EEG COHERENCE BIOMARKERS FOR DIFFERENTIATING ATTENTION STATES

ROHIT TYAGI

(M.B.B.S.,

L.L.R.M. Medical College, Meerut, India

M.M.S.T.,

Indian Institute of Technology, Kharagpur, India)

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Declaration

I hereby declare that this thesis is my original work and it has been written by me in its entirety. I have duly acknowledged all the sources of information which have been used in the thesis. This thesis has also not been submitted for any degree in any University previously.

Rohit Tyagi

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Table of Contents

Summary

Selective Attention is an integral higher mental function and helps us in focusing on relevant stimuli or tasks which help in fulfilling our goals. Current research shows that the ability to pay attention depends on interactions between specific areas of the brain – mostly in the frontal and parietal lobes. The actual mechanism of how these areas control and direct attention is incompletely understood and the studies done during this work facilitate our understanding of these processes. Electroencephalogram (EEG) is a way to study the electrical changes produced by neurons in the brain, by applying electrodes on the scalp and indirectly estimate brain's inner functioning. EEG provides comprehensive data which can be processed digitally in both time and frequency domains. During the course of this work various experiments were designed and conducted to collect EEG data. The method to analyze EEG data was to estimate statistically significant connectivity changes between different channels in all the major frequency bands – Delta, Theta, Alpha, Beta and Gamma at short 100 ms intervals.

In different scenarios it might be useful for a person to pay attention to visual information while ignoring auditory information. Visual information might be more important for an image analyst, while for a SONAR operator it might be more useful to pay attention to the auditory. If the control of attention to a particular sensory domain in these conditions falters, it could result in dire consequences. Thus an objective way to estimate whether a person is paying

attention to visual or auditory stimulus was explored by designing a selective attention task. Connectivity analysis of the EEG data revealed that frontal locations were commonly involved, however left temporal locations were more active in the auditory condition, while right occipital locations were dominant during the visual condition.

The response to a particular stimulus could vary with emotional state. For example a person in a negative mood, might find a stimulus irritating, while when in a good state of mind, he might not be bothered by it. An experiment was conducted to modulate emotional states by presenting participants with emotional as well as neutral images while they responded to different auditory stimuli. Connectivity profiles showed Delta band interactions were commonly observed during the negative state while Beta and Gamma frequency bands were predominant in the positive emotional state.

Mind wandering occurs when our attention wanders towards random thoughts while relaxing or even while doing a task. Such episodes of mind wandering could cause serious lapses in attention. A study to estimate such effects on task performance was studied by having subjects do a memory task interspersed with resting intervals. It was hypothesized that in memory trials just after the rest period the subjects would have a decrease in performance. Behavioural measures confirmed this and connectivity changes were observed. Theta band interactions were common during task phase, while the first trial after the resting interval showed a higher number of connections in the Beta and Gamma ranges, possibly indicating high attentional effort.

List of Figures

Acronyms

ACC	Anterior Cingulate Gyrus
ADHD	Attention Deficit Hyperactivity Disorder
AFC	Activated Functional Connections
AR Index	Accuracy-Reaction Time Index
ATP	Adenosine Tri Phosphate
CC	Corpus Callosum
CD	Connectivity Difference
DLPFC	Dorso Lateral PFC
DMN	Default Mode Network
EEG	Electroencephalogram
EPSP	Excitatory Post Synaptic Potential
ERP	Event Related Potentials
FEF	Frontal Eye Field
fMRI	Functional Magnetic Resonance Imaging
IADS	International Affective Digital Sounds
IAPS	International Affective Picture System
IE-ERC	Inter-Electrode Event Related Coherence
IPL	Inferior Parietal Lobule
IPS	Intra Parietal Sulcus
IPSP	Inhibitory Post Synaptic Potential
IT	Inferior Temporal Lobe
K+	Potassium Ion
LC	Locus Ceruleus

LFP	Local Field Potentials
LGN	Lateral Geniculate Nucleus
MEG	Magnetoencephalogram
MGN	Medial Geniculate Nucleus
MPFC	Medial PFC
ms	milliseconds
MT	Medial Temporal Lobe
Na+	Sodium Ion
Pc	Precuneus
PCC	Posterior Cingulate Gyrus
PET	Positron Emission Tomography
PFC	Prefrontal Cortex
PTSD	Post Traumatic Stress Disorder
s	seconds
SCP	Surface Connectivity Profile
SIT	Stimulus Independent Thoughts
SPECT	Single Photon Emission Tomography
SPL	Superior Parietal Lobule
SSz	Set Size
STG	Superior Temporal Gyrus
TPJ	Temporo Parietal Junction
TS	Time Segments
TUT	Task Unrelated Thoughts
V1-V5	Subdivisions of Visual Area
VSTM	Visual Short Term Memory Task

1 Introduction

Attention is a cognitive ability used in most of our activities – perceiving objects in the world, forming memories or recollecting them or processing information to execute goal directed tasks. From moment to moment different objects in the outside world (visual objects, sounds, smells, etc) and the internal world (sensations, feelings, thoughts, etc) attract our conscious attention towards them, making us recognize them and process those stimuli appropriately – either approaching, avoiding or ignoring them. A large part of attention or awareness is also subconsciously working round the clock to make us aware of our surroundings and help us react to sudden changes by instinctual reactions usually to avoid threats. This intricate working of conscious and subconscious attention is controlled by various parts of the brain forming specific functional networks, mostly involving the frontal and parietal lobes of our brains and their interaction with primary sensory cortices (Vossel, Geng et al. 2013).

Whether it is listening to someone speak, reading an article, writing, driving or trying to memorize a phone number or recall what we need to buy at the store – if we are able to do these tasks consciously with focused attention, there is a high probability that we will be able to accomplish it. On the other hand, if our attention wanders we are more likely to miss an important part of a conversation or an article, jumble up the phone number we heard or forget what we wanted to buy at the store. In situations like driving or operating machinery, such lapses could have very detrimental consequences.

Attention also functions as an underlying component of other cognitive processes like working memory, long term memory and decision making. All these processes can be adversely affected if attention abilities are impaired. An objective method of estimating attention could be useful in many scenarios. The sections below describe some such important situations where such a technique could be applied to increase safety or enhance efficiency of performance.

1.1 Cross Modality Attention

In our everyday lives, we are required to switch attention from one area of our environment to another frequently. Some kinds of actions require more focus on visual objects around us (say when looking for a friend on a busy street), while on other occasions we pay more attention to our auditory environment (when listening to an announcement about the departure of a flight on the airport). If someone is hammering a nail in a wall, he might be using both his visual and sensorimotor systems in close conjunction so as to only hit the nail and not his fingers. Sometimes our attention is drawn by some changes inside our body – like pain, heat, cold or pressure changes. Thus we are required to pay attention to our different sensory modalities from time to time.

In industrial and military settings, the ability to keep attention focused on one of our sensory modalities becomes even more important as some jobs require a particular type of attention. A military image analyst might be more dependent on his ability to control and apply his visual attention to discern minute details of satellite images to find regions of interest, while a sonar operator may require being more attentive of incoming sound signals, thus focusing more on his auditory capabilities. While driving we are more dependent on our visual system, though the auditory information could also be useful. A method for objective monitoring of such qualitative changes in attention between sensory modalities could be useful for alerting the user to any inadvertent lapses while performing their tasks.

1.2 Attention modulation by Mental State

Emotions play an important part in our life and it is commonly experienced that under some emotional states people become more attentive to some specific types of stimuli and react to them in a different way than normally. For example, if a person is in an anxious state, he might have an increased startle response to an object which he perceives as threatening (Angrilli, Mauri et al. 1996). It is observed that our ability to focus attention does not remain constant all the time but might depend on our general mental state or mood. As an example imagine someone sitting in his office when the fan starts making an irritating noise. The attention will be immediately drawn to that noise and after a while he might become habituated with it and would be able to ignore it. Consider that this person has a headache and the same situation repeats. It is very likely that in this mental state that person would take a longer time to get habituated to the same physical sound or maybe he would not be able to concentrate on his work at all and would have to get the fan fixed or change his location of work for the time being. Another situation could be that same person being in a conversation with an old friend whom he is meeting after a long time when the distracting noise starts. Being engrossed in such a conversation, he might totally ignore the sound which could be considered irritating in normal circumstances.

Our responses to external stimuli depend not only on the characteristic of those stimuli but also on the internal mental state at that time. It is thus worthwhile to understand how our mental state could affect our attention capabilities and our ability to do different tasks in different mental states.

1.3 Distractions and Default mode network

When a person is sitting idly and has no particular task at hand, it is observed that they have seemingly random thoughts, also known as Stimulus Independent Thoughts (SITs) or Task Unrelated Thoughts (TUTs) (Smallwood, Brown et al. 2012). This is sometimes attributed to the functioning of a specific network of the brain known as the Default Mode Network (DMN) which becomes more activated in such unoccupied scenarios (Raichle and Snyder 2007). It is observed that such kind of mind wandering can also happen when a person is engaged in those complex tasks in which he is thoroughly trained – like while cycling, driving or even working on a factory assembly line. Sometimes while driving people have an experience where they become lost in thought and feel surprised when they ultimately reach their destination without remembering the details of their driving route. This is mostly harmless but if while driving, a person is having such random thoughts and suddenly there is a situation which requires his attention and action to avoid an accident, it is likely he will not be able to process the required information in time compared to when his attention is completely on the road. Thus activation of DMN at inopportune times might lead to deleterious consequences and requires a way to estimate whether a person is processing the external stimuli efficiently or is engaged in such thoughts.

1.4 Neurological Diseases and Disorders

Many neurological diseases have been associated with attention deficits. One of the most commonly seen condition with attention irregularities in kids and adolescents is ADHD, (Attention Deficit Hyperactivity Disorder) whereby the patients are not able to exercise enough control on their attention faculties and this makes them liable to attention lapses. This could affect their ability to study or even make them predisposed to hyperactivity. Many other neurological conditions like Depression, Schizophrenia, Dementia and Alzheimer's Disease etc also have attention disturbances (Basar and Guntekin 2013).

In depression it is seen that patients are more prone to processing negative stimuli in the environment, while becoming less perceptive of the positive ones. In anxiety disorders, patients become inclined to compulsively pay attention to apparently threatening stimuli (Bar-Haim, Lamy et al. 2007). These changes in the control of attention cause many behavioural problems for these patients. An ability to estimate the level and type of attention might be useful in diagnosing and managing these diseases. This could also help in early diagnosis of some diseases, because it has been seen that smaller changes over time add up to finally reach a clinical level of impairment.

1.5 Objectives

The central aim of this work is to utilize the high temporal resolution of EEG and derive functional connectivity estimates to study significant aspects of attention. The following are the main objectives –

1. To design and conduct cognitive tasks to simulate real life situations pertinent to the attention ability – like switching attention between visual and auditory modalities, the capacity to perform sensorimotor tasks while emotional states are modulated experimentally and also to induce wandering thoughts during a short term memory experiment to observe the effect of distractions on performance.
2. To devise and apply EEG Coherence based objective connectivity measures to study neural dynamics of attention processes.
3. To study connectivity dynamics of attention processes at short 100 ms intervals between all EEG surface locations and all major frequency bands.
4. To apply statistical tests to the connectivity measures to uncover those metrics which are the most reliable in delineating attention states under different experimental conditions.

This way, a deeper understanding of the changing interactions between various EEG electrode locations can be obtained in relation to the cognitive tasks and thus further our knowledge about the neurophysiology of the attention system of the brain.

1.6 Thesis Outline

The next **Chapter (Literature Review)** outlines the current understanding of how the brain works in general and various methods to study its functional activity. It further delves into the advantages of using EEG and computing connectivity based metrics from data to estimate attention states. **Chapter 3 (Methodology)** details the general processing steps applied to the data, including statistical tests to derive the surface connectivity profiles at regular intervals. **Chapter 4 (Cross Modality Attention)** describes the experiment where the subject is cued to switch attention between the visual and auditory modalities detailing the protocol and findings. **Chapter 5 (Emotional modulation of Attention)** outlines the experiment where the emotional state of the experiment participants is modulated by showing them emotional and neutral images while they are presented with auditory stimuli. Their responses to these stimuli are analyzed to study how these responses change with varying emotional states. **Chapter 6 (Effect of Mind Wandering on Attention)** describes the experiment where the participants perform a working memory task in blocks of few seconds which are interspersed with rest intervals which would cause their minds to wander. By studying the effect on their working memory performance because of these rest intervals we are able to estimate the detrimental effect of mind wandering on attention and memory. **Conclusions and Recommendations** from the conducted studies are detailed in **Chapter 7**.

2 Literature Review

This section outlines the background information on the current understanding of how the brain works with more emphasis on brain regions and networks responsible for attention modulation.

2.1 Neurophysiology

The nerve cells or neurons are the basic units of the brain and they are partly electrical and partly chemical in their functioning. The basic structure of a neuron consists of a main cell body, dendrites (which receive signals from other neurons) and an axon (which spreads signals to other neurons) (Figure 2.1). The part of the neuron body where the axon originates is called the Axon Hillock and has an important role in signalling between neurons. The axon is usually covered by Myelin sheath which provides insulation and has Nodes of Ranvier which help in faster travel of impulses along the neuron (Kandel 2000).

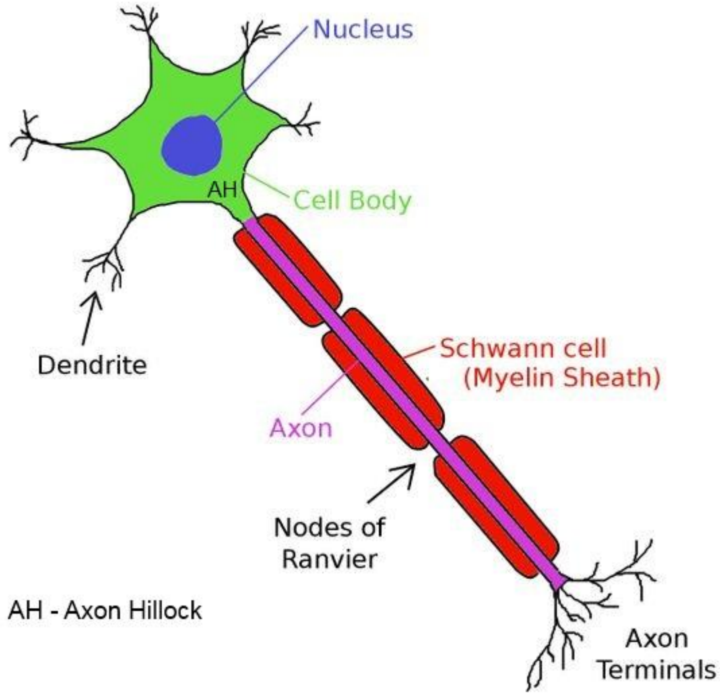

Figure 2.1: Structure of a Neuron [1]

The electrical potential inside and outside of a neuron is different due to the different concentrations of various charged ions like Na+, K+, etc. There is a negative electrical potential on the inside of the neuron compared to the outside of about – 70 mV. When a neuron receives an electrical signal from another connected neuron or sensory receptor this alters the normal membrane potential difference and if it reaches a certain threshold of about – 40 mV at the axon hillock, it causes opening of ion transport channels across the neuron membrane and rapid changes in the potential difference. There is a depolarization phase where the membrane potential rises to about + 40 mV and then decreases back to the resting membrane potential. This return back to the resting membrane potential is called repolarization and is brought about by functioning of active membrane pumps which require energy. These changes travel from the body of the neuron towards its axon terminal from which it may spread to other neurons. This phenomenon is known as an Action Potential or “firing” of a neuron in more common terms (Figure 2.2). This phenomenon lasts for 2-4 ms. After each action potential, the neuron has a refractory period of a few milliseconds (ms), during which if it cannot fire again even if it receives an electrical stimulus above the threshold (Koester and Siegelbaum 2000). Neurons keep firing at some basal rates even when not receiving any inputs from other neurons. Their probability of firing increases if their membrane potential increases towards the threshold value or decreases if the potential become more negative, thus makes them less excitable. These kinds of changes in potentials which increase of decrease the likelihood of firing of a neuron without essentially causing an action potential are known as Excitatory Post Synaptic Potential (EPSP) and Inhibitory Post Synaptic Potential (IPSP) (Kandel and Siegelbaum 2000).

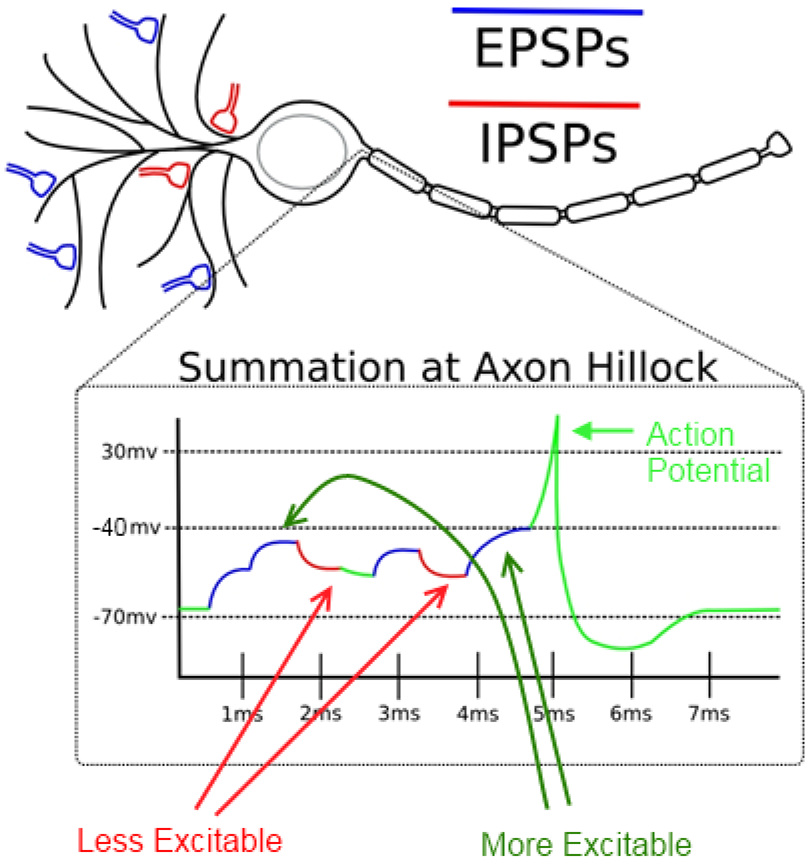

Figure 2.2: EPSP and IPSP [2]

While the action potential travels along the length of a neuron by electrical means, its connections to other neurons are chemical in nature. At the axon terminal neurotransmitters are released which travel to the next neuron. These neurotransmitters could either be excitatory – meaning they could activate or increase the firing rate of the next neuron, or they could be inhibitory – meaning they could deactivate or decrease their firing rate. Thus when a neuron receives an electrical stimulus, it responds usually by altering its action potential firing rate – either increasing or decreasing it depending on the neurotransmitter released from the previous neuron (Schwartz 2000).

A large part of the brain is made up of the Cortex, which is divided into the left and right hemispheres. This is the part which is on the upper and outer side of the brain. There are other subcortical structures of the brain which are smaller in size and located at the central part of the brain under the cortex, but they still have a lot of functional significance (Figure 2.3). Thalamus acts as a relay station for incoming and outgoing signals to and from the brain. Hypothalamus regulates hunger, thirst and body temperature in addition to having some hormonal functions. Amygdala is associated with emotions while Hippocampus is very important for memory. Cerebellum is another component of the brain which is located at the back and lower part of the brain and helps in fine motor coordination and recent research is indicating it could even have cognitive functions. Basal ganglia is involved in motor control (Amaral 2000).

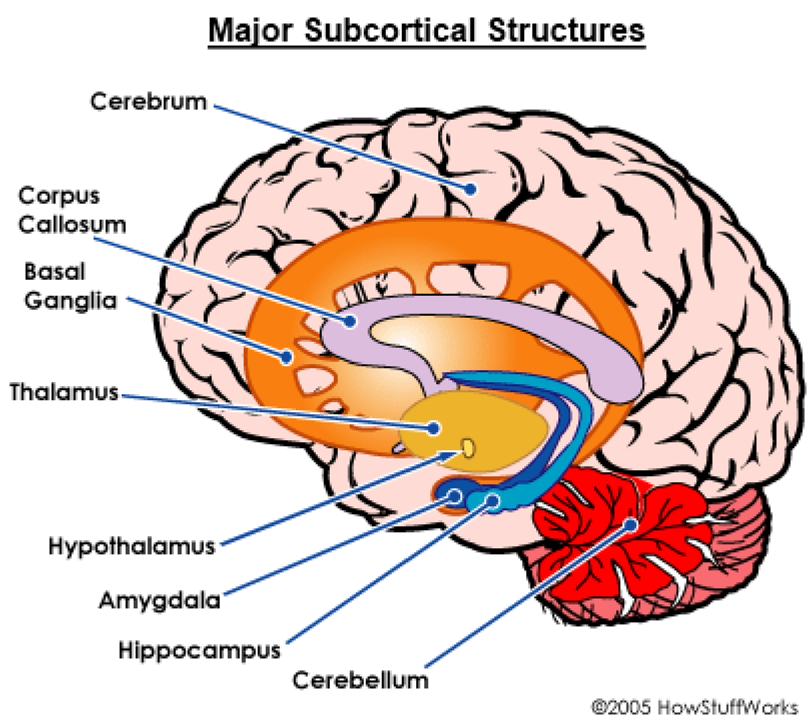

Figure 2.3: Subcortical Structures [3]

The macrostructure of the cortex or Cerebrum or the cerebral cortex can be differentiated into four major lobes – the Frontal lobe at the front, the Parietal lobe at the top, the Occipital lobe at the back of head and the Temporal lobe at the sides (Figure 2.4). The brain has many grooves and bulges on its surface and some of them are consistently found in all people, though some individual variation does exist. These grooves and bulges (scientifically knows as sulcus and gyrus, respectively) are used to demarcate areas in the brain which can then be helpful in naming them and then studying brain functions of different areas systematically.

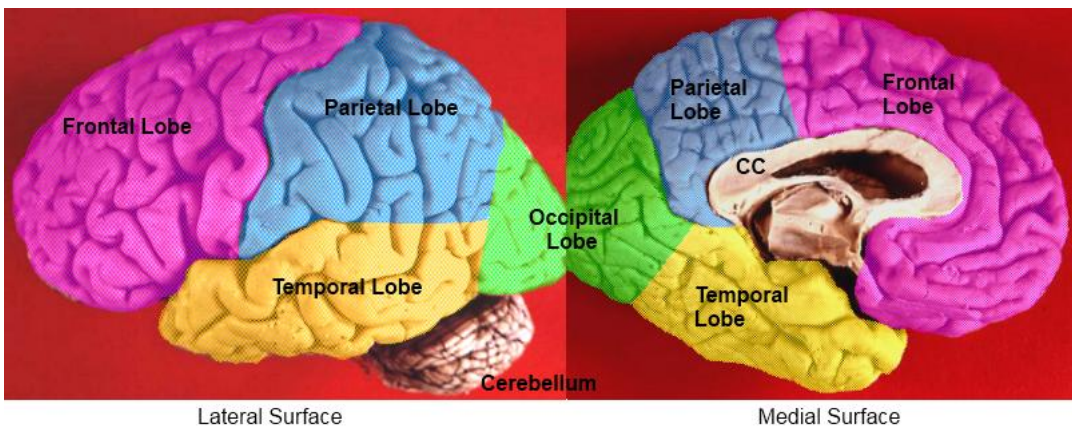

Figure 2.4: Major Cortical Lobes [4, 5]

Classically, each of the cortical lobes has been considered to be involved in different cognitive functions. The frontal lobe is said to be the seat of higher cognitive functions like decision making, working memory, attention and inhibitory control. The parietal lobe is helpful in sense of spatial dimensions and position of the body and other objects is space. It also serves some abstract numerical functions and attention modulation. The occipital lobe is mainly involved in visual functions while the temporal lobe is necessary for auditory function and memory (Figure 2.5) (Kandel 2000). As our understanding of the brain progresses, it is becoming increasing clear that many of the higher cognitive functions not only reside on just one lobe or area, but usually require interaction between many areas of the brain (Engel, Fries et al. 1999). For example to carry out a memory task, it would require integrated control of memory, attention, perceptive and motor areas of the brain. Thus close cooperation between parts of the frontal, temporal, parietal and occipital lobes would be required for successful execution of such a task. These different lobes are further subdivided into smaller parts and it has also been seen that many functions are highly specialized for certain parts of the cortex.

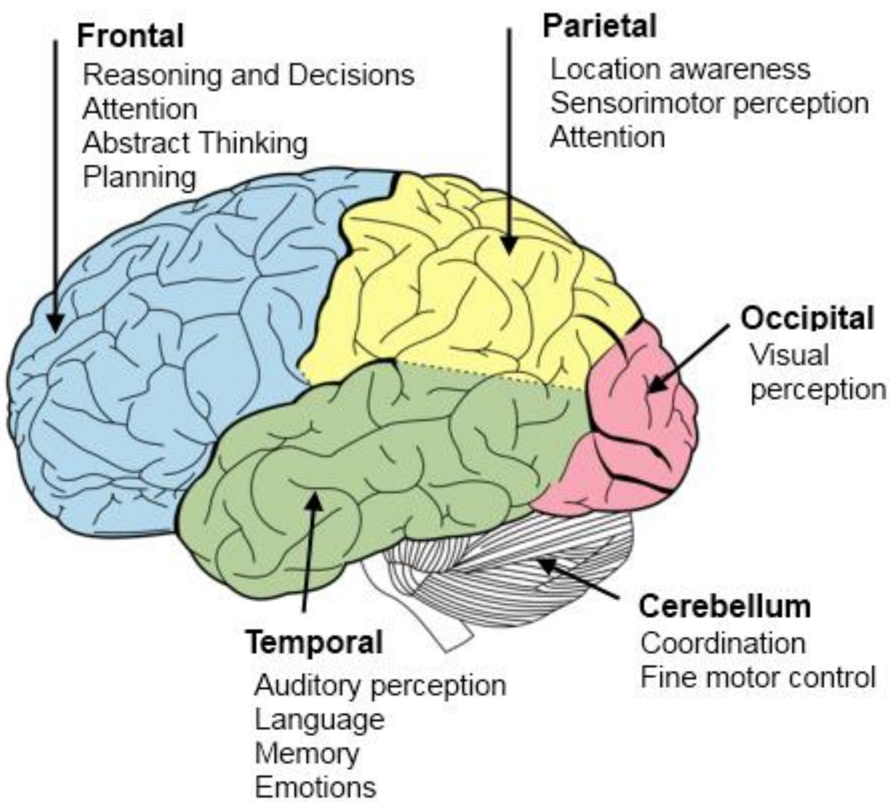

Figure 2.5: Cortex and Cerebellum: Main Functions [6]

It should be noted that one side of the brain receives sensory inputs from the opposite side of the body and also controls that side. For example, a sensation of touch on the right arm will reach the left sensorimotor cortex and if that arm has to be moved, the left motor cortex gets activated and makes that action possible. Both the cortices have numerous interconnections through Corpus Callosum (marked CC in Figure 2.4), which connects corresponding parts of the left and right cortices by nerve fibres.

