at all difficulty levels. This is in agreement with the literature since the subjects are doing more thinking while trying to identify the color in the reading part, thus reporting higher beta power in the reading part. There are no reports in the literature that suggest the relevance/association of one particular channel with the beta power, however, Figure 28 (a – d) suggest that the average beta band power is highest in the Oz channel. It has to be noted that Oz channel is related to the vision and since the task in this thesis, i.e. the stroop test, is a vision based task, the beta power related to concentration is more prominently showed in the Oz channel in this work. However, if the mental task given to the subjects is not vision based then there are chances that the beta power may be more prominently observed in some other channel and not in the Oz channel.

From Figure 28 (d), it can be observed that the beta power in Oz channel is more in the congruent reading part than in the incongruent reading part and also in other channels, it is very difficult to comment on the relationship between the beta power in congruent and than in the incongruent part. It is difficult to comment on the precise reason behind it, however, it can be said that the subjects' concentration drops in incongruent reading parts since identifying the color is more difficult in that case and this results in confusion and in lack of confidence, leading to loss in the subject's concentration. Since beta band is related to concentration and thinking, its shows lower power in incongruent parts.

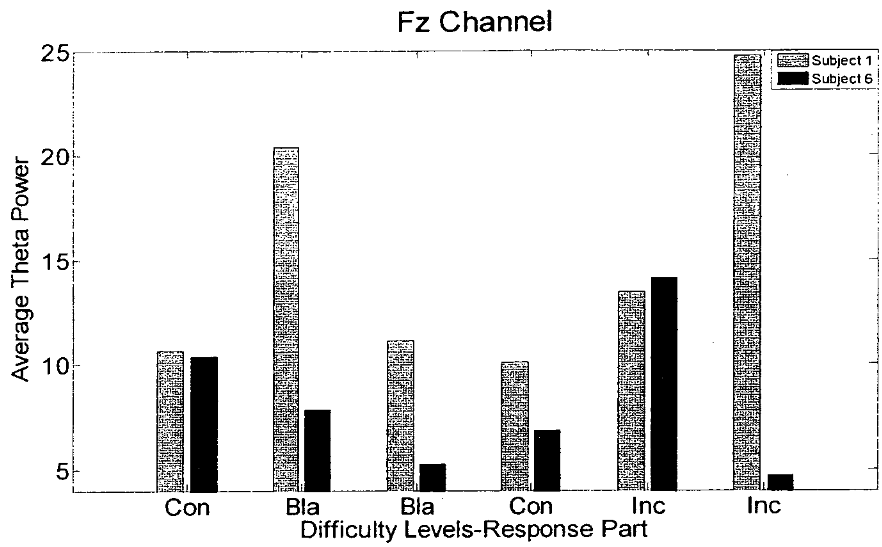
### 4.3.4 Relationship between the performance and EEG band powers



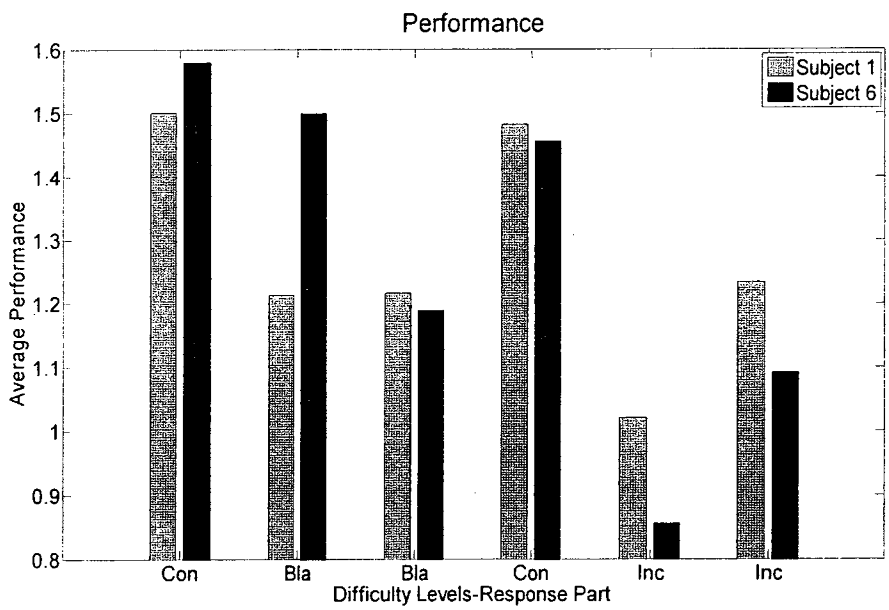

(a)

(b)

**Figure 29: Comparison of (a) the average theta Power in the Fz channel and (b) of the performance of subject 1 and subject 2 at all difficulty levels.**




**(a)**




**(b)**

**Figure 30: Comparison of (a) the average theta Power in the Fz channel and (b) of the performance of subject 1 and subject 6 at all difficulty levels.**

Figure 29 and Figure 30 show the comparison of the theta power and of the performance of subjects 1 and 2 and 1 and 6, respectively. The comparison was done at all the difficulty levels. The motivation behind this thesis is to investigate a relation between the stress and performance during a mental task, however, there does not exists a method which can be used to quantify the mental stress. Since it has been suggested in the literature [53-55] (and demonstrated in this thesis) that the theta power in the Fz channel corresponds to the subject's mental stress during a mental task, this comparison between two different subjects' performance and theta power in Fz channel was performed at all difficulty levels. The theta power at all the difficulty levels was taken for the response part only. In this thesis, the performance was calculated based on the degree of correctness and on the response/reaction time and since the attempt here is to compare the performance and theta powers of different subjects, the theta power for the response part was also chosen to be the one during the response/reaction time.

It can be seen from Figure 29 and Figure 30 that for the difficulty levels Incongruent-Black, Incongruent-Congruent, Congruent-Incongruent, and Incongruent-Incongruent, the subject which gave a better performance in the stroop task also exhibited a higher value of theta power. However, a discrepancy to this trend can be seen in the first two difficulty levels Congruent-Congruent and Congruent-Black. The subject that performed better exhibited a lower theta power than the one that gave a lower performance. The Yerkes-Dodson law suggests that as the mental stress increases the performance increases and after reaching an optimal point in the stress, it drops. This could mean that if two subjects are given a similar task which is independent of their expertise, the person developing more stress would perform better than other if they are in the initial positive-slope side of the Yerkes-Dodson law curve. Since, it in this thesis, a quantitative ranking of the levels of the stroop test according to their "difficulty" was not done, it would not be possible to propose any correlation between the stress (based on theta power) and performance. However, believing that identifying the incongruent task would be more difficult than identifying the congruent task and that the stroop test used in this thesis was not difficult enough to stress the subjects to a level where his performance would drop with further increase, it can be said that these results are in a qualitative agreement with the Yerkes-Dodoson law. However, with these results it is not possible to comment on the possible reason behind the observation that for difficulty levels Congruent-Congruent and Congruent-Black, the subject who gave a higher performance showed lower theta power. Again, since, Congruent-Congruent is bound to be an easier task than Incongruent-Incongruent, it is not possible that the stress level lies on the negative-slope side of the Yerkes-Dodson law curve.

# 5. Conclusions and Future work

## 5.1 Conclusions

An extensive literature review of the assessment of different physiological variables using the EEG was performed. With the motivation of correlating the designer's stress, calculated using the EEG recorded data of the designer, to its performance during a design related mental task, experimental set-up was established in Dr. Yong Zeng's research group. The stroop test was used as a mental task given to the subjects. A protocol was developed to attach electrodes on the scalp, to record the EEG data while the subject is performing the stroop test and to filter the raw EEG data obtained. A segmentation scheme for the filtered EEG data, based on the timings of the mental task (stroop test), was developed and implemented. Algorithms and mathematical methods to calculate the power spectral density of the filtered and segmented EEG data were identified. Using these algorithms and methods, power spectral density of each band of the EEG was calculated from each channel. From the density, absolute power for each band was calculated. The powers for the reading part and the response part of the stroop test were separately calculated. No further analysis of the delta band was performed, since it is usually associated with deep sleep.

Absolute powers calculated for alpha, theta and beta bands of each EEG channel during all the difficulty levels of the stroop test were analyzed. The analysis of the theta band (mental/emotional stress) power showed that this frequency band is more pronounced in the Fz channel. It was also demonstrated that the theta band in the Fz channel is the potential candidate for quantifying the mental stress. Similarly, the analysis of the alpha power (vision) demonstrated that it is more pronounced in the Oz channel. The combined analysis of the alpha power in Oz channel and theta power in Fz channel also showed that, in the color identification task such as stroop test, during the reading and response part of the stroop test, black may not necessarily be more difficult than congruent. The analysis of the beta power (concentration) showed that it was more pronounced in the Oz channel but it could possibly be due to the fact that the stroop task is a vision based task. Non-vision based mental tasks need to be given to the subject to confirm this.