The structure of the brain is fairly similar on both sides of the brain, yet some of the functions are specialized more on one hemisphere than the other. This is especially seen in the domain of language where the left cortical hemisphere plays the dominant role (Morillon, Lehongre et al. 2010). If an adult suffers some neurological injury in the small region of the left temporal lobe, he will likely lose a lot of his speaking or comprehension abilities. In general, the left hemisphere is considered more involved in logical thinking and engages in analytical thinking, details, rational thought, arithmetic, verbal communication, ordering and planning. The right hemisphere on the other hand does more abstract thinking like engaging in intuition, holistic perception, emotions, creativity and non-verbal communication (Corballis 2012).

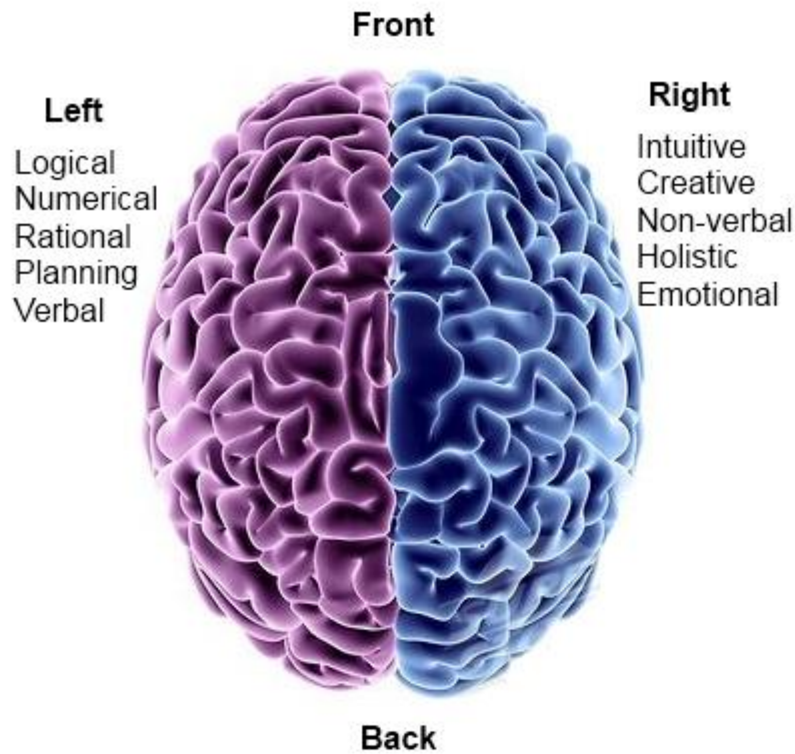

Figure 2.6: Lateralization [7]

The information from the external environment is processed in a mostly sequential manner by the brain. There are some areas which receive signals from peripheral receptors and they are known as primary cortices. The primary visual cortex is in the occipital cortex, the primary auditory cortex is in the temporal lobe and sensory information like the sensation of touch, pressure and temperature on the skin and position of various joints in the body is processed by Primary Sensory area in the parietal lobe. Information from these areas is passed on to the corresponding Secondary areas where further features from the stimuli area extracted and perceived. This processed information then reaches Association areas, which combine information from various primary and sensory cortices to lead to a more complete perception of objects around us (Saper, Iverson et al. 2000).

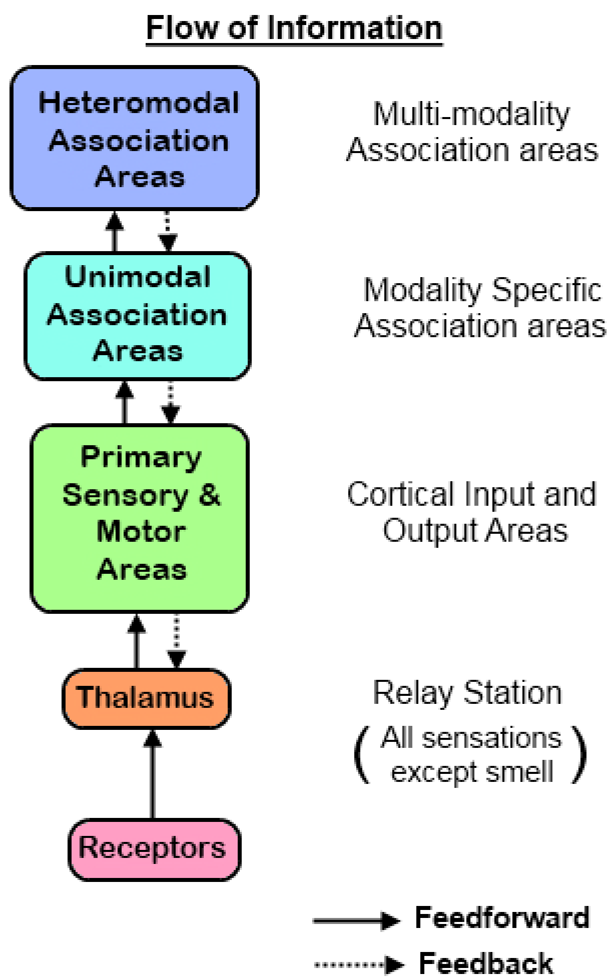

Figure 2.7: Primary, Unimodal and Heteromodal Association areas

The neurons are the basic working units of the brain and are arranged in six layers in the cortex. Neurons are usually activated in groups which form networks in the brain to carry out their different functions. These layers of neurons receive information from other neurons and process it and the information is then passed on to the next layer or to the next relevant part of the brain (Amaral 2000). This layered activation of different neuron layers adds to the complexity of the sequential order of activation of the primary, secondary and association cortices. This hierarchy of activation is very easy to observe in the visual cortex (Figure 2.8). The visual information from the retina in the eyes first reaches a part of the Thalamus (Lateral Geniculate Nucleus) which could processes very simple visual objects like dots. The information then progresses to the Primary Visual area V1 in the occipital cortex which can process lines, orientation and some color. The next area in the visual processing hierarchy is V2 and parts of V3 and VP which mostly act as relay stations. From here on the information proceeds along two different paths – one called the “Where” path which deciphers the location and spatial relational information about the visual objects, and the other path is the “What” path which decodes more detailed visual information like texture, shapes and identifies complex visual objects (Ungerleider and Haxby 1994). In the “Where” pathway, which moves information towards the Parietal cortex, V3 processes some shape information, while V3a and MT (Medial Temporal) regions process movement information. In the “What” pathway which moves information ultimately to the IT (Inferior Temporal) cortex, the V4 area recognizes the color and 2D and 3D shapes. The heteromodal association areas in the Inferior Temporal cortex then extract complex features from the signals and perceive visual objects as a whole (Kandel and Wurtz 2000, Smith, Singh et al. 2001, Dougherty, Koch et al. 2003).

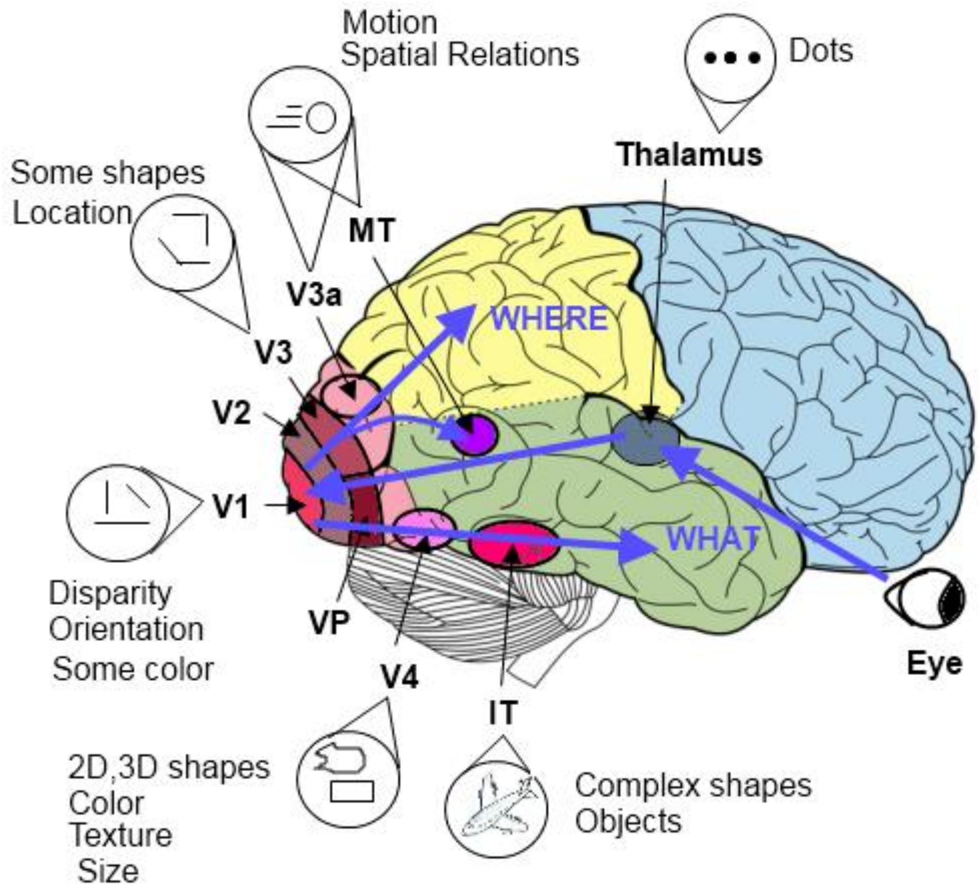

Figure 2.8: Hierarchy of visual area [6]

Thus for successful perception of an object, a systematic processing of the incoming visual signals from the retina is necessary. If for example a person has damage in the V4 area, he might not be able to see colours, even though there is no deficiency in the eyes (Zeki and Bartels 1999, Bouvier and Engel 2006). Similarly someone with V5 damage would not be able to perceive motion in his visual environment (Zeki 1991, Blanke, Landis et al. 2002). Recent research has implicated the frontal premotor areas in perception of motion (Saygin 2007). Other sensory signals from peripheral receptors are also similarly processed systematically and mostly sequentially in different areas of the brain. Sound signals are processed mostly in the auditory cortex in the temporal lobe which sends information also to frontal and parietal lobes (Ahveninen, Jääskeläinen et al. 2006), while touch and some other sensory signals are processed in sensorimotor cortex in the parietal lobe (Gardener and Kandel 2000). The signals from internal receptors of the body usually are processed in the insular cortex (Critchley, Wiens et al. 2004).

2.2 Neuronal circuits and Interaction between areas

As advancement is made in understanding of cognition, instead of just focusing on particular areas which carry out single functions, there is a shift towards studying how different areas interact with each other while cognitive functions are carried out. It has been seen that higher association areas in frontal, temporal and parietal lobes are involved in many tasks, because it is there that most of the information integration and planning for action takes place (Saper, Iverson et al. 2000, Achard, Salvador et al. 2006). It has also been observed that a single brain region could be associated with carrying out different functions. Furthermore there are feedback connections from higher areas to lower areas which help in modulating the perception (Lamme, Super et al. 1998).

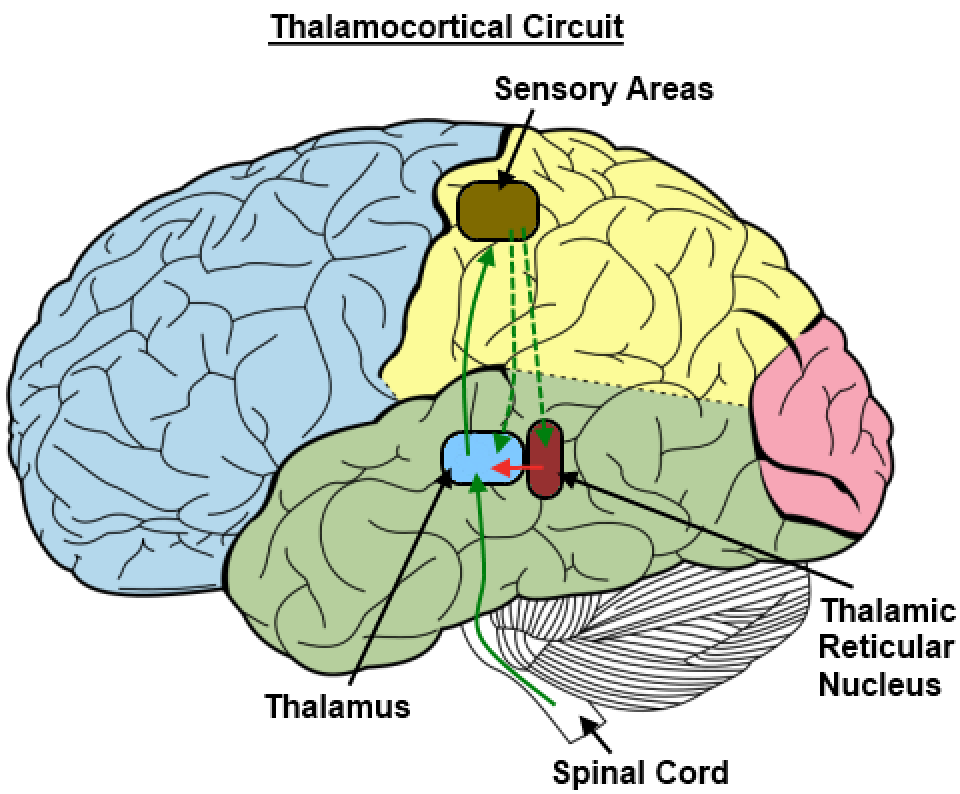

Figure 2.9: Thalamocortical Circuit [6]

The very basic function of the brain is carried out by neuronal circuits and for cortical functioning the Thalamocortical loop is very vital (Figure 2.9). This loop or circuit is usually formed by a Pyramidal neuron in the cortex, a neuron in one of the nuclei of Thalamus and one neuron from the Reticular nucleus of the Thalamus. The Reticular nucleus of the Thalamus contains inhibitory neurons, which receive signals from various cortical regions and inhibit the corresponding thalamic neurons. Different nuclei in the Thalamus relay information from receptors to different cortical regions and thus are involved in different functions (Saper 2000). For example the Lateral Geniculate Nucleus relays the Visual information from retina in the eye to the visual cortex in the occipital lobe, while the Medial Geniculate nucleus is involved in transmitting auditory information from the ears to the auditory areas in the temporal lobe (Amaral 2000). Some other nuclei send information to the Limbic or emotion processing subcortical regions like Amygdala. This passage of some less processed information directly to emotion regions is especially useful in providing instinctual actions against threats (Liddell, Brown et al. 2005). For example if on a dark path in a forest someone sees a coiled object, this information could reach the Amygdala quickly and cause the person to become alert and think it might be a snake. Once more information from the Thalamus reaches to the visual cortex and processing takes place, it can be realized that it is just coiled rope and the person can move on. The cortex then helps in moderating the emotional response (Ohman 2005). This kind of parallel processing for threats in the environment is very important in evolutionary terms.

The neurons in different areas keep firing at some basal rates even when not actively involved in a task. Furthermore their activation levels increase and decrease with time – so that their likelihood of firing an action potential keeps changing (Figure 2.10a) (Koester and Siegelbaum 2000). Such changes in activation levels and likelihood of firing action potentials are controlled by subcortical regions including Thalamus through the Thalamocortical circuits and Locus Coeruleus (McCormick, Shu et al. 2003, Bouret and Sara 2005). This provides one very important aspect for information transfer between different regions. For interaction to take place between any two areas there should be a physical connection between the neurons of those two areas, either directly or indirectly. In addition to that, the two regions should be synchronized – meaning they should have similar activation or deactivation at the same time. If for processing a visual object, information has to travel from the V1 area to the V4 area at a particular time and V1 area is activated and firing but the V4 area is deactivated and not able to fire – then even in presence of physical neuronal connections, the chances of information transfer are very less. On the other hand if at that time both V1 and V4 are in an activated state – meaning both those areas have a high probability of firing, then any action potentials from V1 can reach V4. Such areas are said to be synchronized or coupled (Fries 2005).

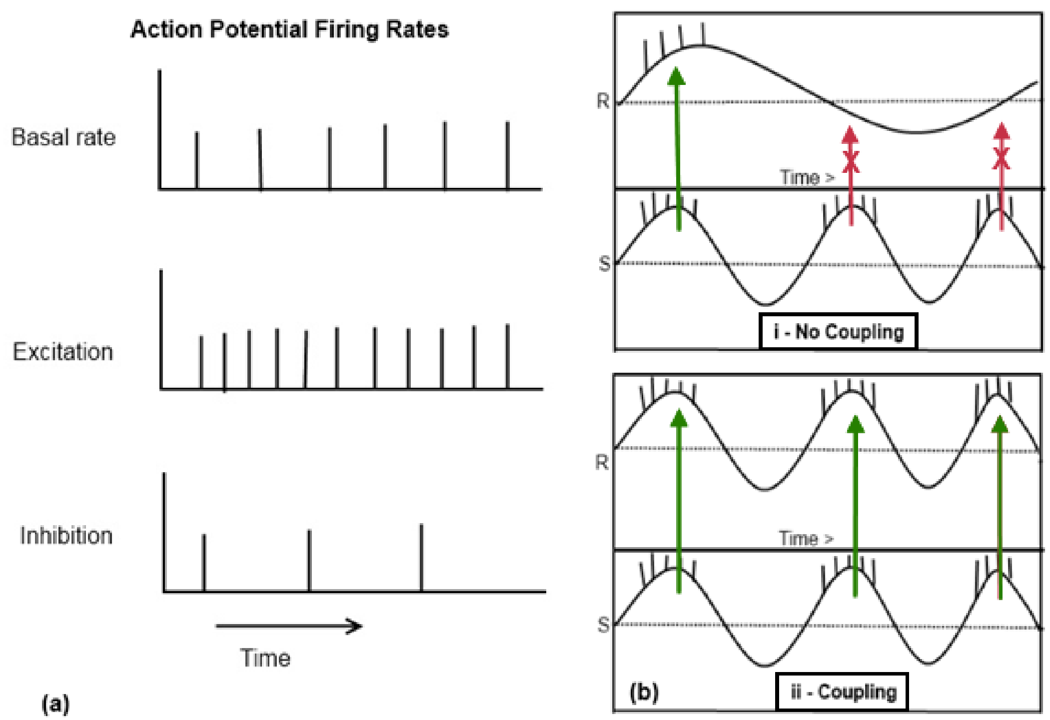

Figure 2.10: Coupling or Synchronisation

If any two areas are coupled and connected then the chances of information transfer between them increases (Figure 2.10b(ii)), while if they are not coupled, the information transfer is not efficient (Figure 2.10b(i)).

2.3 Studying the brain

The previous sections have outlined the basic mechanisms of brain functioning and will help in understanding how those internal processes could be studied from the outside.

Intracranial electrodes can be inserted in experimental animals and in humans undergoing epileptic assessment to study the firing characteristics of a small number of neurons in the brain (Zumsteg and Wieser 2000). This method provides a very direct view of how the neurons fire while processing particular stimuli. There are about 100 billion neurons in the human brain and each could make about 1000 to 10000 connections with other neurons (Sporns, Tononi et al. 2005). Thus it is not possible currently to study all the neurons involved in a function, but still provides insights when used on specific parts of the brain. These electrodes can come in the form of needle like probes (Figure 2.11-A) which could contain multiple contact points and thus can collect electrical signals from neurons at various depths. They could also be in the form of plates where electrodes arranged on them make contact with the flat surface of the brain (Figure 2.11-B and C). These electrodes are used to plot firing characteristics of individual or small groups of neurons. Since this is an invasive procedure, it cannot be used freely in human studies and the results from animal studies give only a limited knowledge about human brain functioning (Lachaux, Rudrauf et al. 2003).

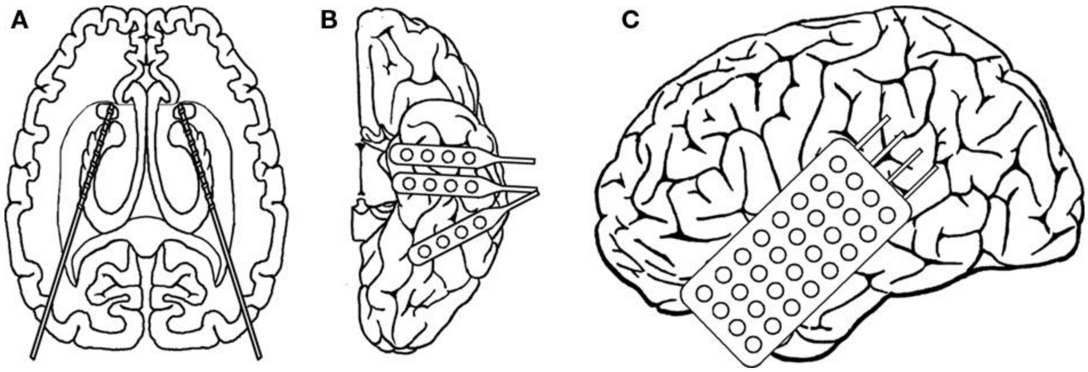

Figure 2.11: Intracranial recording [8]

The neurons function by receiving electrochemical inputs from other neurons or peripheral receptors. Depending on the kind of input received, whether excitatory or inhibitory, they increase or decrease their action potential firing rate respectively. These action potentials are then spread to other neurons connected to its axon terminals. Since these changes in membrane potential of neurons are an electrical activity, like the passage of a current through a wire, it causes electrical potential changes on the scalp. These changes can be studied by applying conducting electrodes on the scalp and collecting the signals. This is the principle for the use of Electroencephalogram (EEG). It is similar in some ways to acquiring an Electrocardiogram (ECG) where electrodes are applied on the hands, feet or chest of an individual to observe the electrical activity of the heart. EEG is explained in greater detail in a later section. This method has good time resolution and data with high sampling rate can be collected easily. The data can be analyzed using various methods in time and frequency domains. The instrument which is used to collect data can be small and portable, thus making this method ideal for use in field conditions. One drawback of this method is that it is difficult to derive the exact brain sources of EEG signals on scalp. Though many methods using brain modelling are in use for extracting brain sources, these have their limitations (Michel, Murray et al. 2004). The effect of noise caused by other activity like eye blinking, muscle movements, etc can also contaminate the EEG data if care is not taken while data collection.

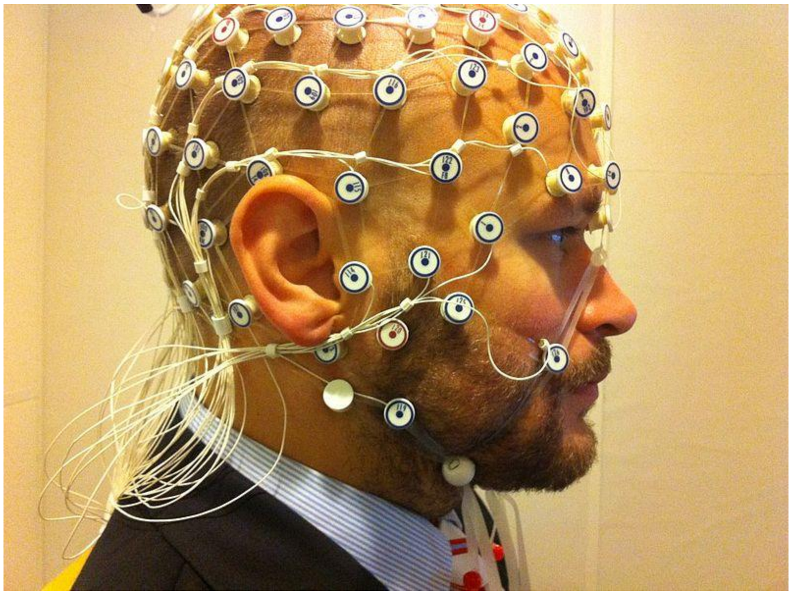

Figure 2.12: EEG [9]

The membrane potential changes in neurons and their passage along axons also causes magnetic changes, just like passage of current through a wire creates changes in the magnetic field around it. These changes can be studied by using a Magnetoencephalograph (MEG) which consists of magnetic sensors arranged around the head of study participants (Hillebrand, Singh et al. 2005). Since these magnetic signals are very small in amplitude it becomes necessary to place the subject and the MEG machine inside a magnetically sealed room, so that noise interference can be minimized (Shigeto, Morioka et al. 2002). MEG has good time and spatial resolution of sources but since the data collection is carried out in a magnetically shielded room, this kind of equipment is not ideal for collecting brain signals in outdoor scenarios.

Figure 2.13: Magnetoencephalography [10]

When a neuron or group of neuron gets activated while getting excitatory signals, it increases its action potential firing rate. This means it will fire repeatedly at short interval and thus the phenomena of depolarization and repolarization will occur frequently. The repolarization part of the action potential is active in nature, meaning it requires cellular energy (usually in the form of ATP) to get the membrane potential back to its resting state. The brain produces energy from glucose and oxygen which are delivered to brain cells through blood. When a part of the brain is activated it extracts more oxygen from the blood in that area. This leads to a lower concentration of oxygen in the blood vessels in that area. Due to this decrease in oxygen concentration the blood supply to that area is increased by vascular mechanisms and thus more oxygen and glucose are delivered to that active area. The change of oxygen concentration in blood can change its magnetic properties. Magnetic Resonance Imaging (MRI) works on the principle of different body areas and tissues having varied magnetic properties. This helps in imaging the different body tissues in great detail. Blood Oxygen Level Dependent Functional MRI or BOLD fMRI utilizes this ability of MRI to differentiate between the magnetic properties of blood with higher or lower oxygen concentration (Ogawa and Lee 1990). By utilizing signal processing techniques fMRI can display those areas in the brain which are active or inactive in various tasks or in disease conditions. This makes fMRI an important way to study the brain in good structural detail (Logothetis and Pfeuffer 2004). Other ways of processing MRI data can also give information about the layout and connections of neuron fibre tracts in the brain. The drawbacks of MRI are high cost of the machine and the large size which makes it impossible to deploy in field scenarios. fMRI data is time averaged; meaning a resulting image from data processing represents brain activity over a period of few seconds (Detre and Wang 2002). Thus the time resolution of this method is not good enough to study the sequence of activated brain areas involved in a task (Heeger and Ress 2002). It is also possible that smaller activated areas might not be discernible with this method for certain tasks (Brazdil, Dobsik et al. 2005).

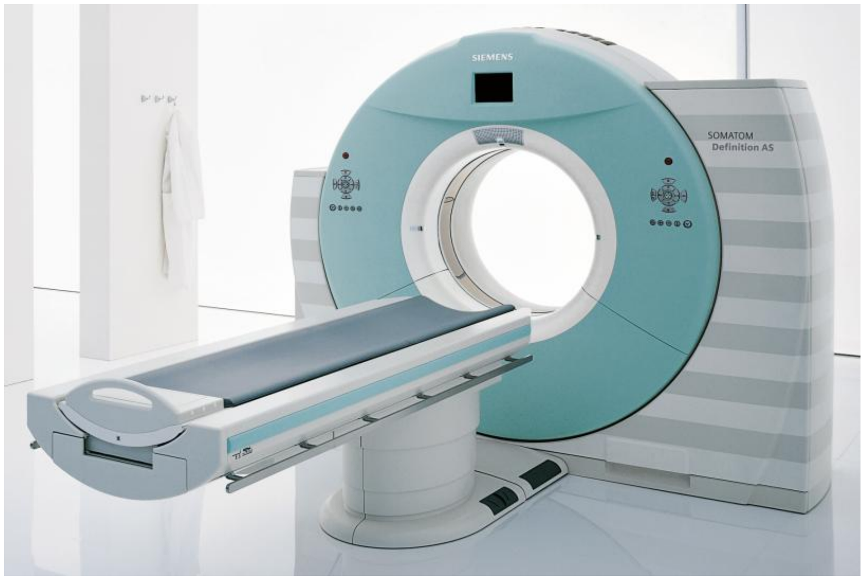

Figure 2.14: M.R.I. Machine [11]

Figure 2.15: PET and SPECT machines [12, 13]

As mentioned above, an active part of the brain will require more oxygen and glucose to continue functioning. This is achieved by increasing the blood supply to the active areas. Some safe radioisotopes when coupled with glucose can be used to study these activity changes in the brain. Positron Emission Tomography (PET) and Single Photon Emission Computed Tomography

(SPECT) are such techniques (Phelps 2000). These methods have good spatial resolution but the machines are also large and expensive, thus not suitable for making portable devices

Figure 2.16 depicts the summary of the main methods which can be used to study the brain structure and function at different levels – from cell level recording to network and region based methods.

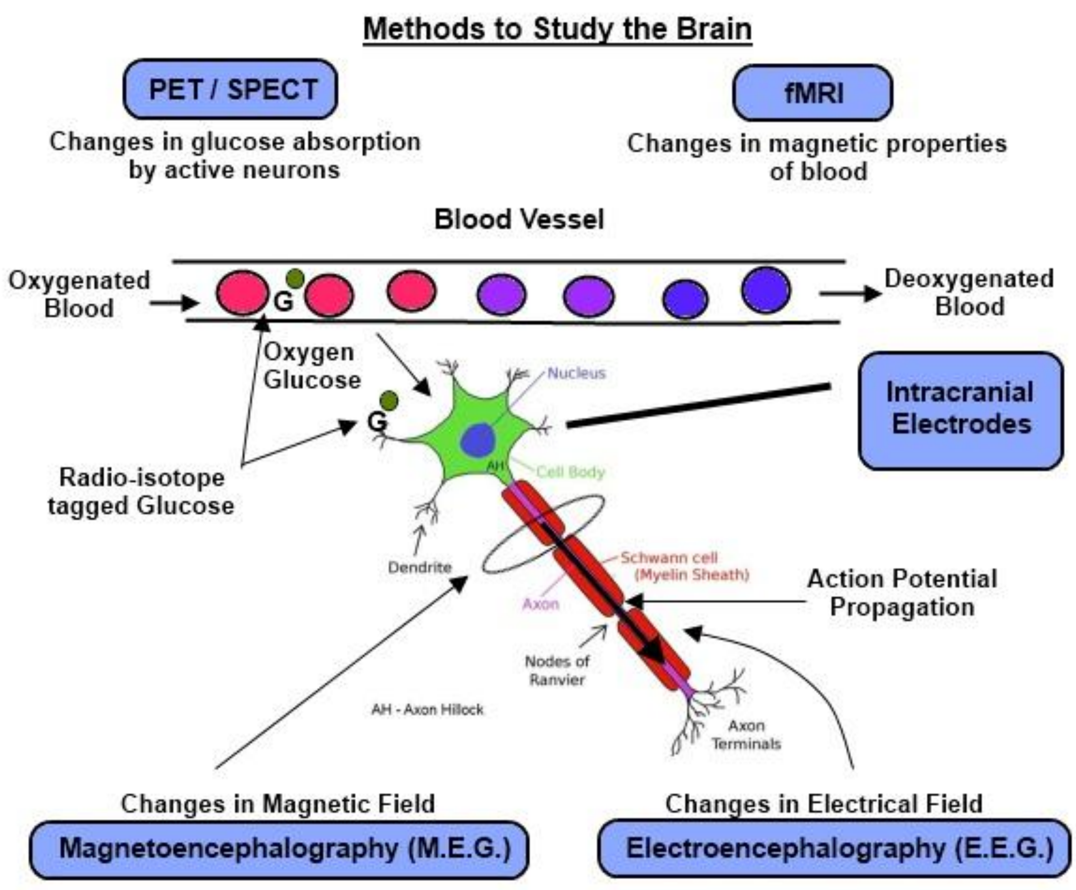

Figure 2.16: Methods to Study Brain Activity

2.4 Other methods to monitor attention

The problem of monitoring attention is important in many scenarios – driving, aviation, industrial work and the military. Many car manufacturers are trying to develop and deploy technologies which would alert the drivers in case their attention wanders. It should be mentioned here that driving is a primarily visual task, thus monitoring of visual attention is primary. For this eye gaze, pupil size and blinking based measures can be utilized by integrating eye-trackers in the car dashboards (Mathôt, van der Linden et al. 2013). Gaze position gives an estimate of the direction in which the person is looking and some regions of interest can be defined which can help in determining whether the driver is paying attention to the task or has become distracted. If the gaze is positioned on the road, the rear view mirrors or sometimes at the instrument cluster this could be taken as a good sign, while if the gaze is detected to be at irrelevant areas, this could be a sign of concern (Zhao, Gersch et al. 2012). Eye blinking frequency and the duration of each blink can also be used as a warning system for sleepiness. When a person gets sleepy, the frequency of blinks increases along with the duration for which eyes are kept closed during blinks. If the eyes remain closed for a couple of seconds and there are sleep like characteristics found, then these are known as microsleeps, which are considered very dangerous during driving. Distinct changes in the activity of the frontal and parietal brain regions have been observed during these microsleeps (Poudel, Innes et al. 2014). Thus eye tracking provides a signal about the internal mental state of the driver and is being implemented by different car manufacturers. Once sleepiness is detected a sound alarm can be activated to make the driver more alert to continue driving or to take a break if needed. There are some other assistive devices which could be used as a warning system. A small device containing accelerometers can be mounted on the ear and tracks the driver's head position. If the head position starts changing and it is detected that the driver is nodding off, then a vibration or sound alarm can be activated to alert the driver. Other techniques for head position monitoring using cameras also work on the same principle. One major downside of this particular method is that it will only activate an alarm once the head position has already changed – and by then the car might have already changed a lane or gone off road.

The eye tracking based attention sensors are easier to implement and more reliable than the head position based sensors, however the positioning of the cameras is critical for these devices to function properly. If the camera cannot see the pupil of the eye and the reflections given off from the cornea, the gaze position will not be accurately calculated. This can happen due to lighting issues, drivers using spectacles and also if the driver is looking away. In these cases, a direct brain monitoring device based on EEG could be a better solution, since it is the brain that is controlling the attention. Secondly, if a person is daydreaming while driving, it is likely that his gaze will be fixed at the road, however instead of efficiently processing the visual cues from the road, his attention will be internally directed at mentation or planning. In these cases, an eye tracker based system would not be able to correctly identify whether the driving is in a dangerous situation. In these cases an EEG based monitoring system would be more robust because it will detect a change in brain functioning when a person switches from external to internal attention. Recently EEG connectivity changes, especially in the Theta band, have been observed during microsleeps (Toppi, Astolfi et al.

2012). Another advantage of an EEG based solution is that it can be used effectively not just for visual attention monitoring but also for other type of attention like auditory attention, because for different working environments, different attention modalities would be important for monitoring. Considering these points, it is advantageous to have an EEG based system to provide reliable and versatile attention monitoring in different settings. However, it should also be mentioned that these peripheral methods could be used in tandem with EEG methods to make the overall system more robust and reliable.

2.5 EEG

The electrical activity of the neurons going on inside the skull produces some potential changes on the on the scalp, which can be measured and collected by applying electrodes on the scalp. This technique is known as Electroencephalogram or EEG and was first used by German neuro-psychiatrist Hans Berger in mid 1920s (Berger 1929, Millett 2001, Stone and Hughes 2013). There is a standardized procedure of applying the EEG electrodes on the scalp called the 10-20 system (Figure 2.17) (Jasper 1958). Recently, the number of the electrodes can range from 62 to 256 and even more for which denser electrode configurations like 10-10 or 10% and 10-5 (Oostenveld and Praamstra 2001) systems have been proposed (Jurcak, Tsuzuki et al. 2007). The position of the electrode is determined by measurements taken from some bony prominences on the scalp – like the nasion in the front and inion at the back of the head. The electrodes are named by their location and whether they are on the left or right side of the head. The brain is divided into four major lobes – the Frontal lobe on the front, the Parietal lobe on the top, the Occipital lobe at the back and the Temporal lobe at the sides of the brain. Thus EEG electrodes roughly on those positions have F, P, T and O in their names. In denser electrode configurations electrodes positioned on overlapping regions could have two letters – for example an electrode over frontal and parietal can be named FP. In addition to letters, these electrodes also have numbers associated with them for easy identification. The electrodes on the left side have odd numbers while those on the right side are given even numbers. The electrodes on the center of the head have a "z" in their names.

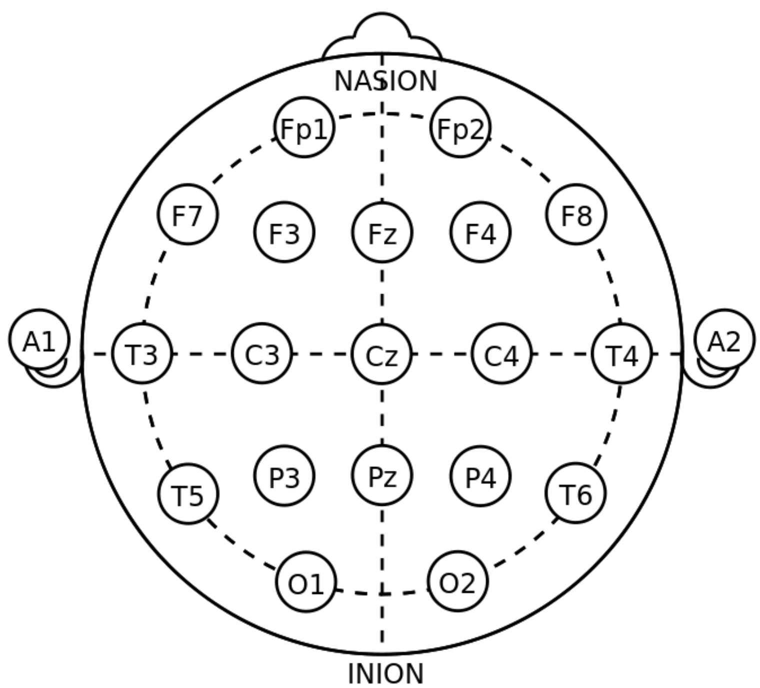

Figure 2.17: EEG 10-20 System [14]

In recent times instead of manually applying single electrodes, there is increasing use of EEG caps made by manufacturers which position the electrodes on a cap made of slightly elastic material. This cap when put on the head of a subject carefully aligns the electrodes in the standard positions (Figure 2.18). Since the electrodes need to make electrical contact with the scalp, a liquid or gel paste is usually injected between the electrode and scalp so that electrical signals can pass to the electrode and thus be recorded. These electrical signals on the scalp are of very low magnitude, thus an amplifier is needed to boost the signals. Furthermore as with any other electrical signal, there is a chance of noise distorting the EEG signal, which could partly be reduced by using various filters and other signal processing techniques.

Figure 2.18: EEG cap and Amplifier (ANT-Neuro) [15, 16]

As previously outlined in Section 2.1: Neurophysiology, the basic building block of the brain is the Neuron or Nerve cell and information processing happens by electrochemical activity in these cells – represented by short duration action potentials (AP) and longer duration changes in resting membrane potentials called as Excitatory Post Synaptic Potential (EPSP) and Inhibitory Post Synaptic

Potentials (IPSP). The AP lasts for about 2 ms and can be easily detected by intracranial measuring electrodes. However, because this potentials reduces rapidly with distance from the neuron, it does not have a major contribution to the scalp EEG signal (Henze, Borhegyi et al. 2000). Another reason for non-contribution of AP to EEG is that since this activity lasts for a very short duration, the temporal summation of individual APs does not occur enough to give rise to a resulting changes in scalp potentials.

The main contributors of EEG are the slower potential changes like EPSP and IPSP which give rise to Local Field Potentials (LFP). These LFPs are maintained in the neurons for longer period of time, thus there is a high possibility of their summation both on temporal and spatial domains. It should also be mentioned that due to the structure of the brain, it is common to see neurons which are closer together to receive inputs from same or neighbouring nerves or other brain regions. Thus usually a cluster of neurons becomes active at the same time, in response to an external or cognitive stimuli (Logothetis, Pauls et al. 2001). Among all the cells in the brain, the pyramidal cells are considered to be the main source of EEG, since they are arranged perpendicular to the cortex thus any potential changes occurring in their apical or basal dendrites will lead to changes in the scalp EEG potentials (Murakami and Okada 2006). Since the brain and the surrounding CSF (Cerebrospinal fluid), skull and scalp behave like a volume conductor, the surface EEG activity is generally a summation of all the underlying polarized neurons which generate an open field. This results in an equivalent dipole which combines all the component dipoles caused by distinct brain regions (Scherg, Vajsar et al. 1989).

Volume conduction could be considered a double edged sword – it makes it possible for electrical changes occurring in the brain reach the scalp, where they could be collected and studied, but it also results in EEG being a summation of all the current ongoing activity in the brain which makes it difficult to tease out the exact location of the sources of these electrical changes. This is called the "Inverse Problem", whereby getting a unique result of underlying sources of EEG is considered almost impossible, without applying forward modelling to constrain the solution space. Various studies have suggested different sizes for the minimum cortical area which needs to be activated – so that it can be detected in the EEG, ranging from 4 to 6 square cm (Hamalainen, Hari et al. 1993, Murakami and Okada 2006). Initially it was suggested that EEG results only from the cortical area closest to the scalp and that regions like hippocampus and amygdala do not contribute to the EEG – because of their depth and closed structure. However, studies have shown that these structures can also contribute to the EEG (Lantz, Grave de Peralta Menendez et al. 2001, Michel, Lantz et al. 2004).

In summary, EEG signals are produced by spatial and temporal summation of underlying neurons, mostly from the superficial cortical layers but also from deeper structures. The pyramidal neurons are the main contributors in the cortex due to their perpendicular orientation to the scalp.

Exactly how each neuron or groups of neurons contribute to the EEG is a matter of intense analytical and modelling research. An early model used a concept of neurons as groups of nonlinear coupled differential equations with interactive properties and closely matched recorder EEG (Freeman 1986). Efforts were also made to model different neurons individually instead of treating them in groups and here the output matched the alpha band rhythmic activity in the brain (Lopes da Silva, Hoeks et al. 1974). A more recent approach combined some features of both lumped and individual modelling to propose a model of cortex where excitatory and inhibitory neurons interact both in the short and long ranges to bring about oscillatory activity (Liley, Cadusch et al. 1999). Other researchers worked on explaining the effect of anaesthesia where a sudden switch of cortical functioning happens from a conscious to an unconscious state. This was explained by some steady states which existed due to interaction of cortical neurons and switching was triggered due to different concentrations of the anaesthetic (Steyn-Ross, Steyn-Ross et al. 2004). Thalamus is a structure where almost all of the traffic to and from the brain goes through and some models tried to incorporate this important structure while explaining the oscillatory activity in the brain (Golomb, Wang et al. 1996, Destexhe and Sejnowski 2003). The neuronal generator itself has been modelled in different ways to match and explain its neurophysiological properties (Avitan, Teicher et al. 2009). Any interested reader is advised to follow the various referenced articles to delve deeper into various analytical, mathematical and computational approaches associated with EEG sources.

EEG signals can be processed using two broad methods – time domain and frequency domain. When displayed in the time domain, the EEG signal looks like a random signal. A common method of studying EEG data associated with specific stimuli is by computing the Event Related Potentials. The brain at any given time is involved in many functions – processing visual objects, sounds, smells, executing motor actions, planning the future or remembering the past. When a subject is made to do a cognitive task – say a simple vigilance task where the subject is required to press a keyboard button when a black circle is shown on the screen – this occurrence of the stimuli can be marked on the EEG signal. Later all the segments or epochs of EEG data with occurrence of that particular stimulus can be added and averaged over time. This adds up all the activity which is associated with that specific stimulus or task, while mostly removing EEG activity due to all the other brain processes. The resultant signal is called an Event Related Potential or ERP.

These ERPs show some consistent positive and negative peaks and these peaks are named according to their positivity or negativity and the time frame at which they occur. The earlier occurring peaks are usually caused by the activity of lower brain regions processing the stimulus, while the later parts of the ERP are generated by higher cortical areas. While doing different tasks, these peaks show enhancements or reductions which can be associated with specific brain functions (Sur and Sinha 2009).

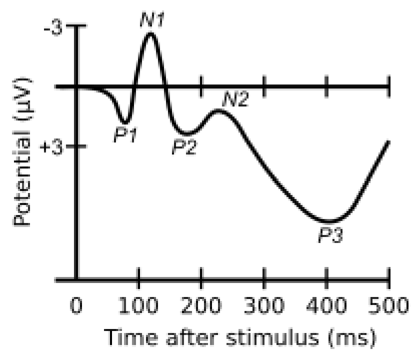

Figure 2.19: Main ERP peaks [17]

In the Frequency domain, one of the main methods of processing EEG signals is transforming the EEG signal into its component frequencies, mostly by using the Fourier transforms. It is seen that most of the activity in EEG occurs in five major frequency bands – Delta (up to 4 Hz), Theta (4 – 7 Hz), Alpha (7 – 13 Hz), Beta (13 – 30 Hz) and Gamma (30+ Hz). All these bands have some functional significance (Buzsáki and Draguhn 2004). Delta activity is most commonly seen in deep sleep but also associated with emotional functions (Crunelli and Hughes 2010, Knyazev 2012), Theta activity is associated with attention and memory functions (Sauseng, Klimesch et al. 2005) and Alpha is associated with attention, inhibitory function and as a basal resting rhythm for primary cortices (Başar, Schürmann et al. 1997). Beta is associated with attentive processing of stimuli and Gamma is considered important for higher brain functions like perceiving all the components of a stimulus together (also known as "binding"), planning and executive decision making, etc (Basar, Basar-Eroglu et al. 2001, Engel and Singer 2001).

Activities in these classical frequency bands also seem to be associated with specific regions of the brain. For example, while collection of EEG data if a subject is told to close his eyes, then the Alpha content of the occipital channels increases significantly. This is why Alpha is considered to be a basal resting or "idling" rhythm for the visual cortex which is located in the occipital region (Laufs, Holt et al. 2006, Barry, Clarke et al. 2007). Similar idling rhythms in the Alpha frequency range have been found in the Primary auditory cortex (Tiihonen, Hari et al. 1991) and the Motor cortex (called Mu-rhythm) when those areas are not actively involved in a task (Pfurtscheller and Neuper 1994).

The brain acts as a volume conductor and changes the character of these signals – like making it have less amplitude and also acting as a low pass filter. Though the neuron can fire at higher rates, the EEG signals show activity mostly up to the 45 Hz range due to this filtering effect of the brain and skull. Newer studies have associated some higher brain functions with oscillations in the upper Gamma range (100 Hz and above).

Another way of displaying EEG data is by Time-Frequency analysis in different channels. By using this method, for any channel, the signal is separated into its frequency components and their relative power is calculated over time. This gives information about the dominant frequencies in that channel at various time points. For a simple visual task, it could be seen that before stimulus is applied, Alpha could be the dominant frequency in the Occipital electrodes. Once a visual stimulus is presented, Beta, Theta and Gamma frequencies can become prominent as that stimulus is processed.

Coherence gives us a method to estimate the similarities between any two EEG waveforms after dividing them into their component classical bands. If two regions A and B are coupled with each other so that they can communicate it is likely that there would be a high correlation between their EEG signals. Thus high coherence between different regions has been taken as an indication of communication or functional connectivity between those regions (Fein, Raz et al. 1988). This kind of correlation can be high in one or more of the classical EEG bands. In visual attention studies it has been seen some frontal and parietal regions show high Theta and Gamma coherence with the visual cortex in the occipital area when subjects are paying attention (Martini, Menicucci et al. 2012). Thus increases in connectivity brought on by cognitive tasks, could give us a method to study which brain regions are communicating while doing a task.

2.6 Attention

2.6.1 Classifying Attention

One way of classifying the attention is by dividing it into Top-down and Bottom-up attention. Top-down or Endogenous attention is that which can be controlled voluntarily – like focusing on a certain task or sensation, while the Bottom-up or Exogenous attention is the one when our attention is attracted by a major change in our immediate environment, for example a loud sound, a bright flash of light, etc. The Top-down attention system is controlled mainly by the Frontal and Parietal lobes, while the bottom-up attention is modulated by subcortical regions which are a part of our instinctual defence system (Buschman and Miller 2007). It is very important for any animal living in a potentially hostile environment that he be aware of his surroundings for signs of any predators or other life threatening changes. This is why even though today we live in relatively safe places some of the things like loud noises still catch our attention.

According to Posner et al, the functioning of attention can be roughly divided into three basic mechanisms (Posner 2008). Alerting attention is related with the general arousal state of the nervous system of an organism. If an environmental cue predicts the occurrence of a sensory event, then that event is more efficiently processed by the nervous system by increasing the arousal level and suppressing irrelevant ongoing activity. On the other hand if the general arousal level of the central nervous system itself is low, even prominent stimuli can be missed. Orienting attention is a kind of attention which helps in directing the attention to a specific location in space or in a particular sensory modality. For example if a cue predicts the occurrence of a stimulus at a certain area (say a particular hemifield of the eye or one of the ears) then the response to such a stimulus is enhanced, for better processing. Executive attention is the attention involved in performing specific activities, usually consciously and helps in regulating behaviour by resolving conflicts and taking decisions.

2.6.2 Attention Network Regions

Various areas in the brain have been associated with the function of attention and they are mostly located in the frontal and parietal lobe where they form a distributed network. Different areas of this network perform various sub functions to make attending to a particular stimulus possible.

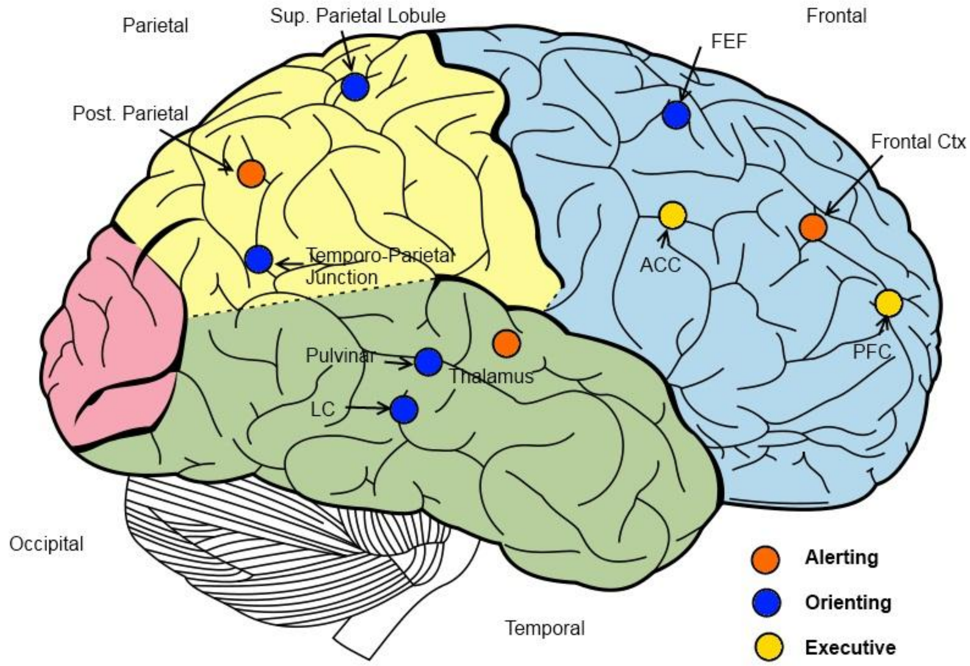

Figure 2.20: Attention Network [6]

Figure 2.20 shows the approximate locations of various main areas forming the attention network. The alerting part of the network is composed of parts of Frontal cortex, Thalamus and Posterior Parietal cortex. The Orienting Network is correlated with the Frontal Eye Field (FEF), Locus Coeruleus (LC), Pulvinar, Superior Parietal Lobule (SPL) and Temporo-parietal Junction (TPJ). Frontal eye fields were earlier thought to control the movements of the eyes to specific locations in the visual field (Fan, McCandliss et al. 2005). Now it has been seen that they are in general also involved in orienting of attention even if the stimulus is of other modality like sounds or touch, etc (Garg, Schwartz et al. 2007). Temporo-parietal junction acts like a circuit breaker for attention – for example, if the attention is focused on a visual target on the left side and suddenly another target appears on the right side which is behaviourally important, then the

TPJ of the right side will become active and disengage attention from the left target and then the Parietal cortical areas of the left side take over and re-focus the attention on the new target on the right side (Corbetta and Shulman 2002). This kind of disengagement and refocusing of attention goes on all the time without over conscious awareness as different stimuli enter our consciousness. The Executive attention network is mostly in the frontal lobe, formed up by parts of the Prefrontal Cortex (PFC) and the Anterior Cingulate Cortex (ACC). Both these areas are involved in monitoring the environment for conflicts and provide inhibitory functions to suppress inappropriate actions and thus to favour suitable ones. ACC is also involved with error monitoring in different tasks and also plays a role in emotional regulation.

These same major areas can be classified differently as Top-Down (Endogenous or Dorsal) attention network and the Bottom-up (Exogenous or Ventral) attention network. Endogenous network, also known as the Dorsal Fronto-Parietal Attention Network, potentiates the goal directed and voluntarily focused attention and includes the Frontal Eye Fields, Superior Parietal Lobule and Intra-Parietal Sulcus areas. The Exogenous attention network, also known as Ventral Fronto-Parietal Network, involves Inferior Parietal Lobule, Temporo-parietal Junction, Superior Temporal Gyrus and the Ventral Frontal cortex (including Inferior and Middle Frontal areas) (Corbetta and Shulman 2002, Capotosto, Corbetta et al. 2012). It has also been shown that attention to cues causes left fronto-parietal activation, while endogenous attention activates the right parietal cortex more (Kato, Matsuo et al. 2001). Recently it has also been suggested that these two networks are not totally separated but extensively interact to attention demands (Vossel, Geng et al. 2013).

The areas in the right hemisphere are more activated in sustained attention tasks compared to the left side. There are indications that the right side contributes to control of attention on both sides of the visual field, while the left side mostly controls the attention for the right visual hemifield (Capotosto, Babiloni et al. 2012). Thus if the subject is trying to pay attention to an object on the right side, both his attention regions in the left and right hemispheres will be activated, while when paying attention to the left side, mostly the right hemisphere will be activated (Kim, Gitelman et al. 1999, Shulman, Pope et al. 2010). Though these areas required for proper functioning of the attention system are found in the cortical hemispheres, yet they depend on some subcortical areas like Thalamus and Locus Coeruleus to provide an adequate level of general arousal. In absence of such basal activation, the attention system would not work because it would not be able to respond to any stimuli at all, as if in a state of sleep or coma. This effect is more apparent for the functioning of the Endogenous or Voluntary attention network and less so for the Exogenous system (Rushworth, Krams et al. 2001).

2.6.3 Oscillatory activities in the Brain

The communication between different spatially located regions of the attention network requires quick and precise interaction to enable formation of synchronized neuronal networks. This results in the formation of long range networks as well as short range networks which change over time during task performance (Fries 2005). Attention basically works by enhancing the information transfer between those neuronal assemblies which represent the particular feature which is relevant and the higher association areas (Womelsdorf and Fries 2007). Sensory Gain Control is one of the mechanisms by which attentional enhancement works (Kastner and Ungerleider 2000). For example if a subject is supposed to look for a horizontal line on the right side of a computer screen. The few neurons in the V1 area, which are preferentially tuned to respond to the horizontal line, would then become synchronized with other higher visual regions. If then the stimulus contains a horizontal line, that information will be processed quickly and passed on to other areas, so that appropriate response can be taken. Thus attention works by making particular neurons in V1 more excitable and increases their efficiency of firing and communication with other neurons (Fries, Roelfsema et al. 1997, Cohen and Maunsell 2009).