The comparison of theta powers in the Fz channel and the performance of two different subjects indicated that the difficulty level of the stroop test is not high enough to make the subject stressed enough so as to decline his/her performance (following the Yerkes-Dodson law). Partial and qualitative agreement with the Yerkes-Dodson law was also demonstrated.

## 5.2 Future work and recommendations

### 5.2.1 Future work

The present thesis, though not a quantum leap in correlating the designer's mental stress with the performance, lays down the necessary and crucial foundation for quantitative validation of Yerkes-Dodson law using the electroencephalogram. The suggested future work is as follows:

- Develop a methodology to quantify the mental stress using the theta power in the Fz channel.

- Develop a stroop test with higher difficulty levels and quantitatively rank the difficulty levels of the stroop test by doing a statistical analysis on a large number of subjects.
- Find the relation between P300, eye blinks, inter-blink-interval and the difficulty levels of stroop test. Study at which location P300 is dominant.
- If possible, quantification of mental stress using P300, eye blinks and inter-blink-interval during stroop test.
- Compare the mental stress and performance relation obtained using the EEG with that obtained using the P300, eye blinks and inter-blink intervals.
- After quantifying the mental stress using the stroop test, the next step is to quantify mental stress during a design process.
- Integrating EEG, eye tracker, HRV, video and linguistic data to understand designers cognitive process.

### 5.2.2 Recommendations

- In the experiments performed in this thesis, the electrodes were manually fixed on the scalp of the subjects. Getting a good contact in this case was quite a challenging task and required a lot of trials to achieve it. A lot of experimental data and time was also wasted due to the loss of contact between the electrodes and the scalp in the middle or towards the end of the experiment. In order to save time and available experimental resources (including the time of the subjects who agree to participate in the experiments voluntarily or for a very minimal returns) and to get reliable data, it is strongly recommended to use the electrode cap for future experiments.

- The other recommendation is about the noise in the EEG data. Though all the possible filters were used to eliminate the noise in the data, it is strongly recommended to somehow reduce the noise that is generated due to the ventilation system in the lab. To avoid this kind of noise, a change the location of the lab or the use sound proof cabinet is recommended.
- Performing the data analysis separately for each segment and repeatedly modifying the MATLAB codes for different segmentation scenarios takes a lot of time. This problem will be further aggravated while segmenting the design task related EEG data. Though not reported in the thesis, a graphic user interface (GUI) was also developed in this work. The GUI developed should be generalized for further analysis.

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# Appendix

## GrassLab Configuration and Operation details:

1) Open Grasslab window on the computer screen then go to Start >> Apply configuration
2) In Apply configuration choose **Input Channels** tab. Enter a sample rate in the Master Sample Rate box.
3) Select channel from the Analog input channel list, which is located on the left side of the window.
4) Select whether to acquire the channel in Grasslab recorder. To acquire the channel, ensure the Acquire Channel in Recorder option is checked. By default all channels are to be set. Check marks in the analog input channel list indicate channels that will be acquired.
5) After applying Input channels choose **Display Views**
6) Enter a name for the display view in the Display View Name Box. Then choose Add button to the right of this box. The display view will be added to All Display Views list.
7) Add necessary input channels to the display view. Select an input channel from the Input Channels list. Then choose the Add button to the right of the Input channel list.
8) Adjust properties of the channels in the Display Channels list.
9) When you are finished all setting then save this configuration. Choose the Save button. The Save File As window will open. Select the drive, folder and enter a filename for the configuration file.
10) Choose the save button and your file will be saved.
11) We can use this file for the configuration during future experiments.

### GrassLab Recorder

12) After finish the configuration you are ready to recording data.
13) Open GrassLab window ,choose Start>>Recorder from the menu bar. The Open Configuration File window will open.
14) Select the drive, folder, and application configuration file to load. After selecting file choose the Open button. The configurations stored in the file will be loaded and GrassLab recorder will start.
15) Choose Edit>>Preferences and select recording duration.
16) Choose M15 tab form GrassLab Recorder and do amplifier settings.
17) Choose traces from GrassLab Recorder button go to filter option and do digital filter settings.

18) Choose exit button to close the trace properties window.

19) Choose File >>Recording>> Start. The file name window will open.

Select a drive, folder, and file name for the recording. The default location is C:\Grasslab\Data. Then choose save. A folder will be created with the file name you specify. The Grasslab recording file will be saved in this folder with the specified file name. The recording will begin. To stop the recording, choose File>>Recording>>Stop. The Start/Stop button can also be used to start and stop recording of a file. The Start/Stop button is located in the top left corner of the window.