2.6.3.1 Gamma and Beta

Frequencies in the higher Beta and Gamma range are optimal for such synchronization and information transfer (Bekisz and Wrobel 2003). Thus in the presence of physical connections between different areas, modulation of functional connectivity by synchronization helps in the process of selective attention. It is a common experience that we can only pay attention to a small range of activities at a time. This kind of bottleneck of attention and cognitive control is probably because of the limited capabilities of the main executive and voluntary control areas in the lateral frontal and prefrontal areas (Dux, Ivanoff et al. 2006). The neuron is able to integrate the action potentials it receives over a period of about 10 ms which determines whether it is going to fire or not.

Oscillations in the Beta and Gamma range are thus well matched to modulate the firing likelihood of a neuronal network (Engel and Fries 2010).

Gamma oscillations increase in the cortices, hippocampus, brain stem and cerebellum while processing sensory stimuli and there are usually two bursts of Gamma activity (Müller, Gruber et al. 2000, Lee, Park et al. 2007). One occurs around 100 ms of stimulus and probably represents early stimulus processing and another burst occurs around 300 ms after stimulus presentation (Meador, Ray et al. 2002). The second burst is dependent on the cognitive tasks that the subject is involved in and represents communication between higher association areas. Other oscillations also show such temporal dynamics due to attention and perception (Palva, Linkenkaer-Hansen et al. 2005).

Conscious perception of any stimulus itself seems to happen when some functionally connected neuronal assemblies are formed in response to a stimulus. Mere firing of neurons in early sensory areas might not be enough for perception (Fries, Roelfsema et al. 1997). There are many theories about how conscious perception arises, but most consider that functional binding of distinct neuronal networks or circuits by synchronization is important for this phenomenon (Baars 2005). The Gamma band oscillations are considered important in bringing about such global synchronization of various neuronal assemblies to make things conscious but might not be the only condition necessary for it. A basal level of arousal, stimulus feature processing, selection of relevant features or objects and working memory all are required for perception and consciousness. Attention can work even in the absence of conscious awareness, as seen in the cases of some patients who have damaged some regions of their brain. When given the chance to perform an attention task, such patients benefit from valid attentional cues but at the same time they have no awareness of that cue (Barbur, Watson et al. 1993). This kind of non-conscious action of attention is more easily seen with exogenous cues which might engage the orienting network of the attention system (Mulckhuyse and Theeuwes 2010).

The two eyes process slightly different areas of the physical world with regions overlapping in the center of the visual field. These dissimilar views of the world result in the perception of depth. If both eyes see completely different objects, then one eye usually dominates at a particular moment and the object in that eye is perceived while the other one is ignored. These dominant perceptions can switch from favouring one eye to the next over time. This is called Binocular rivalry. In experiments on cats, which were shown gratings moving in opposite directions in different eyes, Gamma band oscillations were increased in the neuronal networks coding for the dominant percept (Engel, Fries et al. 1999).

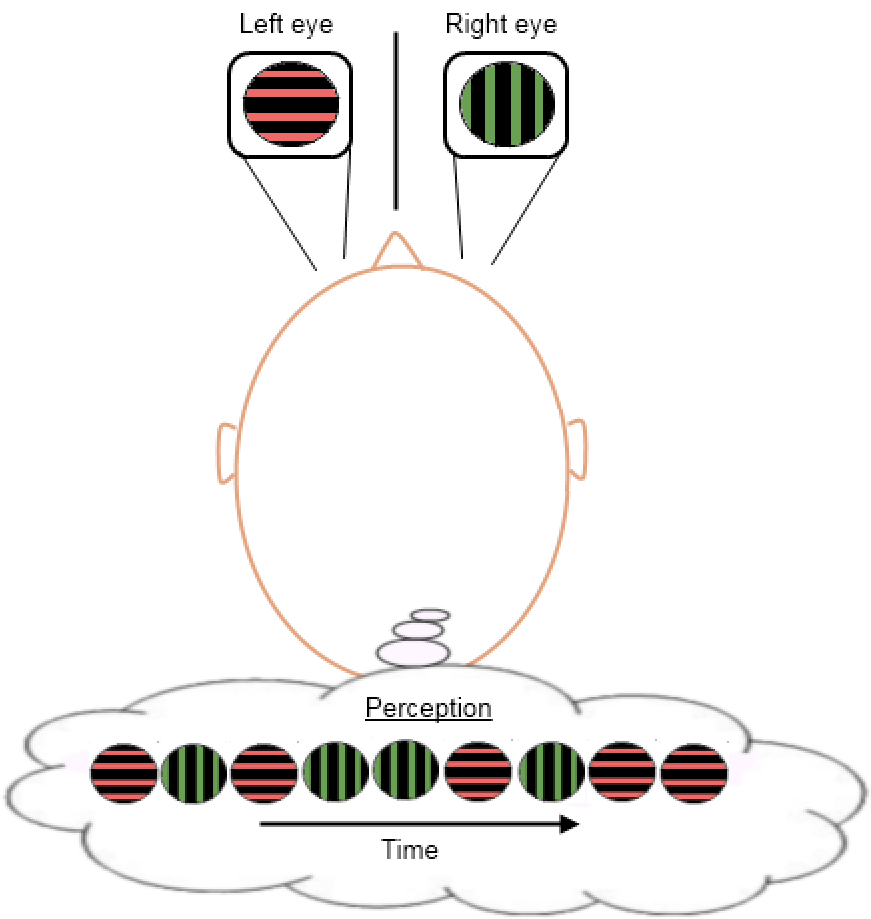

Figure 2.21: Binocular rivalry

2.6.3.2 Alpha

In addition to Beta and Gamma the Theta and Alpha frequency ranges are also correlated with attention. Alpha activity is usually related with idling of sensory cortices and in inhibitory activity of the frontal regions (Başar, Schürmann et al. 1997, Klimesch, Sauseng et al. 2007). Alpha can also show an increase with drowsiness and when a subject is exerting effort to perform a task. In cross modality cognitive tasks, where a subject is required to pay attention to different sensory modalities, like visual and auditory, causes increase in Alpha oscillations (Sakowitz, Schurmann et al. 2000). At the cellular level in animal studies and some human studies, Alpha activity is seen in the hippocampus, thalamus, the reticular formation and some cortical areas. The upper part of the Alpha band (also called Alpha 2) is seen to be associated with the long term memory system, while the lower band (also called Alpha 1) is more related to attention processes (Basar and Özgören 2004, Palva and Palva 2007).

Inhibition plays an important role in maintaining attention, in addition to activation and synchronization. Everyday tasks require that attention be paid to only a few things while ignoring many others. That is determined by the salience of different stimuli – how easily they can catch attention and by our current goals. If while driving a person pays equal amount of attention to everything on the road, the people on the sidewalk, the shops, the electric poles, etc he might very easily get distracted from the action of driving itself or at least feel exhausted. Thus inhibiting irrelevant items from our consciousness also enhances the attention that we pay to relevant things by increasing the contrast between them. The anterior cingulate cortex (ACC), dorsolateral prefrontal cortex (DLPFC), inferior frontal gyrus, posterior parietal cortex, and the anterior insula are said to be involved in bringing about this kind of inhibition (Garavan, Ross et al. 2002, Dodds, Morein-Zamir et al. 2011).

When paying attention to one side of the visual field, Alpha band power increases in the visual areas on the same side indicating inhibitory processes on that side, while it decreases on the opposite side (Sauseng, Klimesch et al. 2005). As mentioned earlier, most sensory information from one side of the body is processed by the opposite cerebral hemisphere. This kind of crossover is also present in the visual system, as shown in Figure 2.22. If the subject is asked to pay attention to an object in the right visual hemifield, Alpha power would decrease on the left side, while increasing on the right side (Thut, Nietzel et al. 2006). In addition to such local changes in Alpha frequency band, changes are also seen in synchronization between distant areas – like between the frontal and occipital regions during visual processing. In these long range interactions it is seen that Alpha increases on the opposite or contralateral sites as compared to short range dynamics where it decreases indicating that long range Alpha changes might be functionally different from those in the short range (Palva and Palva 2007).

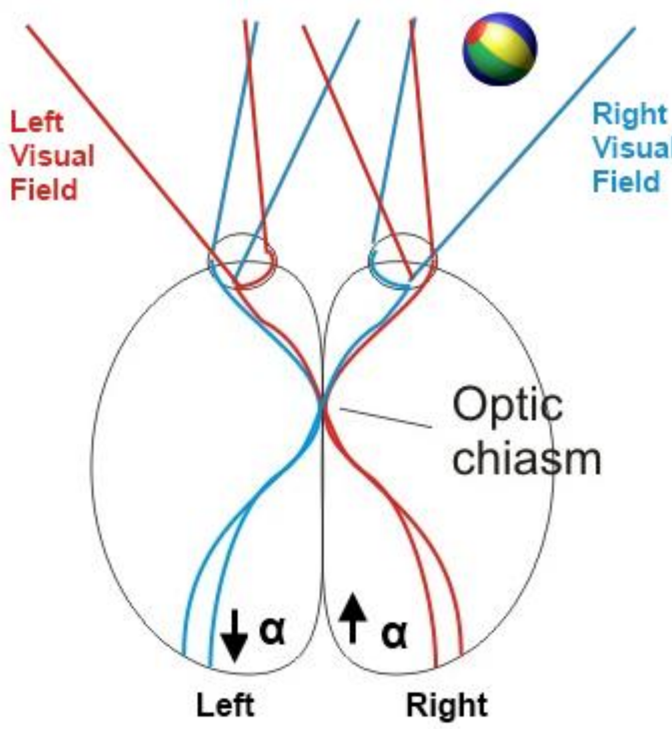

Figure 2.22: Visual field crossover [18]

2.6.3.3 Theta

The Theta frequency band is usually associated with memory functions (Basar, Basar-Eroglu et al. 2001, Sauseng, Klimesch et al. 2005). At the cellular level hippocampus, the septal nucleus, the reticular formation and some cortical areas could be the source of EEG Theta oscillations (Mitchell, McNaughton et al. 2008). Furthermore Theta is also related to emotional appraisal (Ertl, Hildebrandt et al. 2013) and some forms of selective attention (Bekkedal, Rossi et al. 2011). A pervasive increase in Theta is seen in attention tasks when the vigilance decreases and an increase in Theta in the midline and frontal regions can be seen when highly attention demanding tasks are done (Choi, Jung et al. 2010).

Different regions of the brain preferentially oscillate in different frequency bands, called its major operating rhythm. The major operating rhythm of the frontal lobe is considered to be Theta, while that of the occipital lobe and central cortical areas is Alpha (Basar 2004). The Theta power in the frontal cortices increases when a subject is presented with bimodal stimuli – say a combination of auditory and visual stimuli in comparison to a stimulus in only one modality (Sakowitz, Schurmann et al. 2000). Theta is also high while learning a new task and it reduces once the task becomes familiar (Basar 2004). While doing a working memory task, Theta power increases in those trials where the subject successfully forms and retrieves a memory compared to when such attempts were unsuccessful (Osipova, Takashima et al. 2006). Such changes observed in the Theta range are present only in certain time windows of task performance (Doppelmayr, Klimesch et al. 2000).

Theta oscillations could also be seen as a carrier wave for Gamma oscillations where Theta could code for the context of a situation while Gamma codes for specific stimuli. Theta could also be a good carrier for long range cortical coupling between functional regions (Sirota, Montgomery et al. 2008).

2.6.3.4 Delta

The Delta frequency band is usually seen in deep sleep and consists of low frequency but high amplitude oscillations in most brain areas. But Delta changes are also seen in some cognitive tasks. Oddball tasks entail the subjects paying attention to periodic stimuli which are of usually two types. One set of stimuli has a high frequency of presentation and is called the standard stimuli, while the other stimuli is only presented rarely and is called the oddball stimulus. In these kinds of experimental paradigms Delta is seen to increase in the parietal regions when using auditory stimuli and in the frontal and central regions when using visual stimuli (Başar-Eroglu, Başar et al. 1992).

These major frequency bands do not function in isolation but show concurrent increases and decreases while performing different tasks. For example while processing complex signals, forming associations and memory retrieval Theta and Gamma power is seen to increase in the occipital regions, while frontal areas show increase in Theta and Delta oscillations (Basar 2004).

The timing of these frequency band changes is also very important. This raises the question about the length of time segment which will be ideal to study the connectivity changes. A very small time segment say 10 ms, will increase the computations required, while a very long segment length (500 ms or more) might not give a reasonable time resolution to see the connectivity changes. The activity of neurons themselves is very fast and they could fire repeatedly every 2-4 ms. However, the electrical activity observed on the scalp is a result of combination of the firing of several groups of neurons and since the skull and scalp layers act as low pass filters, only lower frequency activity is observed in EEG. Thus using very short time segments might not give physiologically relevant results. The event related oscillations correlated with cognitive tasks have been seen to occur in only certain time segments locked to stimulus presentation and task demands. It is observed that while perceiving a stimulus Alpha increase early on after stimulus presentation, followed by Beta and Theta increases. Gamma changes occur early on in those trials where subjects become aware of objects followed by more changes in later periods of stimulus processing. Gamma oscillations increase in the cortices, hippocampus, brain stem and cerebellum while processing sensory stimuli and there are usually two bursts of Gamma activity (Lee et al., 2007; Müller et al., 2000). One occurs around 100 ms of stimulus and probably represents early stimulus processing and another burst occurs around 300 ms after stimulus presentation (Meador et al., 2002). During a covert attention task, Delta and Theta band synchronization was found to increase during the 200–300 ms duration while Alpha band desynchronization was seen around 500 ms (Treder, Bahramisharif et al. 2011). Memory tasks also evoke Alpha band synchronization about 100–200 ms after stimulus. Event related Theta oscillations have also been observed in selective attention tasks, especially around 200–300 ms after the stimulus (Basar 2004). It has been suggested that in response to cognitive tasks, the brain changes its configuration into some set patterns know as microstates, which act as building blocks or functional units of mental processes, which are necessary to carry out the cognitive tasks (Lehmann, Strik et al. 1998). These configurations are activated in sequences according to task demands to fulfil the mentation requirements (Wackermann, Lehmann et al. 1993, Pascual-Marqui, Michel et al. 1995). The widely accepted Neuronal Workspace model of consciousness also proposes that the microstates are maintained for a certain duration of time close to 100 ms (Baars 2002, Dehaene, Sergent et al. 2003). Furthermore, EEG microstates remain reasonably stable for 100 ms segments (Van De Ville et al., 2010). Keeping these time dynamics in view a 100 ms time segment has been used in these studies. This gives a balance between using very short time segments which might be computationally intensive and very long segment lengths which would smear the oscillatory changes over time thus decreasing the timing resolution.

Furthermore, the same oscillation could have more than one functional role, while the same function could be associated with multiple oscillations (Basar 2004). These kinds of time based changes in various frequency bands could vary from task to task depending on what kind of stimulus is presented in an experiment and the response required.

This section emphasizes that change in various frequency bands can be caused by different states of stimulus processing and attention control. It is therefore important to look at all the major frequency bands as well as their modulations along different time windows.

2.6.4 Attention Modulation by Emotions

Human beings are emotional and our internal mental states vary over time, due to external or internal events. As our state changes, our ability to pay attention to specific stimuli also changes. When someone is hungry, his attention is almost automatically drawn towards food items and after eating his attention goes back to other things (LaBar, Gitelman et al. 2001). Similarly if for some reasons a person is in a bad mood, even everyday events like getting stuck in a traffic jam could start to seem more irritable. The internal mental states and especially emotions could change how we process and react to external stimuli (Pichon, Rieger et al. 2012). If someone is engaged in a skilled task which requires his full attention, then unwanted changes in mental states can affect his ability to function effectively. This requires a method to judge effects of internal mental states on attention.

Emotions mainly arise by the action of subcortical regions which are older part of the brain in evolutionary terms. Similar brain structures are seen in other mammals and primates and are involved in generating emotional states. The main regions involved in emotional function are Amygdala, Hypothalamus, Hippocampus, Ventral Striatum and Nucleus Accumbens (Baars and Gage 2010). For humans, the neocortical areas are highly developed and some medial parts like the Cingulate cortex and Ventromedial Prefrontal cortex are also involved in emotions. These neocortical areas give us the ability to cognitively appraise the emotions and have sophisticated feelings and also to regulate them as necessary (Golkar, Lonsdorf et al. 2012).

Amygdala is one such structure involved in emotions and is mainly seen to be activated when a threatening stimuli is present in the environment leading to fear. But recently amygdala has also been seen to activate in some positive emotions (Phelps and LeDoux 2005). Visual information from the Thalamus can reach the amygdala very quickly and allows a person or animal to take evasive action if a threat is perceived. This kind of a short route to Amygdala depends on visual signals being processed in a crude manner by Superior Colliculus and Pulvinar instead of being processed by the visual cortex. At a later time more processed information from the visual information also reaches the Amygdala (Pessoa and Adolphs 2010).

The Hypothalamus has important regulatory functions and helps in modulating our attention in response to hunger, thirst, body temperature, etc. The Amygdala is highly connected with the hypothalamus and when activated it can change important functions of hypothalamus. For example in case of a threat, our feeding drives will become inhibited, while we make efforts to find a place where we can be safe from that threat. Once such a condition passes, the hunger drive is released from inhibition and it can be felt and acted on (Baars and Gage 2010). The hippocampus is very important for memory functions, but its function is modulated by emotions and amygdala (Phelps 2004). It is seen that emotional stimuli are easier to commit to memory compared to neutral stimuli (Hamann 2001). But if the stimuli or the context is too emotional then it is detrimental for memory formation, which is why people tend to forget details if they had been in a big accident (Sandi and Pinelo-Nava 2007).

This intricate system of processing emotional stimuli provides a means of developing adaptive actions in response to different situations. It is known that the visual cortex becomes more activated when perceiving an emotional stimulus compared to a neutral stimulus (Phan, Wager et al. 2002). Patients with amygdala damage failed to show such activation in the visual cortex (Vuilleumier, Richardson et al. 2004). Thus Amygdala enhances the processing and perception of those stimuli which are important by modulating how the visual cortex functions. This is also seen for other modalities like sounds. Sato et al showed that Amygdala increases its Gamma frequency oscillations in response to emotional sound stimuli (Sato, Kochiyama et al. 2011).

There is evidence for specialization of the left and right cerebral hemisphere regarding some emotional functions. The right hemisphere is more involved in emotional functions, but it is also seen that the left frontal cortex activates more after positive stimuli, while the right side responds more after negative ones (Harmon-Jones, Gable et al. 2010). In depressive patients over-activation of the right frontal cortex has been seen (Hecht 2010). Transcranial magnetic stimulation to inhibit the functioning of the right frontal cortex can relieve some signs of depression (Rossini, Lucca et al. 2010).

There are many methods to produce emotions in experiment participants which could be external stimuli or internal mentation based. In order to standardize emotion induction it is advisable to use external stimuli. The characteristics of an emotional stimulus can be categorized in two major dimensions. Arousal dimension measures how activating an stimulus is – for example an image of a basket would be less activating, while an image of your favorite football team winning a Championship will be more arousing. The valence dimension indicates whether the stimulus produces a positive or a negative effect – for example an image of a flower would be seen as positive, while that of an accident would be seen as negative (Bradley and Lang 1994).

The International Affective Picture System is a depository of picture stimuli which have been given such Arousal and Valence ratings by many participants. Using pictures from the IAPS is a common method to invoke emotions in subjects (Britton, Taylor et al. 2006). Similar depositories are present for sound (IADS) (Bradley and Lang 2007) and facial stimuli (NimStim database) (Tottenham, Tanaka et al. 2009).

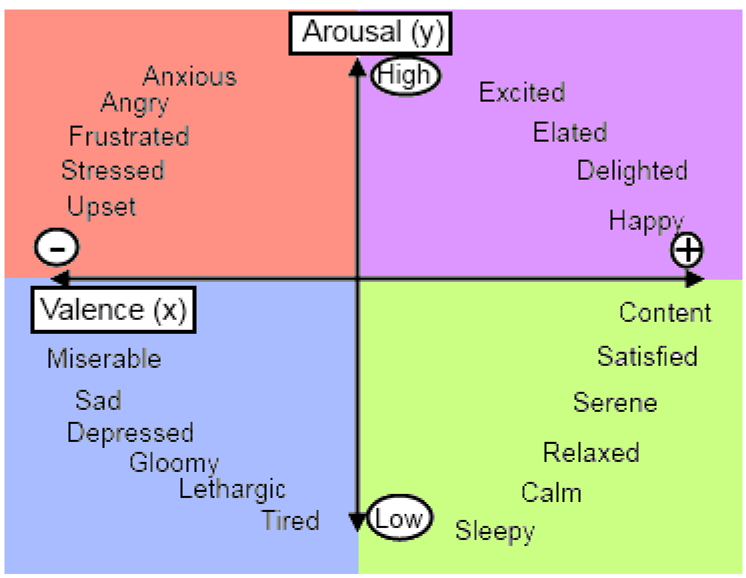

Figure 2.23: Arousal Valence model

Schirmer et al used emotional sounds to study how differently they are processed. The syllable "dada" was spoken in a neutral, happy and angry tone and EEG ERP results showed that the response to those three kinds of stimuli were significantly different from each other (Schirmer, Striano et al. 2005). This shows

that emotional content of a sound determines how the stimulus is processed. It is believed that such processing of emotional stimuli becomes maladaptive in anxiety (Eysenck, Derakshan et al. 2007) and PTSD disorders (Vasterling, Brailey et al. 1998). In these disorders attention is allotted preferentially to negative or threatening stimuli (Bar-Haim, Lamy et al. 2007, Pannu Hayes, LaBar et al. 2009)
.

In a recent study frontal Theta rhythm modulated Beta band activity in response to emotional stimuli in healthy individuals while this effect was not present in PTSD patients. These patients also showed an increase in Beta activity regardless of emotions (Cohen, Shalev et al. 2013). Emotional words could also induce reductions in Alpha and Beta power in general along with Theta reductions in specific regions (Alfimova and Uvarova 2008). Delta, Theta and Beta bands have also been implicated in other emotional modulation studies (Balconi, Brambilla et al. 2009, Kostandov, Kurova et al. 2010, Miskovic and Schmidt 2010, Putman 2011, Lipsman, Kaping et al. 2013). Gamma band activity is also observed in response to emotional facial stimuli and this activity is seen in specific time interval around 250-350 ms (Balconi and Pozzoli 2009). In a study exploring the effect of emotional musical pieces, Alpha band activity was seen to be modulated in specific brain regions. There were some differences between males and females (Flores-Gutierrez, Diaz et al. 2009).

2.6.5 Cross modality attention

Sensory modalities function by collecting information from the receptors and processing that information in respective brain regions to make us aware of the environment. Visual system consists of the retina in the eyes, which sends signals to the Lateral Geniculate Nucleus of the Thalamus and then to the visual regions in the occipital cortex. The visual cortex itself has many subregions (Figure 2.8) which analyze different aspects of a visual object and finally give rise to visual perception (Dougherty, Koch et al. 2003). The processing of sound involves signals from the ears going to the Medial Geniculate Nucleus of the Thalamus and then reaching the auditory cortex in the temporal lobe. The signals are processed by the Primary and Secondary cortices and then passed on to higher association areas (Hudspeth 2000). The sensory information from the skin like touch, pressure, temperature and pain reach the Sensorimotor area in the Parietal cortex through the spinal cord and thalamus (Gardener and Kandel 2000).

The ability to pay attention to one sensory modality involves the interaction of the attention network regions with one of these sensory regions. If a person is required to pay attention to a visual object, then areas in the frontal and parietal cortices interact with the visual areas in the occipital region to enhance processing of visual stimuli (Kastner and Ungerleider 2000). In much the same way interaction of frontal and parietal areas with auditory areas could enhance processing of sound signals.

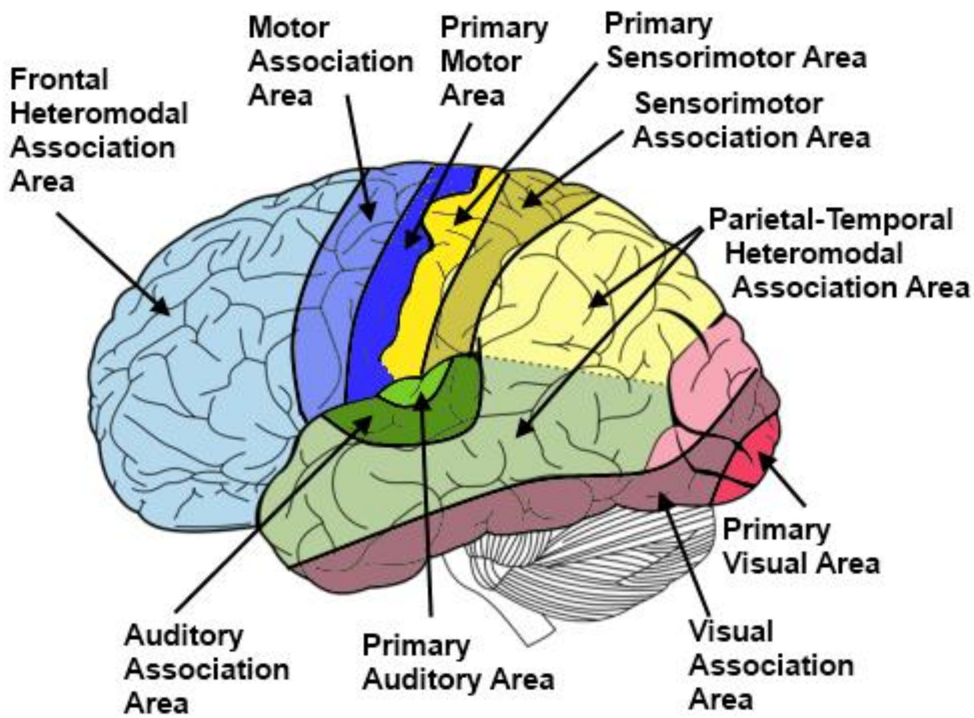

Figure 2.24: Brain areas aud visual [6]

Gamma range synchronization between prefrontal and visual areas has been observed to be involved in selective attention (Fell, Fernandez et al. 2003, Jensen, Kaiser et al. 2007, Gregoriou, Gotts et al. 2009). The top-down influence of frontal and parietal attention areas on occipital visual regions is important for attentional enhancement of stimuli (Kastner and Ungerleider 2000). Gamma band activity also shows changes with regards to visuospatial attention as increased power in contralateral hemisphere (Müller, Gruber et al. 2000). Attention increases or decreases the Gamma oscillations in different brain regions (Tallon-Baudry, Bertrand et al. 2005). In addition to the gamma band, Alpha activity is also associated with visuospatial attention (Sauseng, Klimesch et al. 2005, Thut, Nietzel et al. 2006, Doesburg, Green et al. 2009). Theta band activity has is also implicated in attention and can also be modulated by task demands (Sauseng, Hoppe et al. 2007).

In the auditory domain, an interplay of auditory and fronto-parietal regions is observed for bringing about attentional reorienting (Brunetti, Della Penna et al. 2008). The right Temporo-Parietal Junction (rTPJ) is seen to be activated during auditory attention tasks (Larson and Lee 2013). The right hemisphere has a dominant role in auditory attention, just as in the case of visual attention (Petit, Simon et al. 2007). Furthermore the left auditory areas are specialized for processing speech, while the right side is more responsive to musical sounds (Tervaniemi and Hugdahl 2003).