**GrassLab Reviewer**

After completing experiment we review our data and transfer it in different format

20) Open GrassLab window. Choose the Reviewer button or Start>>Reviewer from the menu bar. A file selection window will open.
21) Select the drive, folder, and file for review. By default, the following path will be used: C:\Grasslab\Data
22) After selecting the file, choose the Open button. The file will be opened in the GrassLab Reviewer window.
23) Choose File >> Export>>ASCII. Enter the desired file name into the text box under ASCII File Name. You can select the range of data.
24) To include a channel in the exported file, select it from the Channel selection drop down menu and click the Include button. To exclude it, click the Exclude button. To exclude all channels, click the Exclude All button.
25) Click OK. The file will be created in the same directory as the original data.
26) To close GrassLab, choose File>>Exit from the GrassLab Main Menu window.

# Algorithms for Analysis

## For Profile 1

```
clear all; clc; close all;
p = load('samir 10 august.txt'); % loading subject data
Fs = 200;
% Filter using IIR 5 point Butterworth (0.3-35 Hz);
n = 5; Wn = [0.3 35]/Fs;
[b,a] = butter(n,Wn);
p1 = filtfilt(b,a,p);
Wn = 400;
Ws = 400/2;
NFFT = 1024*Fs;
c=mat2cell(p1,[71800 108000 60200],[6]);
ss=c{2,1};
c1=mat2cell(ss,[36000 36000 36000],[6]);
ss1=c1{1,1};                    % Profile 1
c2=mat2cell(ss1,[6000 6000 6000 6000 6000 6000],[6]);
ss2=c2{1,1};
c3=mat2cell(ss2,[600 600 600 600 600 600 600 600 600 600],[6]);
ss3=c3{1,1};
c4=mat2cell(ss3,[100 300 200],[6]);
ss4=c4{2,1};
y1=ss4;
c5=mat2cell(ss2,[600 600 600 600 600 600 600 600 600 600],[6]);
ss5=c5{2,1};
c6=mat2cell(ss5,[100 300 200],[6]);
ss6=c6{2,1};
y2=ss6;
c7=mat2cell(ss2,[600 600 600 600 600 600 600 600 600 600],[6]);
ss7=c7{3,1};
c8=mat2cell(ss7,[100 300 200],[6]);
ss8=c8{2,1};
y3=ss8;
c9=mat2cell(ss2,[600 600 600 600 600 600 600 600 600 600],[6]);
ss9=c9{4,1};

c10=mat2cell(ss9,[100 300 200],[6]);
ss10=c10{2,1};
y4=ss10;
c11=mat2cell(ss2,[600 600 600 600 600 600 600 600 600 600],[6]);
ss11=c11{5,1};
c12=mat2cell(ss11,[100 300 200],[6]);
ss12=c12{2,1};
y5=ss12;
```

```
c13=mat2cell(ss2,[600 600 600 600 600 600 600 600 600 600],[6]);
ss13=c13{6,1};
c14=mat2cell(ss13,[100 300 200],[6]);
ss14=c14{2,1};
y6=ss14;
c15=mat2cell(ss2,[600 600 600 600 600 600 600 600 600 600],[6]);
ss15=c15{7,1};
c16=mat2cell(ss15,[100 300 200],[6]);
ss16=c16{2,1};
y7=ss16;
c17=mat2cell(ss2,[600 600 600 600 600 600 600 600 600 600],[6]);
ss17=c17{8,1};
c18=mat2cell(ss17,[100 300 200],[6]);
ss18=c18{2,1};
y8=ss18;
c19=mat2cell(ss2,[600 600 600 600 600 600 600 600 600 600],[6]);
ss19=c19{9,1};
c20=mat2cell(ss19,[100 300 200],[6]);
ss20=c20{2,1};
y9=ss20;
c21=mat2cell(ss2,[600 600 600 600 600 600 600 600 600 600],[6]);
ss21=c21{10,1};
c22=mat2cell(ss21,[100 300 200],[6]);
ss22=c22{2,1};
y10=ss22;
Y=[y1;y2;y3;y4;y5;y6;y7;y8;y9;y10];
EEG = Y(:,4);
for k= 1: Ws:(length(EEG)-Wn);
    x = EEG(k:k+Wn-1);
    [Pxx, Fxx] = pburg(x, 8,NFFT,Fs);
    F = Fs/2*linspace(0,1,NFFT/2);
    dF = max(F)/length(F);
    F1=floor(4/dF);
    F2=floor(7/dF);
    F3=floor(12/dF);
    F4 = floor(20/dF);
    F5 = floor(30/dF);
    alphaPower = sum(Pxx(F2:F3));
    betaPower = sum(Pxx(F3:F4));
    deltaPower = sum(Pxx(1:F1));
    thetaPower = sum(Pxx(F1:F2));
    TotalPower = sum(Pxx(1:F4));
    BrainPower = [deltaPower; thetaPower; alphaPower; betaPower;];
    BrainPower = (BrainPower/TotalPower)*100;

end
```