2.6.6 Default Mode Network

When a person is not doing anything in particular, a chain of thoughts starts (Stimulus Independent Thoughts, SITs or Task Unrelated Thoughts, TUTs) and the person becomes more focused on them, until an external event disrupts it (Mason, Norton et al. 2007). This function is carried out by another brain network called the Default Mode Network (DMN) which is seen to become active when a person is resting and awake (Biswal, Yetkin et al. 1995, Raichle, MacLeod et al. 2001). The functional relevance of DMN is still not totally clear, but the indication is that such spontaneous thought is the activity needed to maintain the major connections in the brain in the higher association areas (Andrews-Hanna, Reidler et al. 2010). The DMN regions are seen to be in connection with each other and their activation slowly fluctuates at about 0.1 Hz frequency that is about once every 10 seconds (Cordes, Haughton et al. 2001). A remarkable finding regarding this DMN is that it functions in an anti-correlated fashion with the attention networks responsible for external focus and task demands. If the focus is on performing an external task, then the activity in the DMN becomes suppressed (Christoff, Ream et al. 2004). It has been also seen that if the activity of the DMN increases, while that of task related networks decreases, then the number of errors in a task increases (Li, Yan et al. 2007, Eichele, Debener et al. 2008). Changes in DMN activity have been seen in ADHD (Yu-Feng, Yong et al. 2007) and depression patients (Sheline, Barch et al. 2009).

The DMN is formed by Medial Prefrontal Cortex (MPFC), Posterior Cingulate Cortex (PCC) and Precuneus (Pc) on the medial side of the brain. The Inferior Parietal Lobule (IPL) on the lateral side of the cortex also forms an important part of the DMN (Figure 2.25) (Raichle and Snyder 2007).

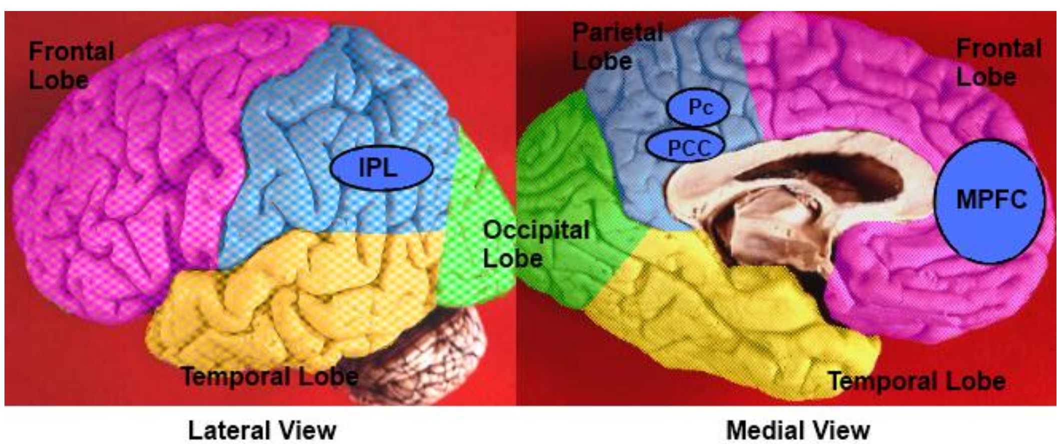

Figure 2.25: DMN regions [4, 5]

The activity in these regions during awake and restful periods is seen because they serve some important functions which are required even while not being focused on any particular task. Posterior Cingulate and Precuneus are associated continuously gathering sensory and spatial information from the environment to maintain a state of awareness about any significant changes (Vanhaudenhuyse, Demertzi et al. 2011). The Medial Prefrontal Cortex along with the Orbito Frontal cortex is associated with regulating and expressing emotions and integration of those feelings with cognition. The Medial Temporal Lobule has important memory functions and could help in reactivating memories or envisioning future scenarios (Buckner, Andrews-Hanna et al. 2008). The wandering thoughts that we notice while in relaxed situations are usually in relation to reminiscing about the past or thinking about the future. Thus these DMN regions are seen to activate when subjects are engaged in such activities (Christoff, Ream et al. 2004).

The regions of the DMN show slow coordinated changes in their activation level which indicates a level of functional connection between these DMN regions (Fransson 2005). Some brain regions like Insula and anterior cingulate are responsible for maintenance and switching between the DMN and the external attention network regions (Gao and Lin 2012, Tang, Rothbart et al. 2012).

Some neurological diseases like Autism and Schizophrenia show increased activation of the DMN, which causes an increased focus in the individual towards the internal mentations and thus external activities become deficient. Depression, Obsessive Compulsive Disorders, Attention Deficit Hyperactivity Disorder and Post Traumatic Stress Disorder also show irregularities in DMN activation (Buckner, Andrews-Hanna et al. 2008). Alzheimer’s disease is a progressive dementia which affects older individuals due to amyloid deposits in brain areas. It has been seen that the areas involved in the DMN area especially prone to amyloid deposition and some researchers suggest that DMN overactivity might be responsible for it (Hamilton, Furman et al. 2011). Patients with Balint's syndrome have damage to DMN areas like Cuneus and Precuneus and show an inability to pay loose awareness to their environment apart from a narrow region of attention (Andrews-Hanna, Reidler et al. 2010).

If the DMN regions become activated while task performance, it could have detrimental effects on the external task. It was seen that when attention lapses happened, the activity of the DMN regions had increased, while that of the Attention Network regions had decreased (Eichele, Debener et al. 2008). Such activation of DMN regions was also associated with forgetting target words in a memory task (Cohen and Maunsell 2011). Thus it becomes important to estimate the interference caused by DMN during task performance.

Attention and memory are interlinked and often higher association areas like the prefrontal and parietal cortex are involved in both these functions (Coull, Frith et al. 1996, Grimault, Robitaille et al. 2009). The hippocampal formation is another main region involved in memory functions. Initially it was considered to be more important for short term memory and consolidation (Fanselow and Dong 2010), but lately the interaction of this region with the frontal cortex has been seen to have a more complex role in memory formation and transformation (Wang and Morris 2010, Nadel, Hupbach et al. 2012). Oscillatory activity in the Theta band is important for memory functions (Doppelmayr, Klimesch et al. 2000, Lega, Jacobs et al. 2012), but Gamma and Alpha bands have also been associated with it (Osipova, Takashima et al. 2006, Grimault, Robitaille et al. 2009, Düzel, Penny et al. 2010). Though Alpha band activity is usually considered to be associated with idling or inhibitory activity, yet in complex memory paradigms it shows an increase in the prefrontal regions along with a decrease in the occipital regions (Sauseng, Klimesch et al. 2005). Thus it becomes clear that a complex cognitive capability like memory depends on functional interaction between different brain regions in the major frequency bands.

2.7 Section Summary

The above discussion about the anatomy and function of the brain in general and attention networks in particular brings forth the following main points

1. The Neuron or nerve cell is the fundamental building block of the brain has chemical and electrical properties. Dendrites of a neuron receive signals while the axon sends signals to other neurons.
2. A neuron functions basically by firing or generating action potentials which carries electrical signals to other neurons.
3. The membrane potential of a neuron, and thus its excitability, is modulated by the action potentials it receives from other neurons. Similarly a neuron can modulate activity of other neurons – making them more (activation) or less excitable (inhibition).
4. The brain is divided into various anatomical regions which have specific and sometimes overlapping functions.

5. The primary sensory cortices receive signals from sensory receptors, process it and make it available to the higher association cortices for further processing and action.
6. There are numerous feedforward and feedback interaction between the lower and higher brain regions while processing a stimulus.
7. Various brain areas need to act in concert to process complex stimuli and produce goal directed action.
8. Synchronization or coupling between brain regions is a mechanism by which disparate and spatially separated regions could be functionally linked to perform their functions.
9. Attention results from the interaction of a distributed network of regions in the frontal and parietal cortices which act on other sensory areas by modulating their function.
10. Different sensory domains are important for perception of the environment, which requires switching of attention between these domains.
11. Some scenarios require attention on a particular domain with the exclusion of others.
12. Such focus on a particular domain would bring about functional connectivity changes between attention network regions and the sensory cortices.

13. Attention can be modulated by internal emotional states, thus the same sensory stimulus would be processed in different ways depending on the state.
14. When a person is not involved in a focused external task, the mind tends to wander to sometimes irrelevant thoughts and the focus shifts to internal mentation.
15. These shifts could cause a detrimental effect on the ability to process external stimuli and carry out a goal directed cognitive task.
16. The activities of a neuron bring about changes in electrical, magnetic and blood oxygenation properties which could be used to estimate brain function.
17. EEG is the method of measuring electrical potentials at the scalp by applying electrodes.
18. The obtained EEG signal can be processed to give insights on the inner functioning of the brain.
19. Various cognitive activities show changes in the major frequency bands of Delta, Theta, Alpha, Beta and Gamma.
20. These different bands represent oscillatory activity in the brain and temporal changes in their locations are observed while cognitive task performance.
21. Attention causes changes in the Gamma and Alpha bands. Theta and Beta band changes can also be observed.

22. Emotional modulation leads to changes in the Delta band along with Beta and Gamma bands.
23. Memory functions are represented by Theta and Gamma bands, along with Alpha band activity.

2.8 Gaps in Current Understanding

However, there are some gaps in the knowledge regarding the functioning of the attention system, which this work seeks to cover.

1. Most fMRI studies give detailed information about the regions involved in cognitive tasks but since data is averaged over a few seconds, the precise order of activation of the areas remains elusive.
2. Furthermore in EEG studies where coherence is used to study interaction between various electrode locations, either only a few channel pairs are considered or the time segments in which data is analysed is kept in the range of seconds.
3. The activity of neurons is very fast and sub-second reaction times are common in simpler cognitive tasks. This signifies the necessity to study neural connectivity dynamics at a resolution closer to the natural brain functioning (100 ms) (Van De Ville et al., 2010).
4. Newer mathematical methods like Wavelet transforms can be utilized for accurate calculation of coherence in short time intervals, but these dimensions of attention have not been previously studied.
5. Generally only a few frequency bands are mentioned to be important for attention, but considering that same frequency bands could have different

functions and same functions could invoke oscillations in different frequency bands, it becomes extremely important to apply a statistical approach in finding relevant differences between conditions.

3 Methodology

3.1 Measuring Interaction

From the above sections about the neurophysiological working of the brain it is clear that the brain can be functionally divided into many areas which are specialized to process specific stimuli. However, higher cognitive functions result by complex interactions between those regions. These interactions require the passage of information from one area to the other by modulating the functional connectivity between the regions. It is thus evident that a technique to measure such changes in connectivity can be a good method to estimate attention or other cognitive functions.

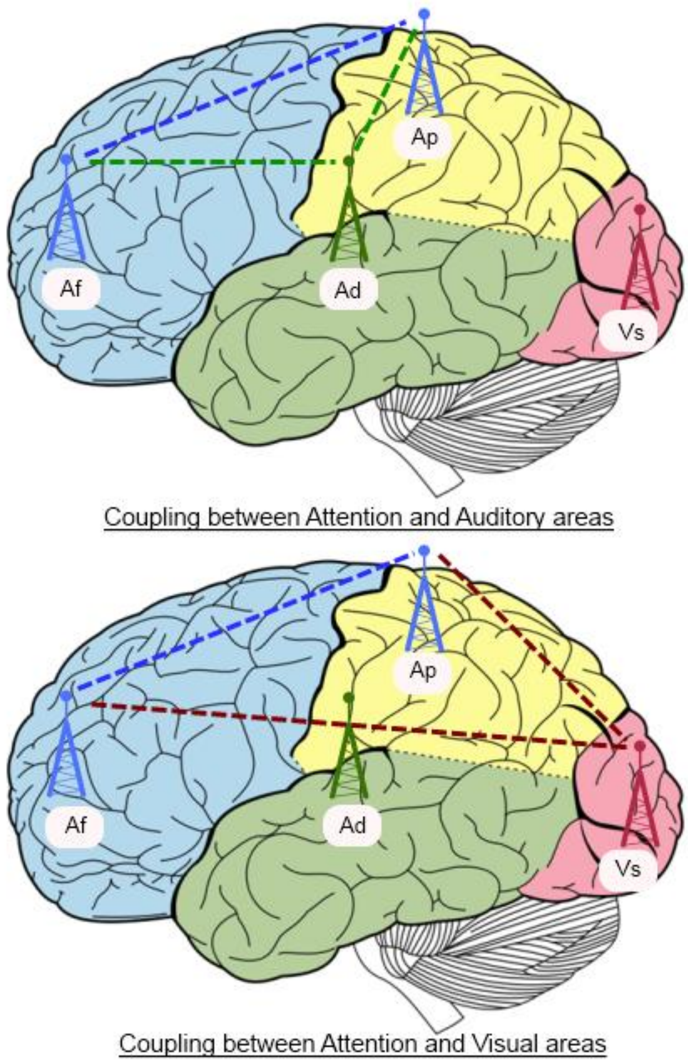

Figure 3.1: Brain Regions Synchronization [6]

The communication mechanism between brain regions is understood to be through synchronization of oscillations (Please refer to Section '2.5.3 – Oscillatory Activities in the brain' and '2.5.5 – Cross modality Attention' under Literature review for details). As a simple analogy, it is similar in a way to transmission of radio signals. Many different radio channels send out their signals into the atmosphere. A radio receiver can choose to access any of those signals by oscillating at the same frequency as a particular radio channel and bringing about synchronization. Figure 3.1 shows possible mechanism of attention switching between auditory and visual stimuli. In the upper part attention is required to be paid to the auditory signals, thus functional connectivity between Attention areas in the Frontal (Af) and Parietal (Ap) regions is established with the auditory processing areas in the Temporal lobe (Ad). This enhances the processing of auditory signals. In the lower part of Figure 3.1 synchronization is established between the Attention areas (Af and Ap) and the Visual cortex (Vs), thus augmenting the visual signals.

EEG gives us a non-invasive way to study the functioning of the brain in real time. The EEG equipment is fairly cheap and more portable compared to MEG, MRI and PET or SPECT scanners. EEG also contains rich dynamic information which could be processed in the time or frequency domain and help in understanding cognitive processes. It supplies spatial information in the form of channel locations which provide signals from different areas over the skull (Figure 3.2). Since the sampling rate of the EEG signal is high, it can provide data with high time resolution.

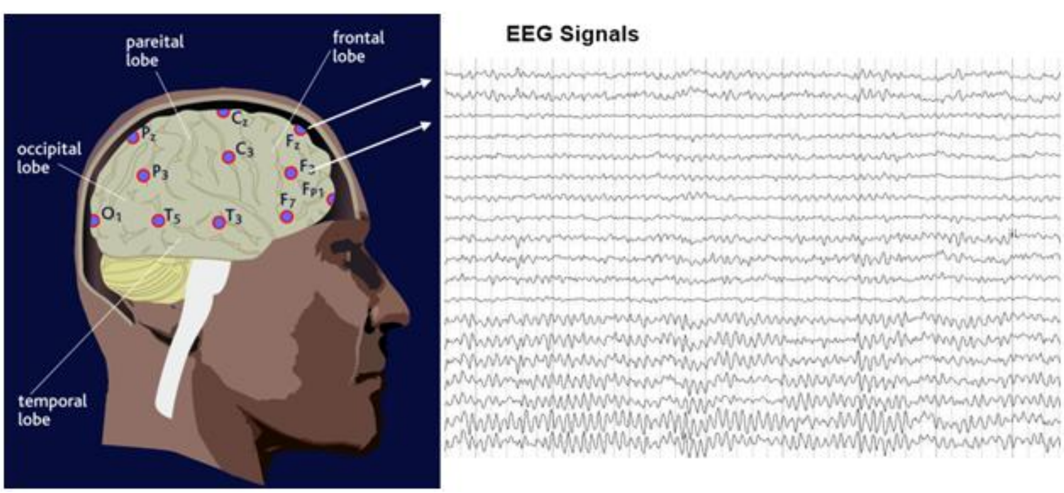

Figure 3.2: EEG Signals [19, 20]

In addition to the location of the interacting regions, it is highly important to assess this interaction in appropriate time segments while task performance. For example if a subject is performing a simple vigilance task, where he is required to press a response button as soon as a target is presented on a screen, then the response times are in the range of about 300-500 ms. This means that within about 500 ms, the visual target is processed by various areas of the visual cortex, a decision is taken to act on the stimulus and motor signals are sent to the finger muscles to press the response button. All this happens in a sequential manner and the functional connectivity between regions will change as the visual information passes through early visual areas, to late visual areas, to association cortices and then to the motor areas of the brain. Thus it becomes pertinent to estimate the connectivity between areas in appropriate time segments. This way the changing connectivity profile of EEG signals can be studied in relation to task performance. However, because of volume conduction of the electrical signals through the brain, there is some spread of the signals and thus the same brain source could affect signals on two closely located EEG electrodes and electrical activity from two closely located brain sources could be captured by the same EEG electrode on the scalp. Keeping this in mind, caution is advised when making inferences about the exact location of brain sources causing changes in the EEG signals. Nevertheless, for application purposes, the electrode locations are still useful. Because if there is a need to cut down on the number of electrodes to reduce the computation time, those electrode channels which show statistically significant changes can be retained while data from other channels can be discarded during processing.

3.2 Requirements of a method

An ideal method to estimate connectivity between various brain regions should have the following characteristics to provide a good understanding of attention control –

1. It should provide information on the major functional frequency bands which are important in a task.
2. It should supply the connectivity profiles in short time segments, so that the dynamic functional connections between different regions can be observed with good time resolution.
3. It should be able to assess which electrode channels carry the most distinguishing information for differentiating attention states, so that fewer channels could be used for specific situations.
4. The equipment used for this estimation should be portable so that it can be applied easily in various field scenarios.
5. The method should provide statistically significant results while differentiating between attention states.
6. It should be adaptable for use with machine learning classifiers.

3.3 Inter-Electrode Event Related Coherence

Coherence is a way to detect similarity between two waveforms and provides a way to estimate functional connectivity between regions of interest.

The method presented here relies on coherence between the sixty two surface EEG electrodes.

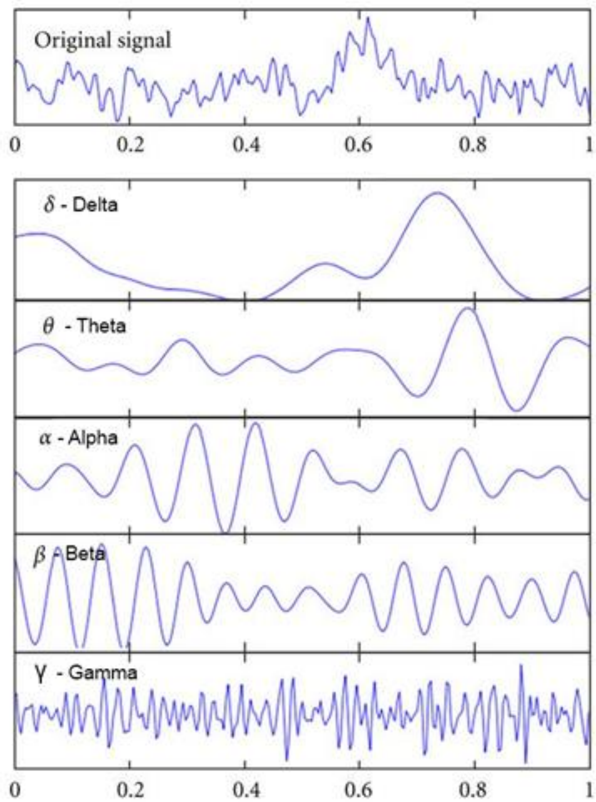

Figure 3.3: EEG components [21]

A complex waveform like EEG seems like a random signal to an untrained observer. But complex signals can be separated mathematically into its component frequencies using methods based on the Fourier transform (Cooley and Tukey 1965) (Figure 3.3). Once EEG signals from different electrodes are separated into their component frequencies it becomes easier to see the dominant spectral bands in various electrodes and how they change during a cognitive task. The component oscillations in the major frequency bands have different sources and functions during cognitive task performance as outlined in the previous chapter. By comparing these component oscillations from different EEG electrodes (Inter Electrode), an estimate can be made about the functional connectivity between these electrodes.

Coherence, when used on EEG channel data, can indicate whether two channels are oscillating in the same frequency band or not – thus indicating if those two regions are coupled and communicating (Fries 2005). Using coherence on short segments of data gives us the ability to look at interactions between different brain regions in a high temporal resolution. At any particular time, a lot of processing is going on in the brain which could be unrelated to a task that the subject is performing. This generally can cause contamination of task related EEG changes with those changes which are not specific to the task at hand. To decrease this contamination, EEG data to be processed are taken only when a relevant event occurs (Event Related). Then data from these relevant epochs can be averaged within subjects or processed on a trial by trial basis. Coherence can then be calculated in very short intervals using Wavelets up to every 100 ms or even less and this is timed with the different events like presentation of a stimulus or the subjects' response etc. This is known as Event Related Coherence (ERC). Wavelet transform gives the ability to calculate accurate coherence values in short time intervals (Sakkalis 2011, Freeman and Quiroga 2013). In the proposed method of Inter Electrode ERC – an estimation of various EEG electrodes' interaction in all major frequency bands during short 100 ms time segments is made, while the subject does an attention task.

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

Equation 1: Fourier Transform

Where *X(f)* is frequency domain function, *x(t)* is time domain function, *i* is the square root of -1, *f* is the frequency in Hertz and *t* is time in seconds.

Classically, the Fourier transform has been used to decompose digital signals like EEG and subsequently coherence is calculated. However a major limitation of Fourier transform is that it assumes a signal to be stationary in the time domain – having the same spectral properties or frequency components for the whole duration of the signal. Though this is not a problem in pure engineering systems where stationary signals are more common, in the biological domain, non-stationary signals are commonly encountered. EEG is one such signal where the spectral components can change rapidly with time due to cognitive processes. Thus when using Fourier transform, a non-stationary signal with different frequency components present in distinct time segments will show the same spectral components, as a stationary signal (Figure 3.4b) which has those frequency components throughout the duration of the signal. Figure 3.4a shows a stationary signal which is composed of a summation of 10, 25, 50 and 100 Hz sinusoidal components, while 3.4b shows its Fourier transform with four peaks at these frequencies.

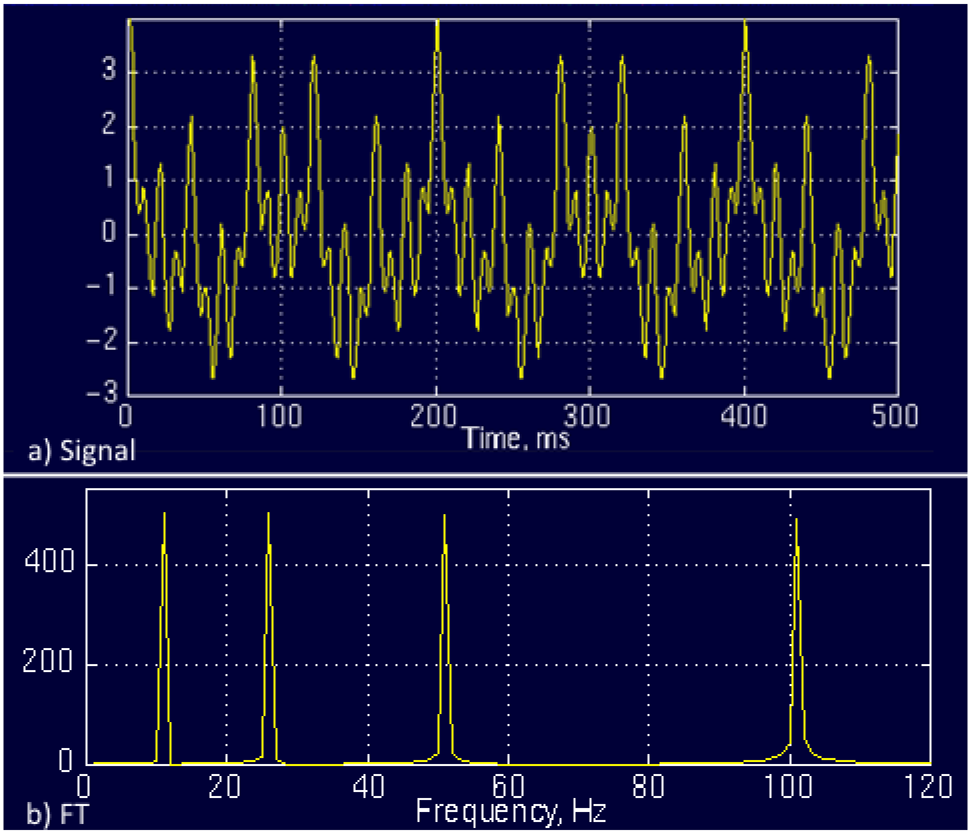

Figure 3.4: Stationary Signal and its Fourier Transform [22]

Fourier Transform does not provide any timing-location information and cannot be used to determine where exactly during the whole time period was a frequency component present. Figure 3.5a shows a non-stationary signal comprised of a 100 Hz sinusoidal waveform present during the first 250 ms time segment, followed by 50, 25 and 10 Hz waveforms present in the subsequent 250 ms time segments. Its Fourier Transform, shown in Figure 3.5b, shows four peaks at these frequencies, and is basically similar to Figure 3.4b. If this Fourier transform is used to recreate the signal from its components, it would look as the signal in Figure 3.4a, rather than that in Figure 3.5a, since there is no timing information provided by the Fourier transform. This is not ideal for non-stationary signals like EEG which could show quick changes in spectral characteristics at short time intervals.