**For Profile 2**

```
clear all; clc; close all;
p = load('samir 10 august.txt'); % loading subject data
Fs = 200;
% Filter using IIR 5 point Butterworth (0.3-35 Hz);
n = 5; Wn = [0.3 35]/Fs;
[b,a] = butter(n,Wn);
p1 = filtfilt(b,a,p);
Wn = 400;
Ws = 400/2;
NFFT = 1024*Fs;
c=mat2cell(p1,[71800 108000 60200],[6]);
ss=c{2,1};
c1=mat2cell(ss,[36000 36000 36000],[6]);
ss1=c1{2,1};                % Profile 2
c2=mat2cell(ss1,[6000 6000 6000 6000 6000 6000],[6]);
ss2=c2{1,1};
c3=mat2cell(ss2,[600 600 600 600 600 600 600 600 600 600],[6]);
ss3=c3{1,1};
c4=mat2cell(ss3,[100 300 200],[6]);
ss4=c4{2,1};
y1=ss4;
c5=mat2cell(ss2,[600 600 600 600 600 600 600 600 600 600],[6]);
ss5=c5{2,1};
c6=mat2cell(ss5,[100 300 200],[6]);
ss6=c6{2,1};
y2=ss6;
c7=mat2cell(ss2,[600 600 600 600 600 600 600 600 600 600],[6]);
ss7=c7{3,1};
c8=mat2cell(ss7,[100 300 200],[6]);
ss8=c8{2,1};
y3=ss8;
c9=mat2cell(ss2,[600 600 600 600 600 600 600 600 600 600],[6]);
ss9=c9{4,1};

c10=mat2cell(ss9,[100 300 200],[6]);
ss10=c10{2,1};
y4=ss10;
c11=mat2cell(ss2,[600 600 600 600 600 600 600 600 600 600],[6]);
ss11=c11{5,1};
c12=mat2cell(ss11,[100 300 200],[6]);
ss12=c12{2,1};
y5=ss12;
c13=mat2cell(ss2,[600 600 600 600 600 600 600 600 600 600],[6]);
```

```
ss13=c13{6,1};
c14=mat2cell(ss13,[100 300 200],[6]);
ss14=c14{2,1};
y6=ss14;
c15=mat2cell(ss2,[600 600 600 600 600 600 600 600 600 600],[6]);
ss15=c15{7,1};
c16=mat2cell(ss15,[100 300 200],[6]);
ss16=c16{2,1};
y7=ss16;
c17=mat2cell(ss2,[600 600 600 600 600 600 600 600 600 600],[6]);
ss17=c17{8,1};
c18=mat2cell(ss17,[100 300 200],[6]);
ss18=c18{2,1};
y8=ss18;
c19=mat2cell(ss2,[600 600 600 600 600 600 600 600 600 600],[6]);
ss19=c19{9,1};
c20=mat2cell(ss19,[100 300 200],[6]);
ss20=c20{2,1};
y9=ss20;
c21=mat2cell(ss2,[600 600 600 600 600 600 600 600 600 600],[6]);
ss21=c21{10,1};
c22=mat2cell(ss21,[100 300 200],[6]);
ss22=c22{2,1};
y10=ss22;
Y=[y1;y2;y3;y4;y5;y6;y7;y8;y9;y10];
EEG = Y(:,4);
for k= 1: Ws:(length(EEG)-Wn);
    x = EEG(k:k+Wn-1);
    [Pxx, Fxx] = pburg(x, 8,NFFT,Fs);
    F = Fs/2*linspace(0,1,NFFT/2);
    dF = max(F)/length(F);
    F1=floor(4/dF);
    F2=floor(7/dF);
    F3=floor(12/dF);
    F4 = floor(20/dF);
    F5 = floor(30/dF);
    alphaPower = sum(Pxx(F2:F3));
    betaPower = sum(Pxx(F3:F4));
    deltaPower = sum(Pxx(1:F1));
    thetaPower = sum(Pxx(F1:F2));
    TotalPower = sum(Pxx(1:F4));
    BrainPower = [deltaPower; thetaPower; alphaPower; betaPower;];
    BrainPower = (BrainPower/TotalPower)*100;

end
```