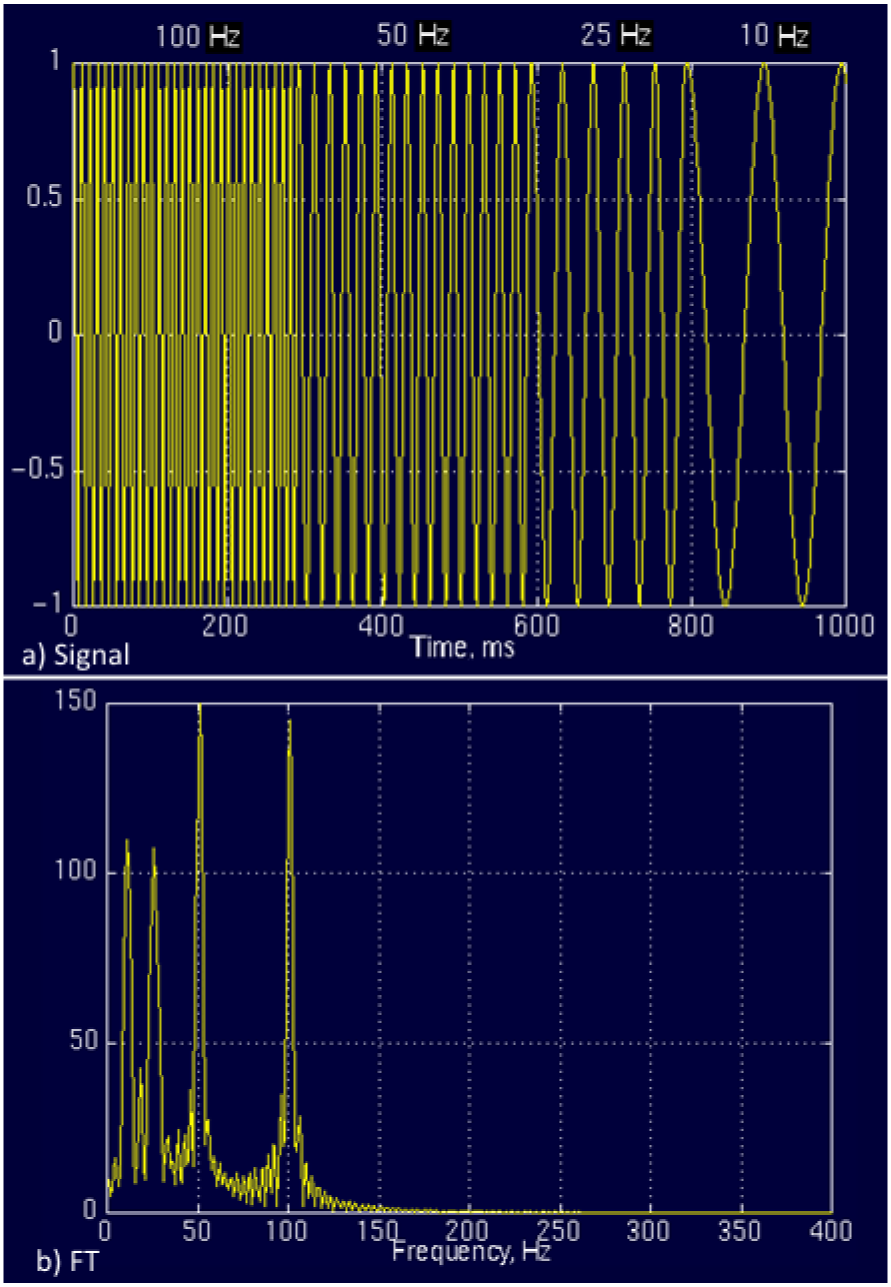

Figure 3.5: Non-Stationary Signal and its Fourier Transform [22]

A preferred way to decompose non-stationary signals into its component frequencies is time-frequency based methods like Wavelet transform, which are now increasingly being used to analyze and process EEG.

$$CWT_x^{\psi}(\tau, s) = \Psi_x^{\psi}(\tau, s) = \frac{1}{\sqrt{|s|}} \int x(t)\psi^* \left(\frac{t-\tau}{s}\right) dt$$

Equation 2: Wavelet Transform

Where τ is the translation factor, *s* is the wavelet scale, ψ is the Mother wavelet, *t* is the time.

The general equation for wavelet transform has two parameters which are used to decompose a signal into its frequency components. The τ (tau) factor which relates to translation or timing information in the signal and the s (Scale) factor which relates to the frequency resolution of the signal. A Wavelet Transform of a signal thus contains both the timing and frequency component information of a signal. The basic method to calculate a wavelet transform consists of taking a prototype wavelet, Morlet wavelet used here (Eq. 3), and then taking a product of the wavelet with the target signal at its start.

$$w(t) = e^{iat}.e^{-\frac{t^2}{2\sigma}}$$

Equation 3: Morlet Wavelet

Where *a* is a modulation factor and σ is the scaling factor

Then this wavelet is translated along the signal and the product is taken at various translated locations (Figure 3.7). This is repeated for a different scale of the same wavelet which tests the signal for a different frequency component along the whole length of the signal. A lower scale corresponds to higher frequency components, while a higher scale detects lower frequency components in a signal (Figure 3.6).

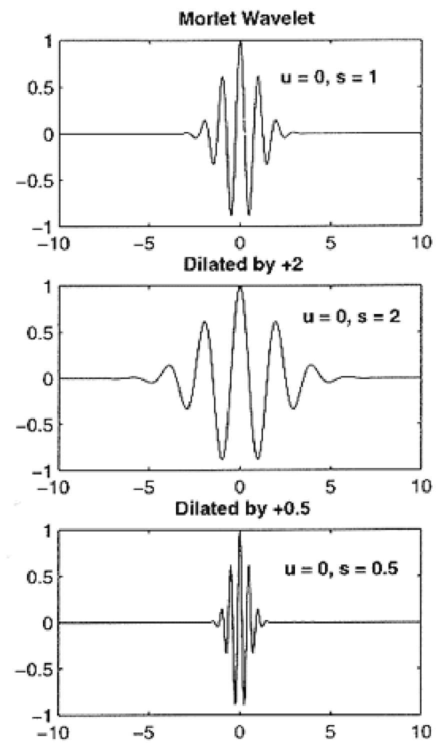

Figure 3.6: Morlet Wavelet at different Scales [23]

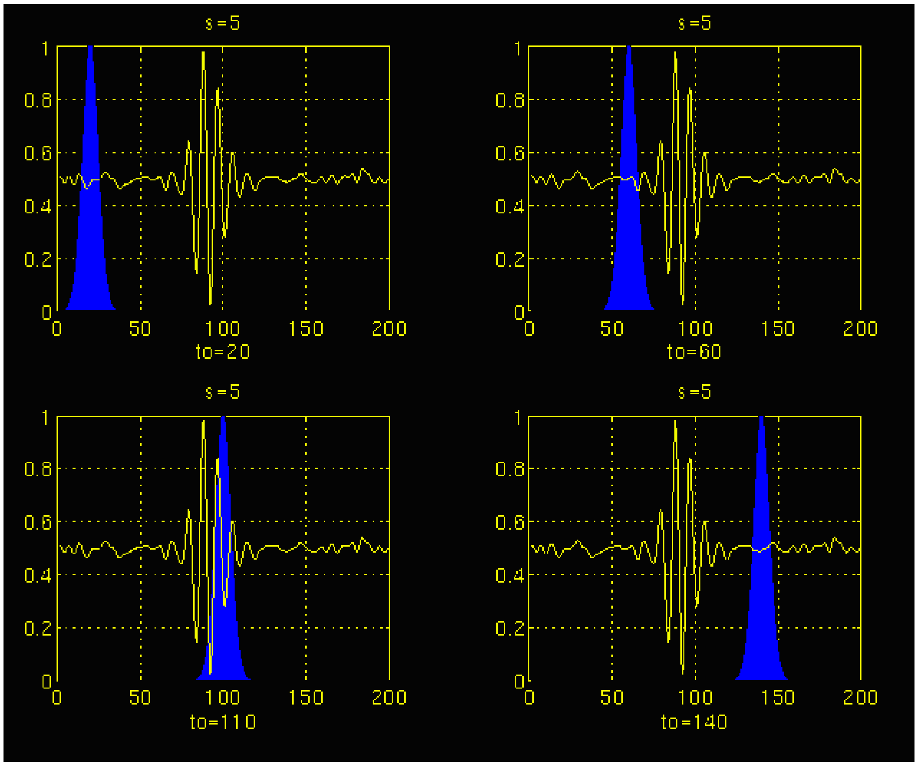

Figure 3.7: Wavelet translation along the signal [24]

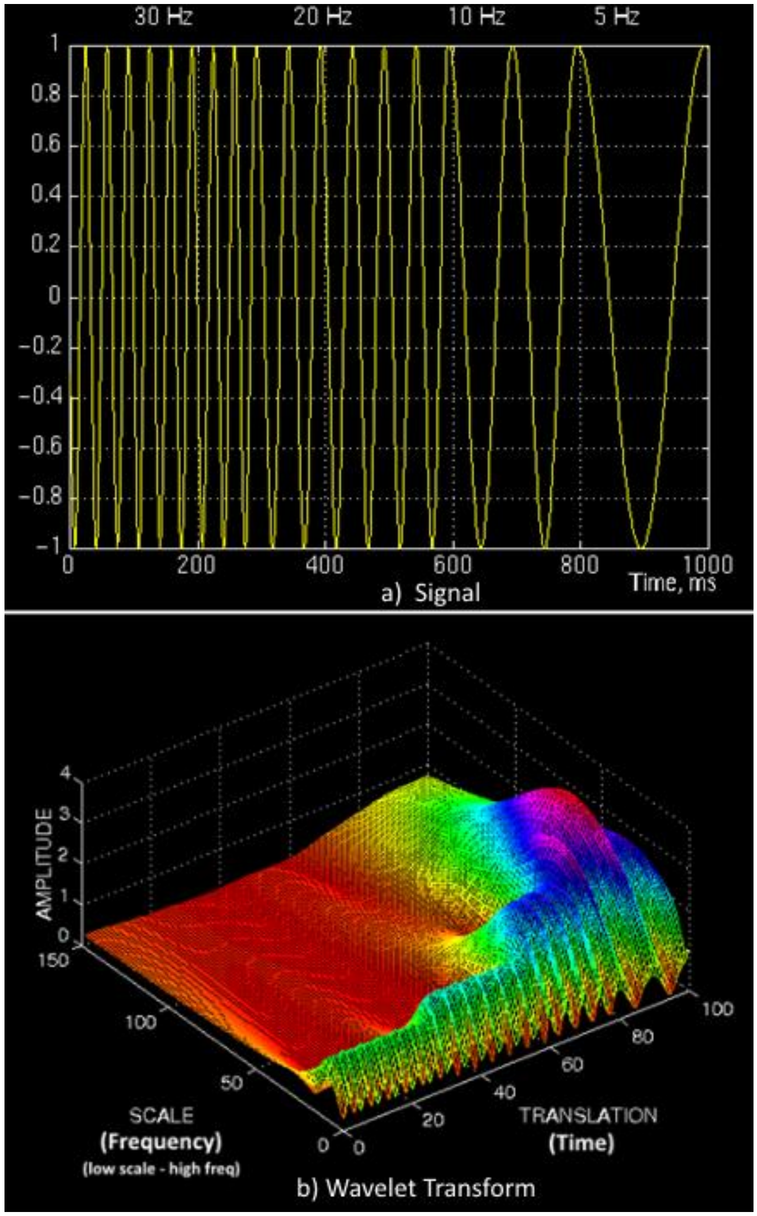

Figure 3.8: Wavelet Transform of non-stationary signal [24]

Since the wavelet transform provides a better way to decompose a signal into its components by extracting both time and frequency information, it is a more appropriate way to process EEG signals. Figure 3.8a shows a non-stationary signal with 30, 20, 10 and 5 Hz components occurring at different 250 ms segments. Its wavelet transform (Figure 3.8b) is able to provide the frequency information about this signal on the Scale axis and it also depicts when these frequency components were present in the signal on its Translation axis. Once components of a signal are extracted, then Coherence can be estimated between corresponding frequency components of two signals at different time segments using the general formula (Eq. 4).

$$WCo(t,f) = \frac{\left|SW_{xy}(t,f)\right|}{\sqrt{SW_{xx}(t,f) \cdot SW_{yy}(t,f)}}$$

Equation 4: Wavelet Coherence

Where *WCo* gives the cross wavelet coherence at frequency *f* and time *t*, *Wxy* is wavelet cross spectral densities of signals x and y, while *Wxx* and *Wyy* are wavelet autospectral densities of the two signals. *S* is a smoothing operator.

Using iteration, coherence values are calculated in 100 ms time segments of event related EEG epochs, between pairs of the surface electrode channels in the five major frequency bands.

The main steps used in the processing are shown in Figure 3.9. The steps are marked with numbers in circles. There is preprocessing stage for EEG data consisting of band pass filtering (1 – 45 Hz) and removal of epochs with lots of artifacts like those due to eye blinking or movement, etc.

1. Once clean data is generated, the relevant epochs of data are selected, in which important events related to the task have occurred – like presentation of the stimulus up to the response of the subject. These epochs are marked “Condition 1” (C1) and “Condition 2” (C2) in the figure. The blue lines in C1 and green lines in C2 are event markers on the EEG data, denoting the times at which Stimulus and Response occur. Taking only this relevant data for processing, reduces the possibility of

data being affected by other processes which might be happening in the brain which are not related to this task. It also reduces the amount of data that needs to be processed, thus making the processing faster.

2. For the sake of understanding let us focus only on the relevant C1 epoch for further processing steps. Since in this method we are estimating connectivity within all the pairs of electrodes, the data from this epoch pertaining from Channels 1 and 2 are extracted out of a total of 62 EEG channels. Furthermore to calculate Event Related Coherence, this epoch is divided into smaller Time Segments of 100 ms each. For Time Segment 1 (TS1), Channel 1 data is separated into its components in the five major frequency bands of Delta, Theta, Alpha, Beta and Gamma. Similarly data from Channel 2 from this time segment is also separated into these frequency bands.

3. To estimate whether Channels 1 and 2 are communicating in the Beta frequency band in this time segment (TS1), coherence is calculated between the Beta components of Channels 1 and 2. This value shows whether in the first 100 ms (TS1) after presentation of a stimulus in the experiment protocol, the channel locations 1 and 2 are communicating in the frequency range of 12 – 30 Hz in the First condition (C1). This gives us the Coherence between Channels 1 and 2, in the Beta band in Time segment 1 and is stored to be compared later with a corresponding value from Condition 2 epoch.

4. Paired t-tests are performed between these corresponding values between the C1 and C2 conditions, once data from all other relevant epochs are generated. If statistically significant, this would be considered an activated functional connection which could help in differentiating these two conditions.
5. This is repeated for other frequency bands in this time segments.
6. Then this comparison is repeated for all other time segments and frequency bands in this epoch.
7. This is then extended to all other channel pairs and all epochs from both conditions for all subjects.

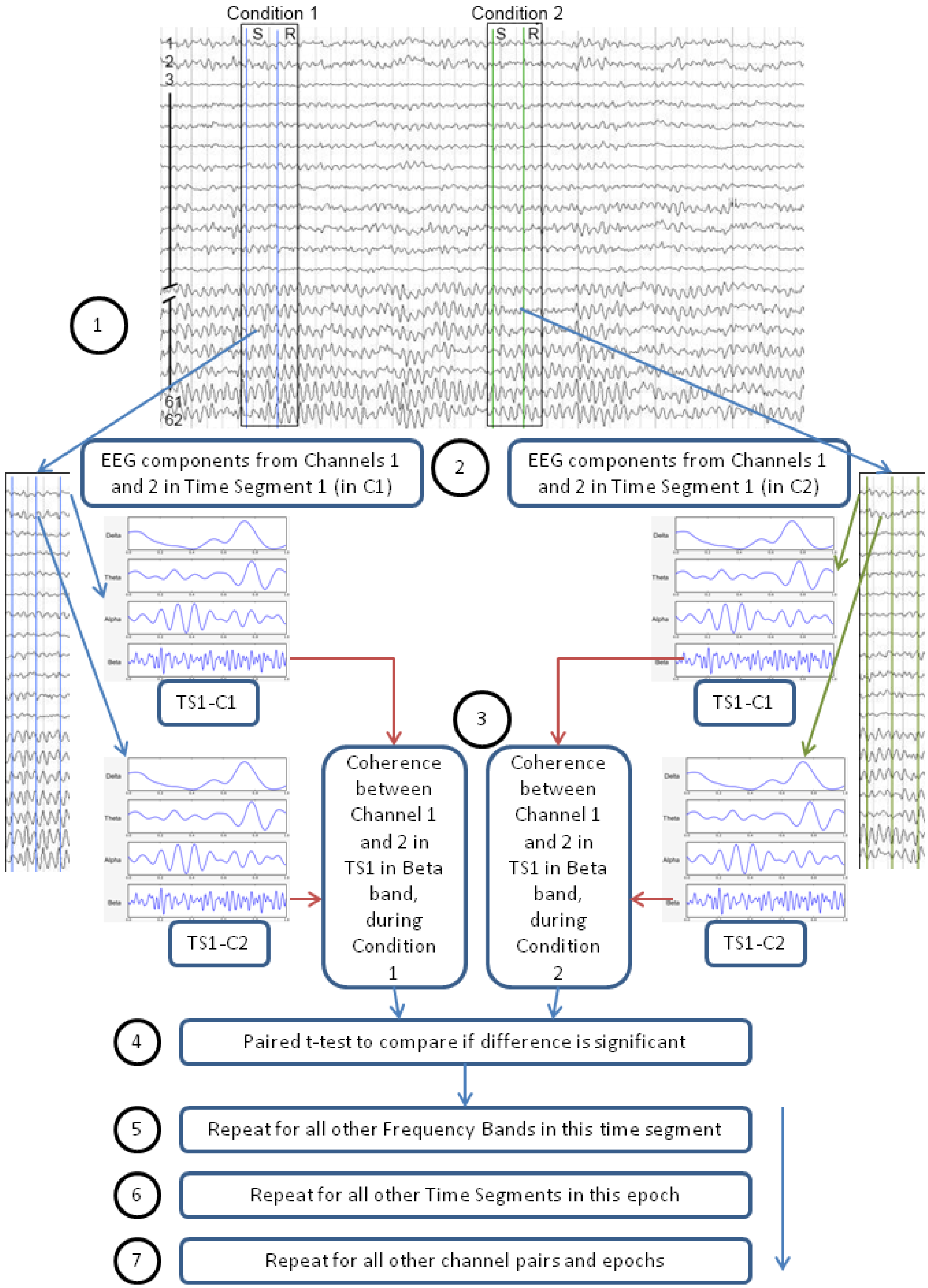

Figure 3.9: Inter Electrode Event Related Coherence (IE-ERC)

3.4 Surface Connectivity Profile

After processing EEG channel data, the result is a set of those IE-ERC values which show statistically significant differences in the two conditions which we need to differentiate. These values indicate those connections between electrodes which were always significantly higher in one condition compared to the other. Thus we are able to produce a Surface Connectivity Profile for each condition, in each time segment and the five major frequency bands. These connectivity profiles can be plotted on EEG electrode locations to depict statistically significant differences visually.

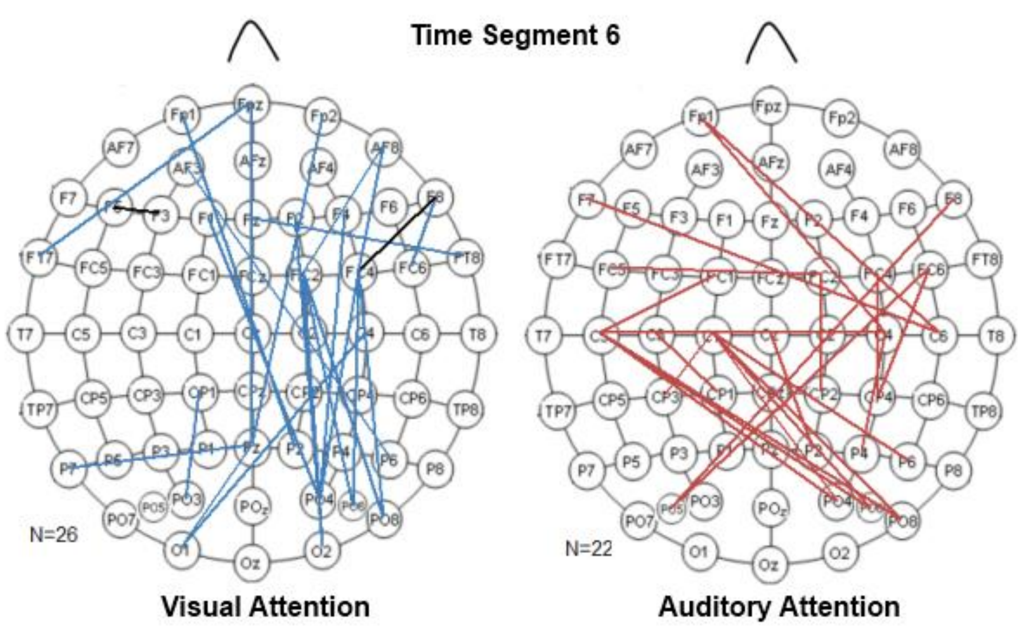

Figure 3.10: Surface Connectivity Profile (AvsV-TS6-Beta)

Figure 3.10, compares Surface Connectivity Profiles of Auditory and Visual attention plotted from actual data from the Cross modality Selective Attention experiment. In the Visual attention condition, the subject has been instructed by a cue to focus on the screen for a visual stimulus and respond when the stimulus is the letter “B” or number “2”. In the Auditory attention condition the cue directs the subject to focus on the sound coming from headphones and respond to a target sound stimulus. This Connectivity Profile is for Time Segment 6 (between 500 ms to 600 ms after Cue presentation) and shows that during that time period, there were 26 connections in the Beta frequency range between EEG electrodes which were significantly higher in the Visual attention condition and 22 different connections between electrodes were higher during the Auditory attention condition. This shows three distinct aspects of the cognitive task – the electrode location, the frequency range and time segment information. Firstly it shows the EEG electrode locations which were involved in these connections. The Visual attention condition clearly shows that more connections between the frontal attention areas and the occipital visual areas were active, while in the auditory condition more active connections were found between Parietal electrodes and central electrodes. Secondly this interaction is in Beta frequency range and a profile for other major bands would show different variations of active connections. Thirdly this profile shows functional connections between electrodes in this time segment, which occurred 500 ms after Cue presentation. In other time segments and frequency bands, different channel connections would be active. Thus processing and portraying data using the IE-ERC method shows us the complex connectivity changes between EEG channels, during different time segments and all relevant frequency bands. This method is well suited to capture the complex neurophysiological mechanisms underlying the cognitive function of attention.

4 Study on Cross Modality Attention

4.1 Introduction

In our daily life, it is necessary to switch paying attention from one sensory modality to other while interacting with our environment. In some scenarios it is more important to process the visual information, while in some other situations auditory information becomes more valuable for taking action. As previously stated in Chapter 2, it is known that the attention network resides in parts of the frontal and parietal lobes of the brain while the auditory areas are found in the temporal lobe and the visual information is processed in the visual cortex in the occipital lobe. The dynamic interplay of these regions makes it possible for us to switch attention from one of these sensory modalities to the other. An experimental protocol is designed for subjects to partake in a cognitive task which gives an opportunity to observe whether functional connectivity between various EEG channels would show differences when focusing on one of the modalities compared to the other. This kind of an estimation of attention focus can also be used in a situation where a person is required to pay attention to one of these sensory modalities while ignoring the other.

4.2 Experiment Protocol and Participants

An experiment is designed to explore cross modality attention between the visual and auditory domains by using cues and simultaneous auditory and visual stimuli. In the experiment, a cue would instruct the participating subject whether to focus on a subsequent auditory or a visual stimulus and respond to that. Both the auditory and the visual stimuli after the cue were presented simultaneously.

The experiment equipment setup is shown in Figure 4.1 and consists of the participant seated in front of an LCD screen, with a keyboard and headphones. The participant wears an EEG cap which is connected to an EEG amplifier. The amplifier is connected to a laptop to collect the EEG signals. A stimulus presentation script is run on the laptop which presents visual and auditory stimuli on the LCD screen and the headphones using Presentation (Neurobehavioral Systems Inc) software. The participant is required to press a response button on the keyboard to valid target stimuli.

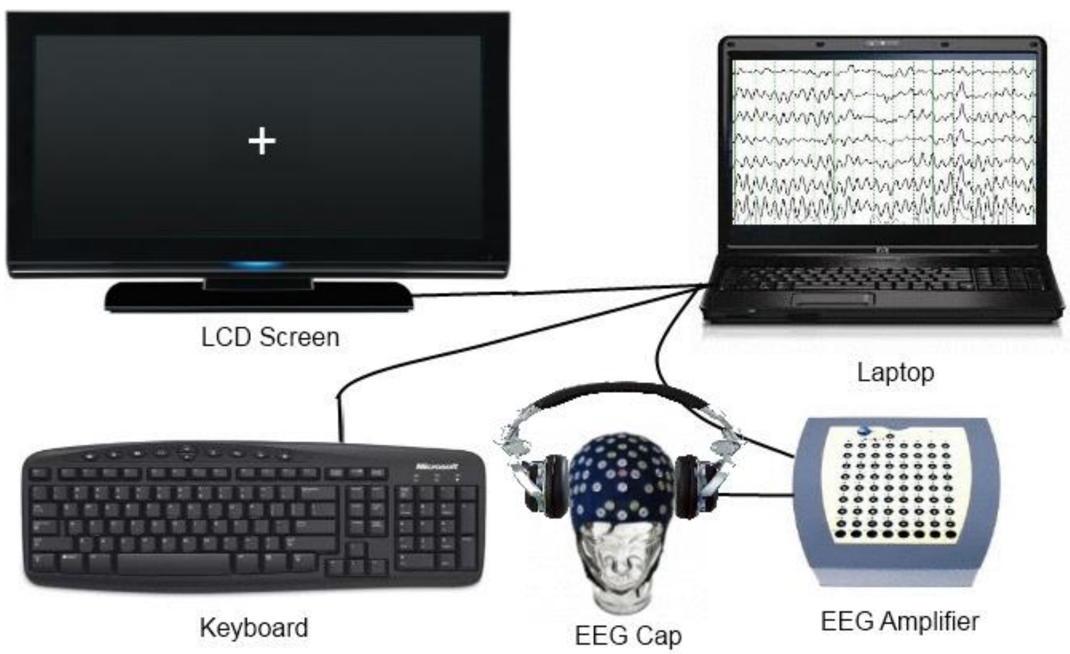

Figure 4.1: Experiment Setup

Figure 4.2 below shows the protocol design schematic. The experiment is divided into two blocks – Block “B” and Block “2”. In Block “B”, the participant is told that the target to which he is required to respond to is the letter B, which could come either as a visual letter on the LCD screen or a sound in his headphones. Every trial of this block has two or three events – one cue, one stimulus set and a response if required. The cue is given on the center of the LCD screen in the form of a picture – either showing a headphone or an LCD monitor. These cues direct the participant to pay attention either to the sound coming from the headphones or the visual stimulus presented on the LCD screen, respectively. The cue remains on screen for 1s followed by simultaneous sound and visual stimuli presented on the LCD screen and the headphones respectively.

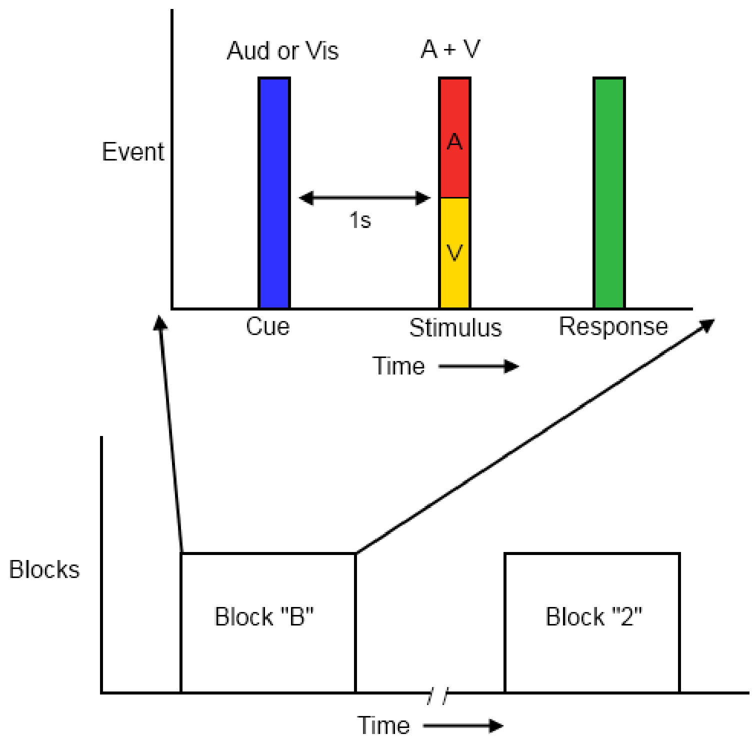

Figure 4.2: Cross Modality Protocol

The different combinations of possible cues and stimuli along with valid and invalid responses are outlined in Figure 4.3 for the Block "B" and Figure 4.4 for Block "2". The first column shows the Block, second shows the possible cues (auditory or visual) and the third shows the possible stimuli set that could be presented after the cues. The stimuli set which require a response are indicated by green arrows from the cue to the stimuli, while those invalid trials which do not require a response have red arrows from the cue to the stimuli.