**For Profile 3**

```
clear all; clc; close all;
p = load('samir 10 august.txt'); % loading subject data
Fs = 200;
% Filter using IIR 5 point Butterworth (0.3-35 Hz);
n = 5; Wn = [0.3 35]/Fs;
[b,a] = butter(n,Wn);
p1 = filtfilt(b,a,p);
Wn = 400;
Ws = 400/2;
NFFT = 1024*Fs;
c=mat2cell(p1,[71800 108000 60200],[6]);
ss=c{2,1};
c1=mat2cell(ss,[36000 36000 36000],[6]);
ss1=c1{3,1};                    % Profile 3
c2=mat2cell(ss1,[6000 6000 6000 6000 6000 6000],[6]);
ss2=c2{1,1};
c3=mat2cell(ss2,[600 600 600 600 600 600 600 600 600 600],[6]);
ss3=c3{1,1};
c4=mat2cell(ss3,[100 300 200].[6]);
ss4=c4{2,1};
y1=ss4;
c5=mat2cell(ss2,[600 600 600 600 600 600 600 600 600 600],[6]);
ss5=c5{2,1};
c6=mat2cell(ss5,[100 300 200],[6]);
ss6=c6{2,1};
y2=ss6;
c7=mat2cell(ss2,[600 600 600 600 600 600 600 600 600 600],[6]);
ss7=c7{3,1};
c8=mat2cell(ss7,[100 300 200],[6]);
ss8=c8{2,1};
y3=ss8;
c9=mat2cell(ss2,[600 600 600 600 600 600 600 600 600 600],[6]);
ss9=c9{4,1};

c10=mat2cell(ss9,[100 300 200],[6]);
ss10=c10{2,1};
y4=ss10;
c11=mat2cell(ss2,[600 600 600 600 600 600 600 600 600 600],[6]);
ss11=c11{5,1};
c12=mat2cell(ss11,[100 300 200],[6]);
ss12=c12{2,1};
y5=ss12;
c13=mat2cell(ss2,[600 600 600 600 600 600 600 600 600 600],[6]);
```

```
ss13=c13{6,1};
c14=mat2cellss13,[100 300 200],[6]);
ss14=c14{2,1};
y6=ss14;
c15=mat2cell(ss2,[600 600 600 600 600 600 600 600 600 600],[6]);
ss15=c15{7,1};
c16=mat2cell(ss15,[100 300 200],[6]);
ss16=c16{2,1};
y7=ss16;
c17=mat2cell(ss2,[600 600 600 600 600 600 600 600 600 600],[6]);
ss17=c17{8,1};
c18=mat2cell(ss17,[100 300 200],[6]);
ss18=c18{2,1};
y8=ss18;
c19=mat2cell(ss2,[600 600 600 600 600 600 600 600 600 600],[6]);
ss19=c19{9,1};
c20=mat2cell(ss19,[100 300 200],[6]);
ss20=c20{2,1};
y9=ss20;
c21=mat2cell(ss2,[600 600 600 600 600 600 600 600 600 600],[6]);
ss21=c21{10,1};
c22=mat2cell(ss21,[100 300 200],[6]);
ss22=c22{2,1};
y10=ss22;
Y=[y1;y2;y3;y4;y5;y6;y7;y8;y9;y10];
EEG = Y(:,4);
for k= 1: Ws:(length(EEG)-Wn);
    x = EEG(k:k+Wn-1);
    [Pxx, Fxx] = pburg(x, 8,NFFT,Fs);
    F = Fs/2*linspace(0,1,NFFT/2);
    dF = max(F)/length(F);
    F1=floor(4/dF);
    F2=floor(7/dF);
    F3=floor(12/dF);
    F4 = floor(20/dF);
    F5 = floor(30/dF);
    alphaPower = sum(Pxx(F2:F3));
    betaPower = sum(Pxx(F3:F4));
    deltaPower = sum(Pxx(1:F1));
    thetaPower = sum(Pxx(F1:F2));
    TotalPower = sum(Pxx(1:F4));
    BrainPower = [deltaPower; thetaPower; alphaPower; betaPower;];
    BrainPower = (BrainPower/TotalPower)*100;

end
```