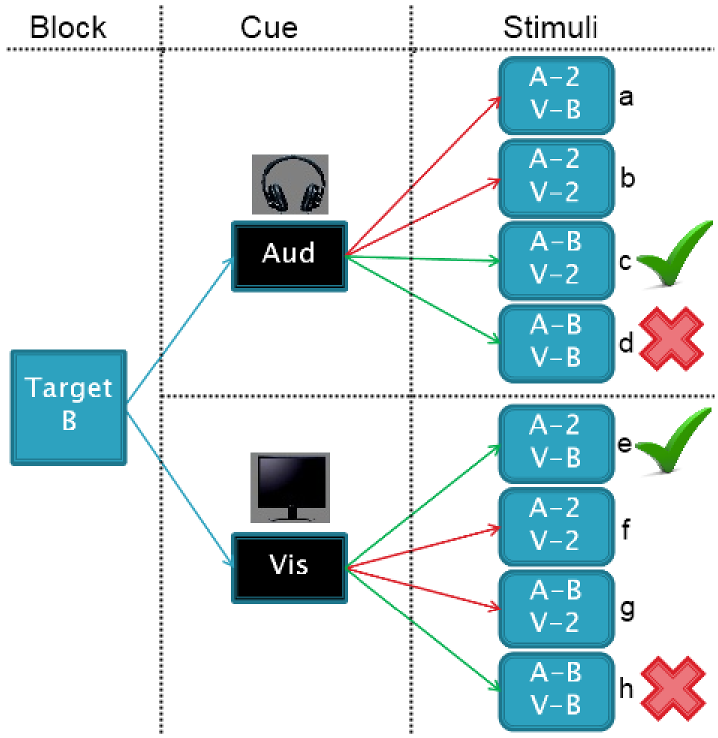

Figure 4.3: Cue Stimulus and Responses in Block "B"

Suppose that "B" was the target (Block "B"), and the cue was LCD Screen (Visual attention), and the stimuli were "2" in the headphones and "B" on the LCD screen (Case e) – in this case the subject will respond by the press of a button on the computer keyboard, since he was supposed to focus on the visual stimuli and the target "B" was presented to him visually, while ignoring the auditory stimuli. On the other hand if in Block B, he was given the Visual Cue and the stimuli were – "2" on the screen and "B" on the headphones (Case g), in this case the subject will not respond since there was no Visual "B". If in a trial the cue was headphones (Auditory focus), and the stimuli were "B" on the headphones and "2" on the screen (Case c), this would require the subject to respond. It should be noted that in Block B, if both the stimuli on the screen and in the headphones are "B", then regardless of the cue, the subject needs to press the response button. Keeping this in mind, this condition is currently excluded from analysis (shown by red X), since it would not be clear whether the subject was paying attention to the visual or the auditory stimulus (Cases 'd' and 'h'). Only the clearly distinguishable stimuli set, Cases 'c' and 'e', are compared when analyzing EEG data.

In Block "2', the target becomes the number "2", while the rest of the procedure remains the same. In this block, Cases 'a' and 'b', after the Auditory cue would require a response, while Cases 'f' and 'g' would require a response after a Visual cue. Since the stimuli sets in Cases b and f are identical (2 both on LCD screen and headphones), they are excluded from analysis.

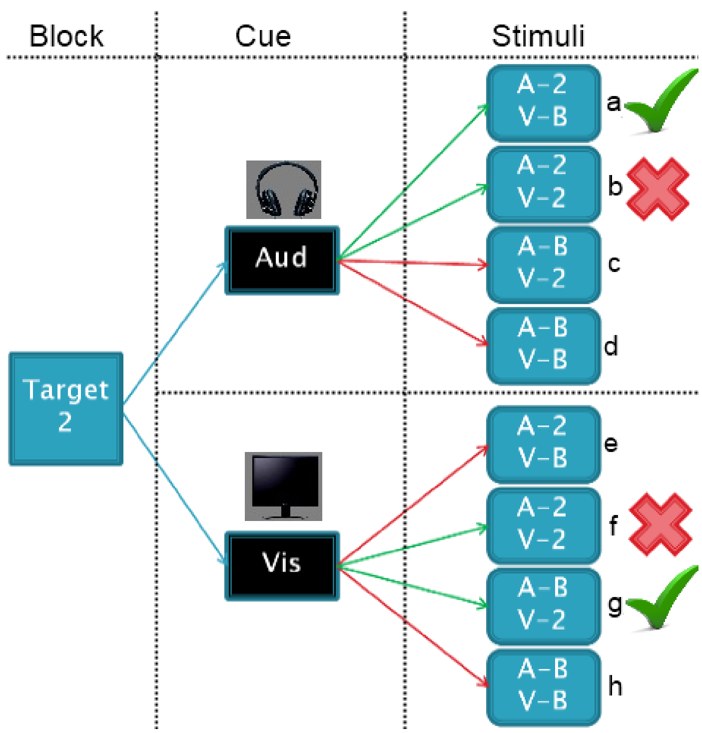

Figure 4.4: Cue Stimuli and Response in Block "2"

Each participant is required to do both these blocks (with 200 trials in each block) and the order of these blocks is randomized between different participants. This experiment thus requires the participant to pay attention to one of his sensory modality, either visual or auditory, while ignoring the other. By processing this set of EEG data by applying IE-ERC method, functional connectivity changes can be assessed between these two conditions of auditory and visual attention.

Ten healthy male volunteers gave informed consent and took part in the experiment, which was approved by the University IRB. All had corrected to normal vision, were right handed and in the age range 20 – 23 yrs (Mean: 21.4; SD: 0.84).

4.3 Results and Discussion

4.3.1 Connectivity after Cue and before Stimulus presentation

EEG data collected during this experiment has event markers for the different cues and stimuli set and data from relevant epochs are extracted and analysed. Each epoch starts at cue presentation and lasts till 500 ms after the stimuli set presentation. Since the main focus of this study is in determining whether functional connectivity differences can be observed when a participant focuses on an incoming visual or auditory stimulus, the analysis using IE-ERC is done from cue to the presentation of the stimuli set. This whole epoch is divided into 100 ms time segments – the segment from cue presentation to 100 ms after cue, being called Time Segment 1 (TS1), the segment from 100 ms to 200 ms after cue being called Time Segment 2 (TS2) and so forth up to Time Segment 10 (TS10) which represents the last 100 ms before stimuli set presentation. This is the relevant time in which the processing related to either visual or auditory attention takes place in this experiment. As previously mentioned EEG from each of these segments is divided into its component frequency bands of Theta (4-7 Hz), Alpha (8-13 Hz), Beta (14-30 Hz) and Gamma (31-45 Hz) and then Event Related Coherence is calculated between corresponding time segments of the two conditions.

The various figures from here on show those activated functional connections which should statistically significant changes at $p<0.01$ across ten participants. Figure 4.5 shows the number of activated connections (y-axis) across ten subjects between the Auditory and Visual attention conditions, changing over progressing time segments (x-axis) in the Alpha band.

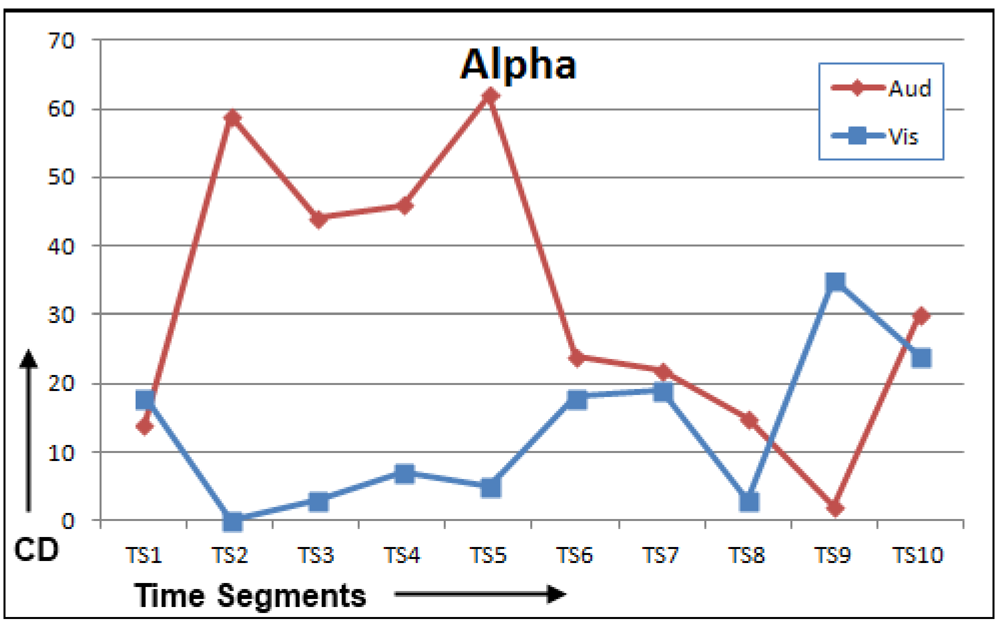

Figure 4.5: Alpha band dynamics (p<0.01) across 10 subjects

In TS4, which represents data between 300 ms to 400 ms after presentation of cue, it is seen that the number of activated functional connections is 46 (N=46) in the Auditory attention condition and 7 (N=7) in Visual attention condition. This means that there were 46 such connections between electrodes in the Alpha band which were more active during the Auditory attention condition than during the Visual attention condition. This gives an estimate of higher functional connectivity during this time segment and frequency band in the auditory condition. Similarly it also shows that 7 functional connections were more active in the visual condition in this time segment and frequency band. In Figure 4.6 CR numbers denote the number of connections which were between closely located electrodes, for example P7 and PO7, depicted with black lines.

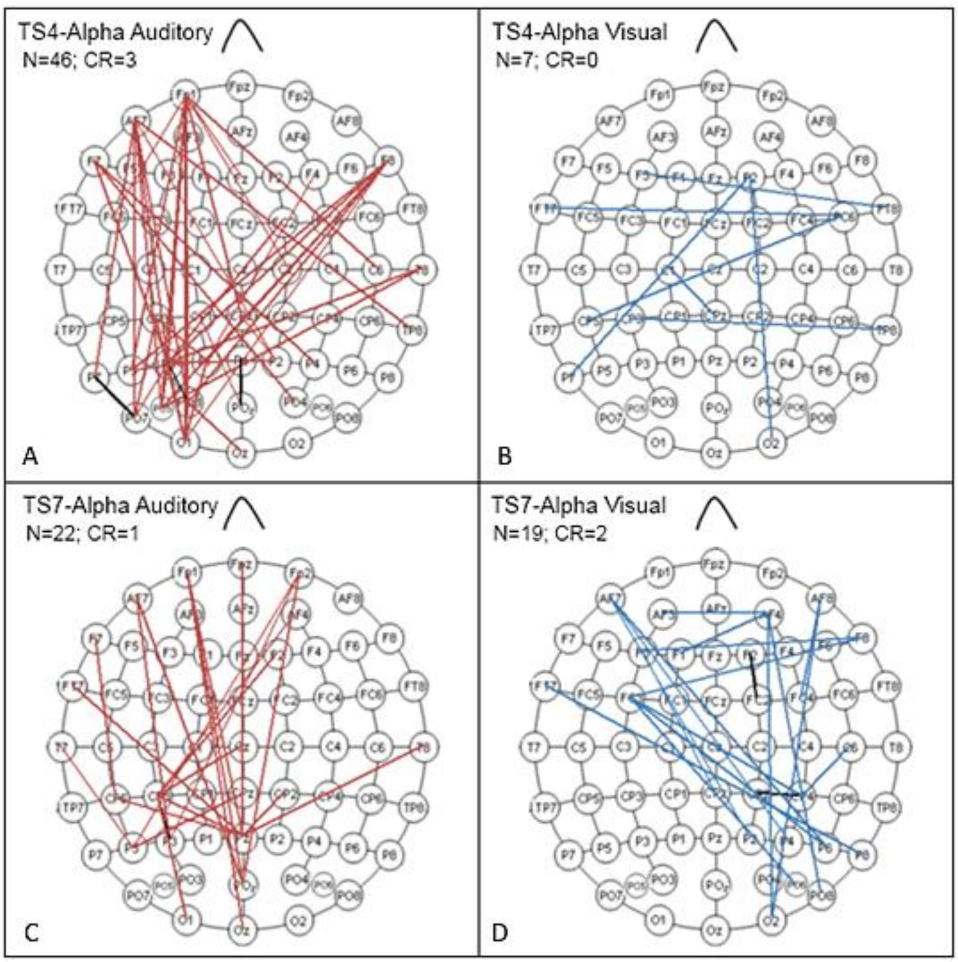

Figure 4.6: Surface Connectivity Profiles during TS4 and TS7 in Alpha band (p<0.01)

The Surface Connectivity Profile (SCP) in Figure 4.6 shows which connections between EEG electrodes were more active in each condition during the TS4 and TS7 in Alpha band. The upper panels A and B show SCP for TS4, while the lower panels C and D show that from TS7. Auditory condition is on the left side (A and C) and Visual on the right (B and D). For TS4, in addition to the number of connections being different, it can be observed that in the Auditory (Panel A) condition more connections on the left frontal and occipital sides are active. Since Alpha range oscillations could represent inhibition (Klimesch, Sauseng et al. 2007), it is possible that during this time period the connections between attention regions in the frontal cortex and visual regions in the occipital regions were inhibited, since the participant was paying attention to the auditory stimulus and ignoring the visual stimulus. On Figure 4.6-B the connections which were more active during the visual condition are depicted. Here it is seen that the connections between the left and right side of the brain in the central and temporal regions are activated. This could mean that temporal regions, which process sounds, are being inhibited by some attention regions in the central and parietal regions as the subject is focusing attention on the visual domain.

Figure 4.6 lower half, shows the SCP during Time segment 7, in which the number of connections is comparable, being 22 in Auditory condition and 19 in Visual condition. But it can be observed that the channel pairs which are active are distinct during these two conditions. Auditory condition (Panel C) shows more active connections on the left hemisphere while the visual condition (Panel D) shows more on the right hemisphere. This could be due to the preferential processing of language in the left auditory regions (Pinel and Dehaene 2010) and could also indicate the though visual stimuli were shown in the center of the visual field, there is a dominance of right occipital regions during visual attention. On comparing the Visual condition in TS4 (Fig 4.6 Panel B) and TS7 (Fig 4.6 Panel D), it can be observed that connectivity in the Alpha band itself changes with time. This represents the changes in functional connectivity which happens over time while processing a stimulus. Using IE-ERC to estimate functional connectivity thus presents a method to see the neurodynamics of cortical functioning during different conditions.

Theta oscillations are associated with memory and attention functions (Basar, Basar-Eroglu et al. 2001, Choi, Jung et al. 2010). Figure 4.7 shows the Surface Connectivity Profiles in the Theta band for some Time Segments (marked TS2, TS5 and TS8). The graphical plot at the center of the figure shows the trend of number of activated connections over time between the two conditions.

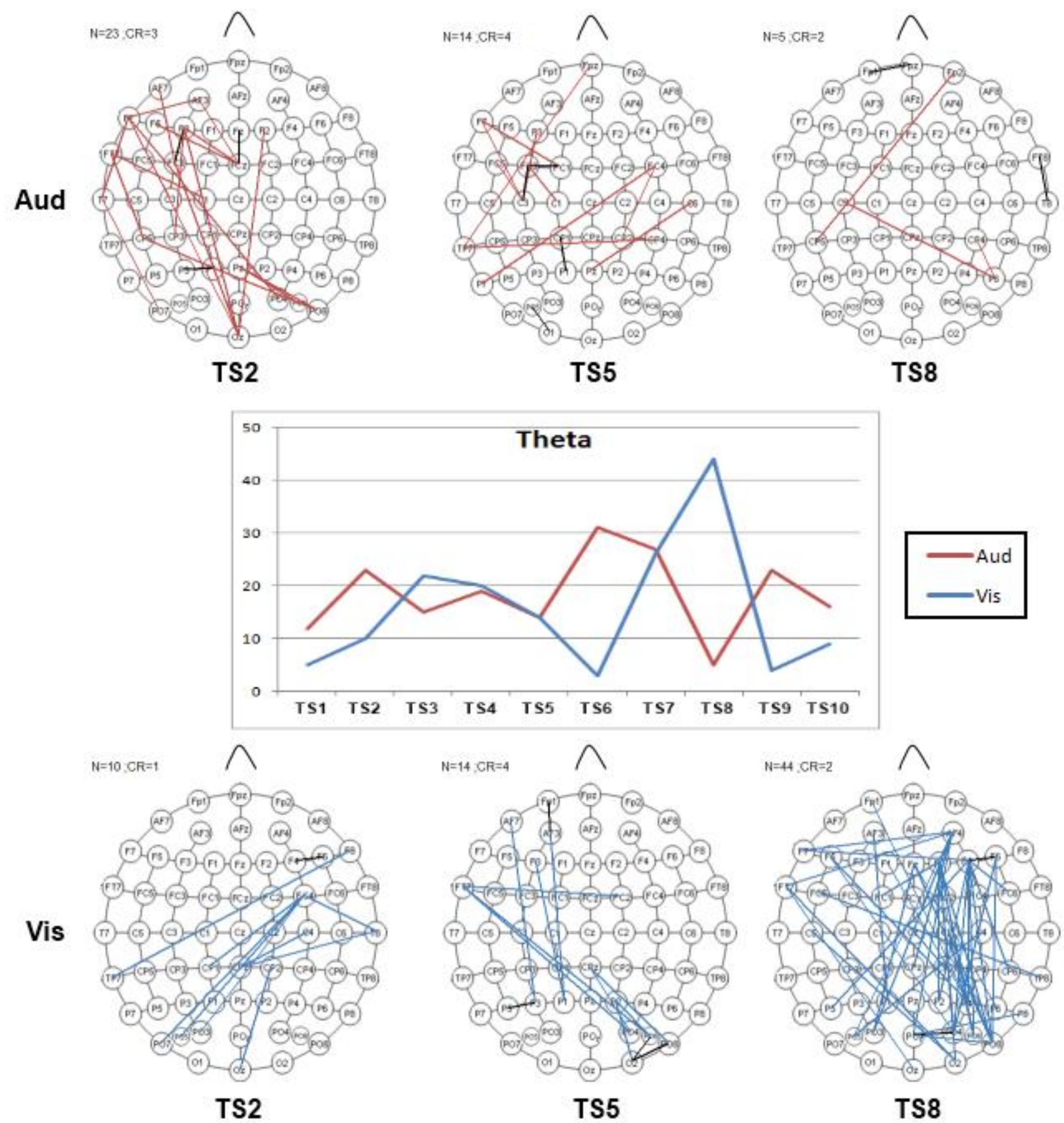

Figure 4.7: Surface Connectivity Profiles in Theta band (p<0.01)

The changing numbers of activated connections show that in the two attention conditions functional connections between different channels are varying with time. In TS6, TS8 and TS9 the two conditions show an opposing trend in AFC numbers. In TS5, where the absolute number of activated connections is the same (14) for both conditions, the Surface Connectivity Profiles of the two conditions show distinct active connections. In the auditory condition frontal and central electrodes on the left side and some central electrodes on the right side are mostly active, while in the Visual condition frontal and central electrodes on left side and occipital electrodes on the right side show more activity. In TS8, there is increased connectivity in the Theta band in the visual condition, while the auditory condition shows very few active channel pairs. Some studies have previously shown that during bimodal stimulation, Theta band activity increases (Sakowitz, Schurmann et al. 2000). By using IE-ERC at 100 ms time segments it can be clearly seen that activity in this band changes over time in the preparatory phase.

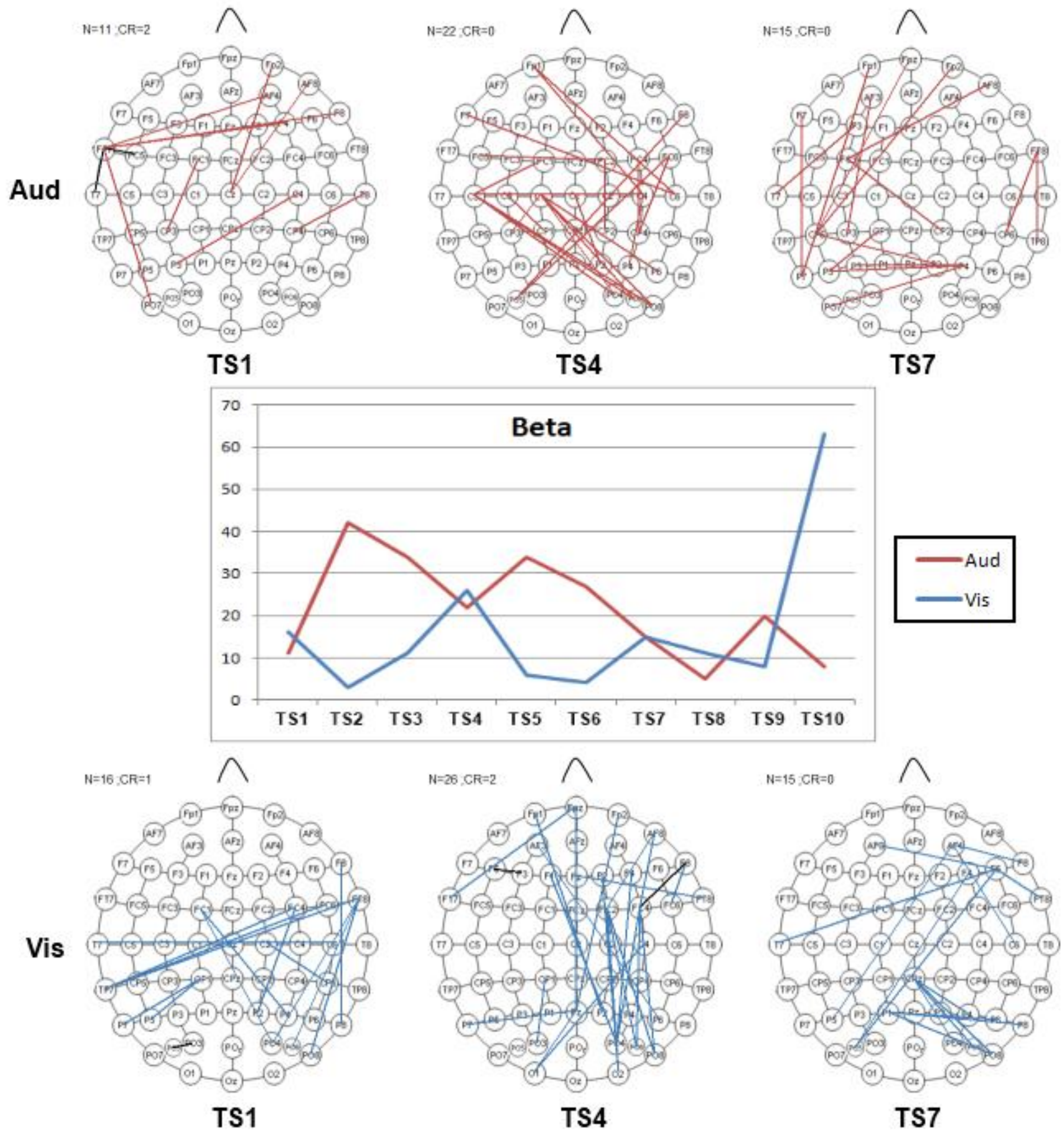

Figure 4.8: Surface Connectivity Profiles in Beta band (p<0.01)

Figure 4.8 shows the comparative Surface Connectivity Profiles in the Beta band at Time Segments 1, 4 and 7. Various changes along the time segments can be observed between the two conditions in this band. The number of Activated Functional Connections (AFC) shows a wave like character in the first 600 ms and this could be related to the switching between the two sensory modalities (Busch and VanRullen 2010). In that study however, phase changes in the Theta band were seen.

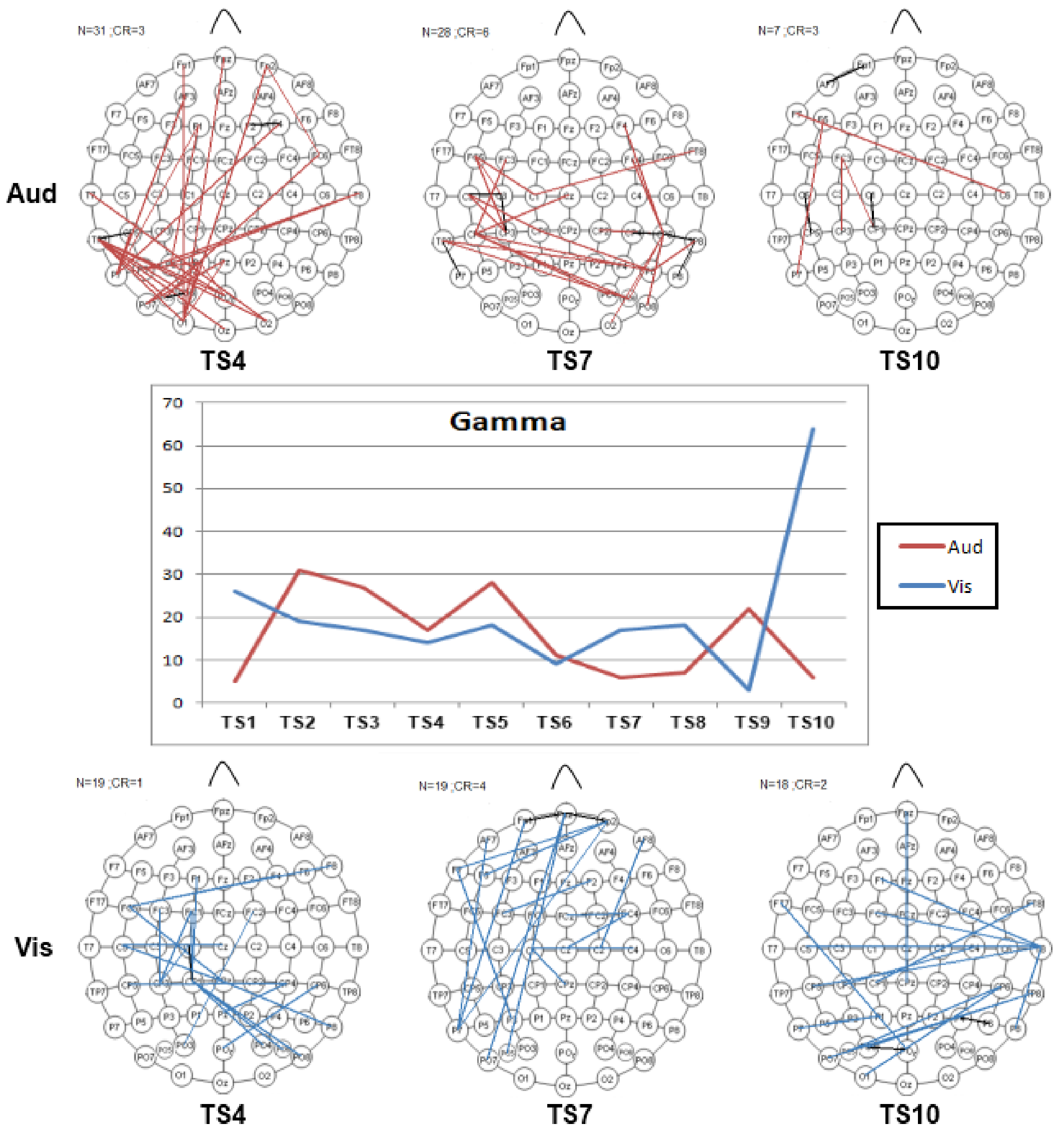

Figure 4.9: Surface Connectivity Profiles in Gamma band (p<0.01)

Surface Connectivity Profiles in Gamma band are shown in Figure 4.9. By comparing the number of activated connections in the Beta and Gamma bands in later time segments, similarities can be noticed. There is some evidence to suggest that the classical Beta band can be subdivided into Beta 1 (13-19 Hz) and Beta 2 (20-30 Hz) bands. Among these sub-bands, the Beta 2 band is closer to the Gamma band in functional significance, while the Beta 1 band is closer to Alpha band. This could be the reason for the Beta band connectivity changes being similar to those in the Gamma band.

4.3.2 Main Active Electrodes

In the results it can be observed that not all channels are active in all time segments and even within every time segments, some channels make more functional connections with others. This also depends on the various frequency bands, since different brain regions synchronize with other regions in specific frequency ranges while processing a cognitive stimuli.

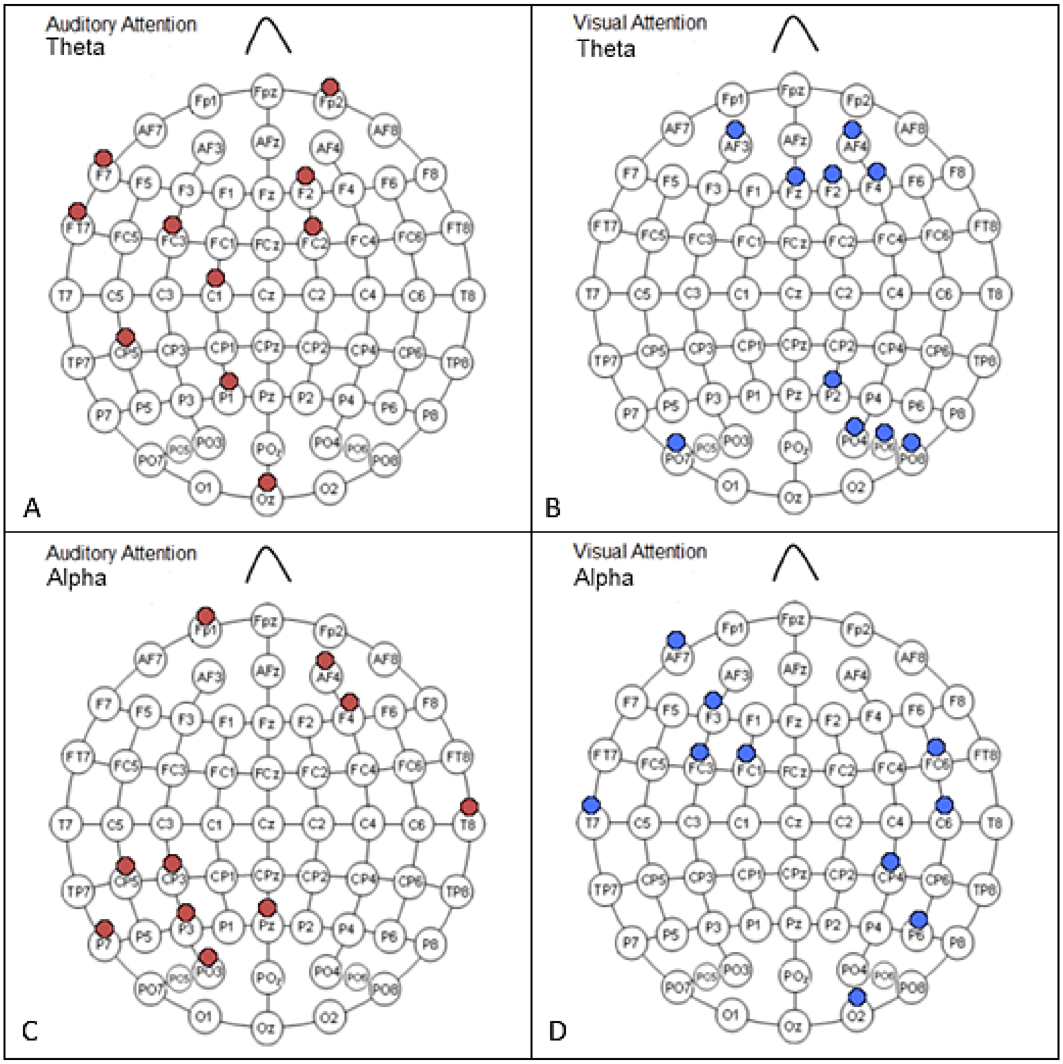

Figure 4.10: Main active channels in Theta and Alpha range

Figure 4.10 shows the top ten electrode locations which are active in the auditory and visual attention conditions in Theta and Alpha frequency bands. This represents the aggregate number of connections made with other channels after cue presentation up to stimulus set occurrence (TS1-TS10). The left side has main active electrodes for auditory attention (Panel A and C) and the right side has those from the visual condition (Panels B and D). Theta oscillations are related to memory and attention processes. In the auditory attention condition, frontal and left central electrodes are active, while in the visual attention condition, frontal and right parieto-occipital channels are active. Alpha is related to idling or inhibition processes but it could also be responsible for attention and other functions (Palva and Palva 2007). For the auditory condition, left temporal and central electrodes are active, which could indicate the association of long range Alpha band functional connectivity between the left auditory area and frontal attention regions. In the Visual condition left frontal locations and right central and occipital channels are active.

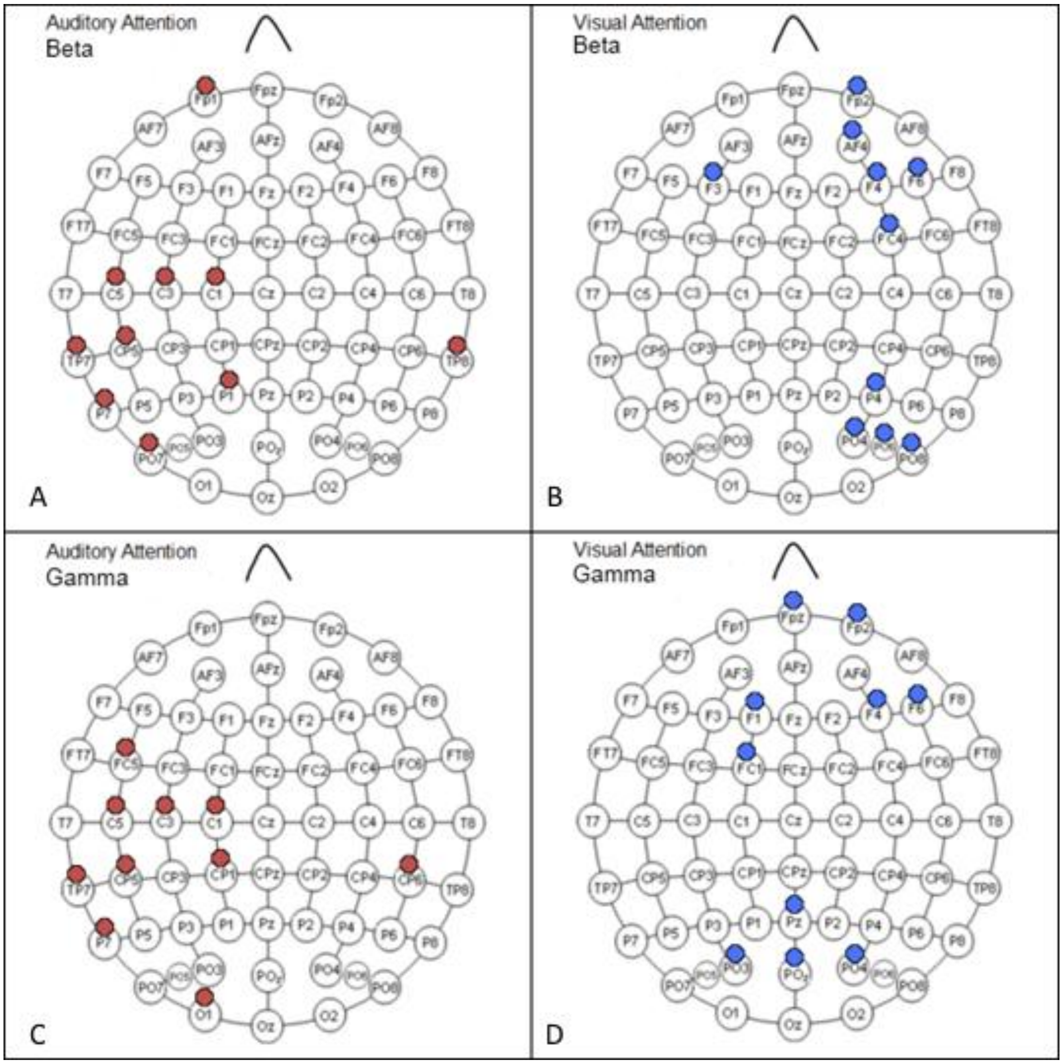

Figure 4.11: Main channels in Beta and Gamma range

Beta and Gamma oscillations are involved with the actual processing of the stimuli and in binding of object features (Meador, Ray et al. 2002, Basar 2004, Tallon-Baudry 2009). Gamma band could be responsible for short range interactions while Beta might represent that over longer distances (Kopell, Ermentrout et al. 2000).This could explain the high activity of temporal and central channels in the auditory condition (Panels A and C) and the occipital and frontal channels in the visual condition (Panels B and D).

4.3.3 Common Connectivity for Visual Attention

In this protocol, after cue presentation and before stimulus gives the participants ample time to prepare and focus on the relevant stimulus modality. If the cue directed them to pay attention to the incoming auditory stimulus, they could recall their target (say “B”) and start paying more attention to their earphones. When the stimuli set is presented, they could quickly decide whether the sound was “B” or not and if it was then they would press the response button. By comparing time segments before and after the stimulus presentation it is possible to assess whether there are any preparatory signals before stimulus presentation which are also present after the stimulus is presented and processed. These functional connections activating in the preparatory phase and then occurring again during actual processing of the stimulus could give insights into the functional connectivity required for attention in a particular domain.

Thus a search was conducted to find those channel pairs which were active both in the pre and post stimulus time segments. For the visual condition, there were 16 such common connections, while for the auditory condition there were 37. These channel pairs and frequency bands could represent those specific functional connections which are required to keep task features in mind during the preparatory phase and then eventually be used in task performance once stimuli set is presented.

There were no common connections seen in the TS1 (0-100 ms after cue) and TS2 (100-200 ms after cue). Figure 4.12 depicts the Surface Connectivity Profiles for TS3 to TS6, showing the active connections in the various frequency bands. Figure 4.13 depicts the same for TS7 to TS10. The stimulus set occurs at the end of the TS10.

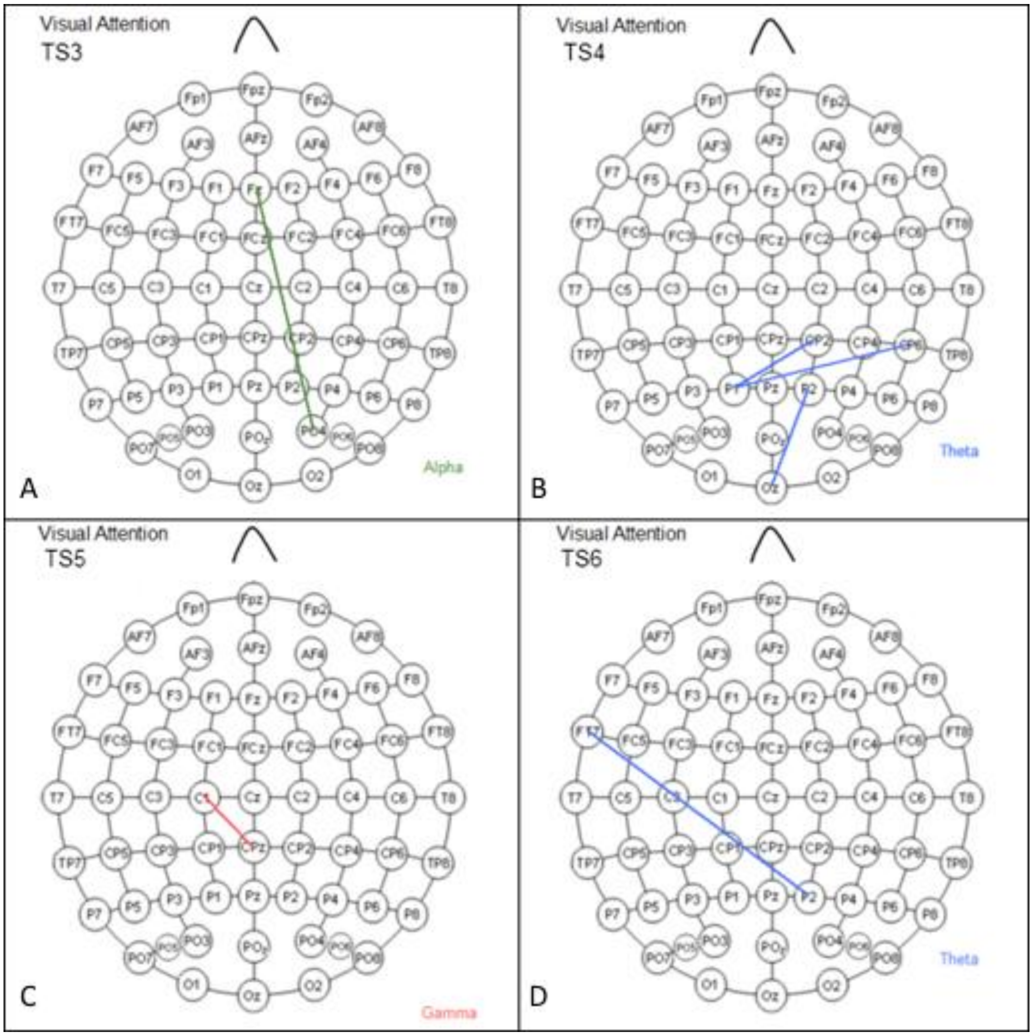

Figure 4.12: SCPs for Visual condition TS3 to TS6

In TS3 (Panel A), one connection between frontal channel Fz and parietal channel PO4 is active in Alpha range, while in TS4 (Panel B) 3 connections between central and parietal and one occipital channel are active (P1-CP2, P1-CP6, P2-Oz), which are all in Theta frequency range. TS5 (Panel C) shows one active connection between central channels C1 and CPz, in Gamma range and TS6 (Panel D) shows one connection between P2 and FT7 in the Theta range.

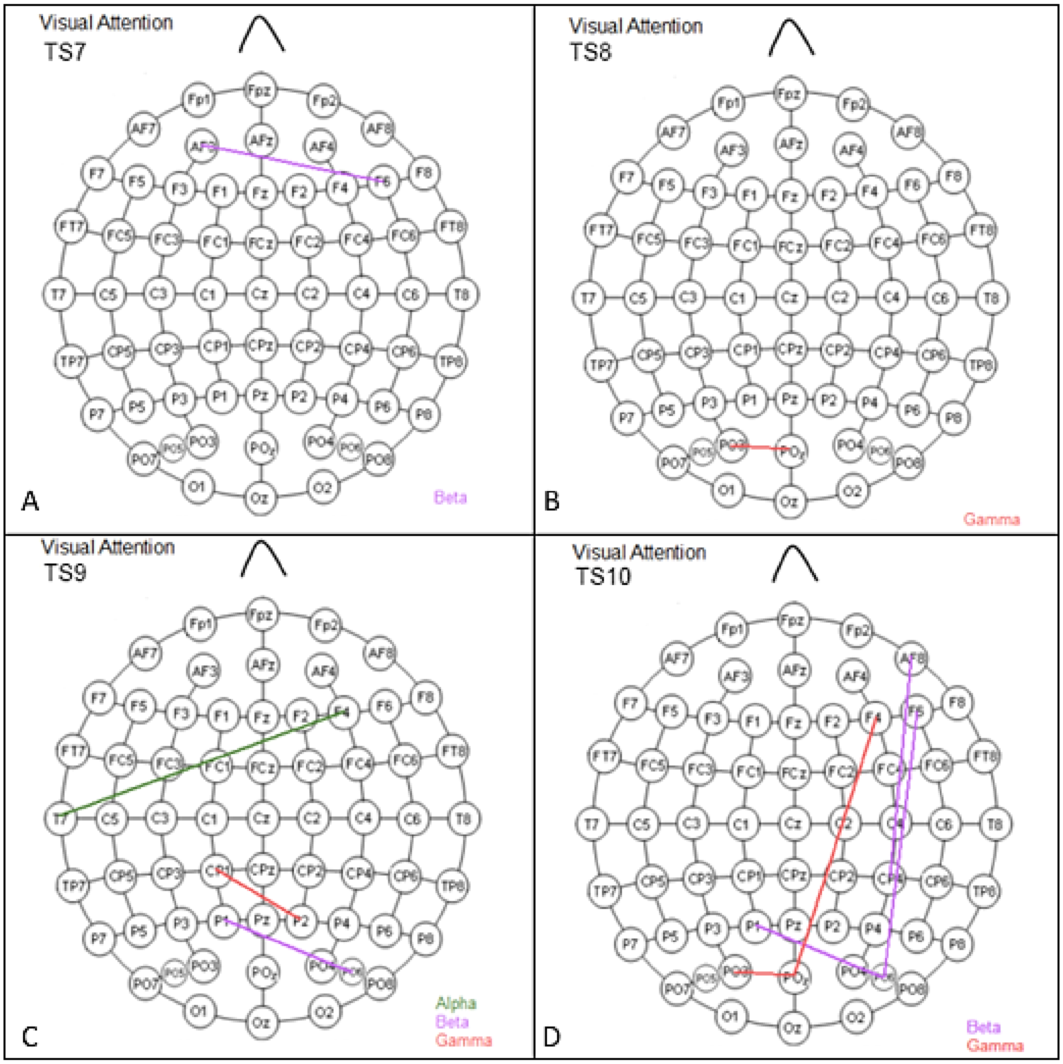

Figure 4.13: SCPs for Visual condition TS7 to TS10

In TS7 (Fig 4.13-A) there is one active connection in the Beta range between channels AF3 and F6, while in TS8 (Fig 4.13-B) there is a connection between PO3 and POz in the Gamma range. TS9 (Fig 4.13-C) shows three distinct connections in different frequency bands – F4-T7 in Alpha, P1-PO6 in Beta and CP1-P2 in Gamma. In TS10 (Fig 4.13-D), the last time segment before stimuli set presentation, there are three active connections in Beta range (AF8-CP4, F6-PO6 and PO6-P1) and two in Gamma range (F4-POz and POz-PO3).

These topographical plots in time segments before the stimulus presentation show how various connections between different channel pairs become activated in various frequency bands in visual attention condition. The next plot shows when these same connections were active while the participant processed the actual stimulus set.

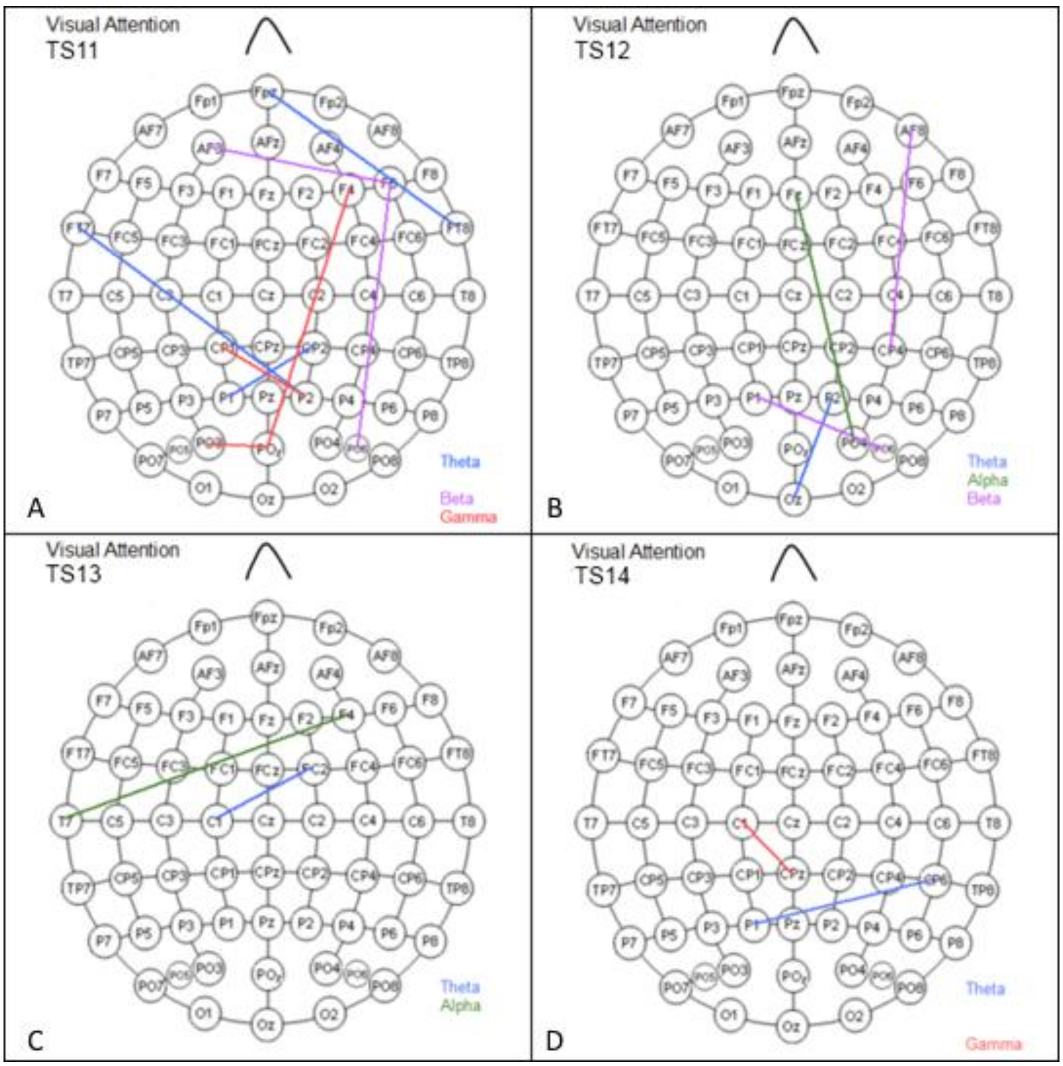

Figure 4.14: SCPs for Visual condition TS11 to TS14

Figure 4.14 shows the same connections becoming active in the post stimulus time segments, which were initially active in the preparatory phase after cue. In TS11 (Fig 4.14-A), just after stimuli set is presented, there is Theta, Beta and Gamma activity. Considering that Theta activity is associated with memory processes, it is reasonable that oscillations in this frequency band will be observed just after stimulus arrives, because the participant would need to recognize whether this is a valid trial. Gamma and Beta activity is responsible for stimulus processing and feature binding and this could explain their presence in this time segment. In the later time segments (Fig 4.14-B,C,D) also different connections in the major frequency bands become active to process the stimulus and make a response.

4.3.4 Common Connectivity for Auditory attention

As in the visual condition, a search was made to find those connections which were commonly active before the stimulus presentation and also after it. There were 37 such connections between TS1-TS10 (after cue and before stimulus) which were also active in TS11-TS14 (after stimulus). These common connections might be responsible for holding the target features in auditory attention and then utilized to process the stimulus once it is presented.

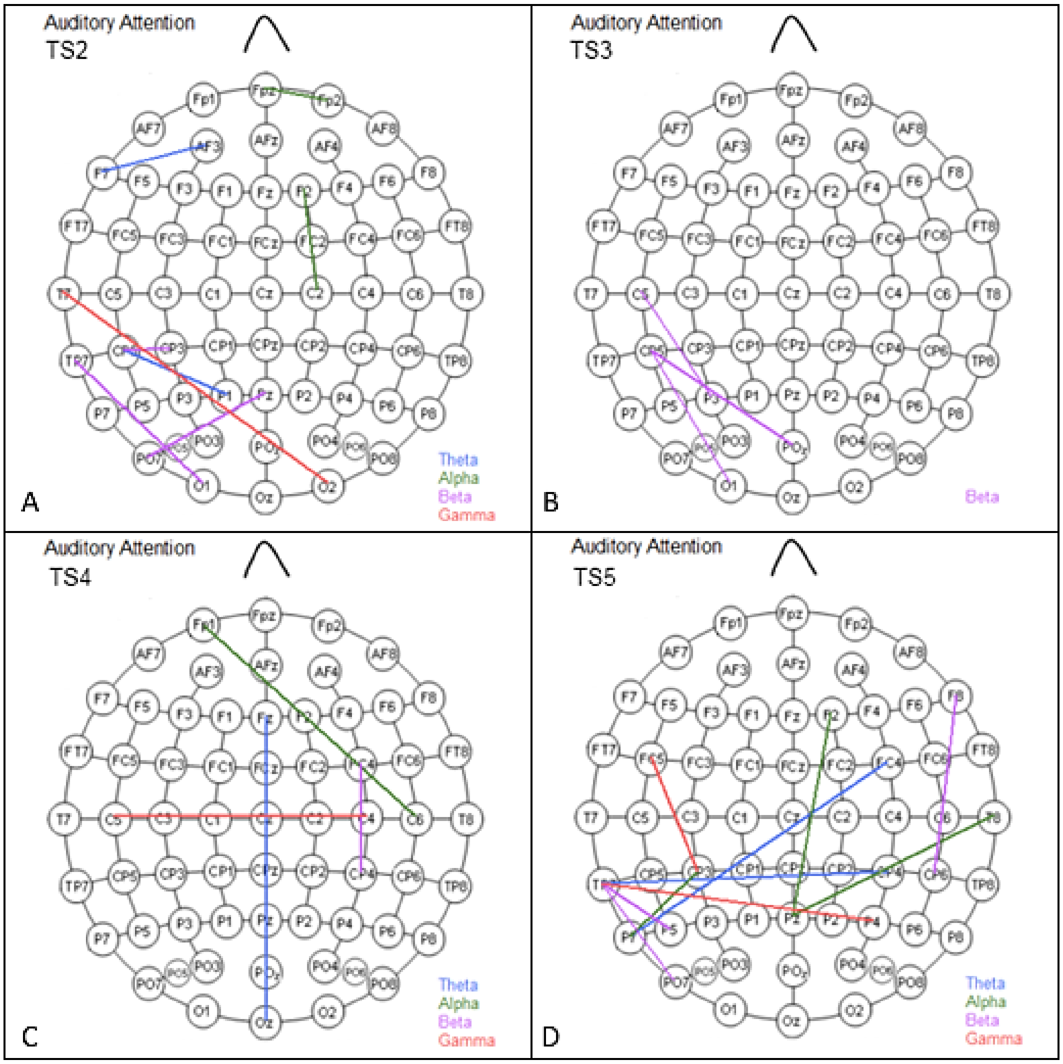

Figure 4.15: SCPs for Auditory condition TS2 to TS5

TS2 (Fig 4.15-A) represents the duration from 100 ms to 200 ms after cue presentation and shows functional connections in all the major frequency bands most of which are between the temporal and the parieto-occipital regions. TS3 (Fig 4.15-B) shows Beta activity between temporal, central and occipital channels. TS4 (Fig 4.15-C) shows Gamma activity across the left and right hemisphere between central electrodes C5 and C4, in addition to Theta activity between Fz and Oz. TS5 (Fig 4.15-D) shows many connections between the left temporal channel TP7 to other parietal and central electrodes.

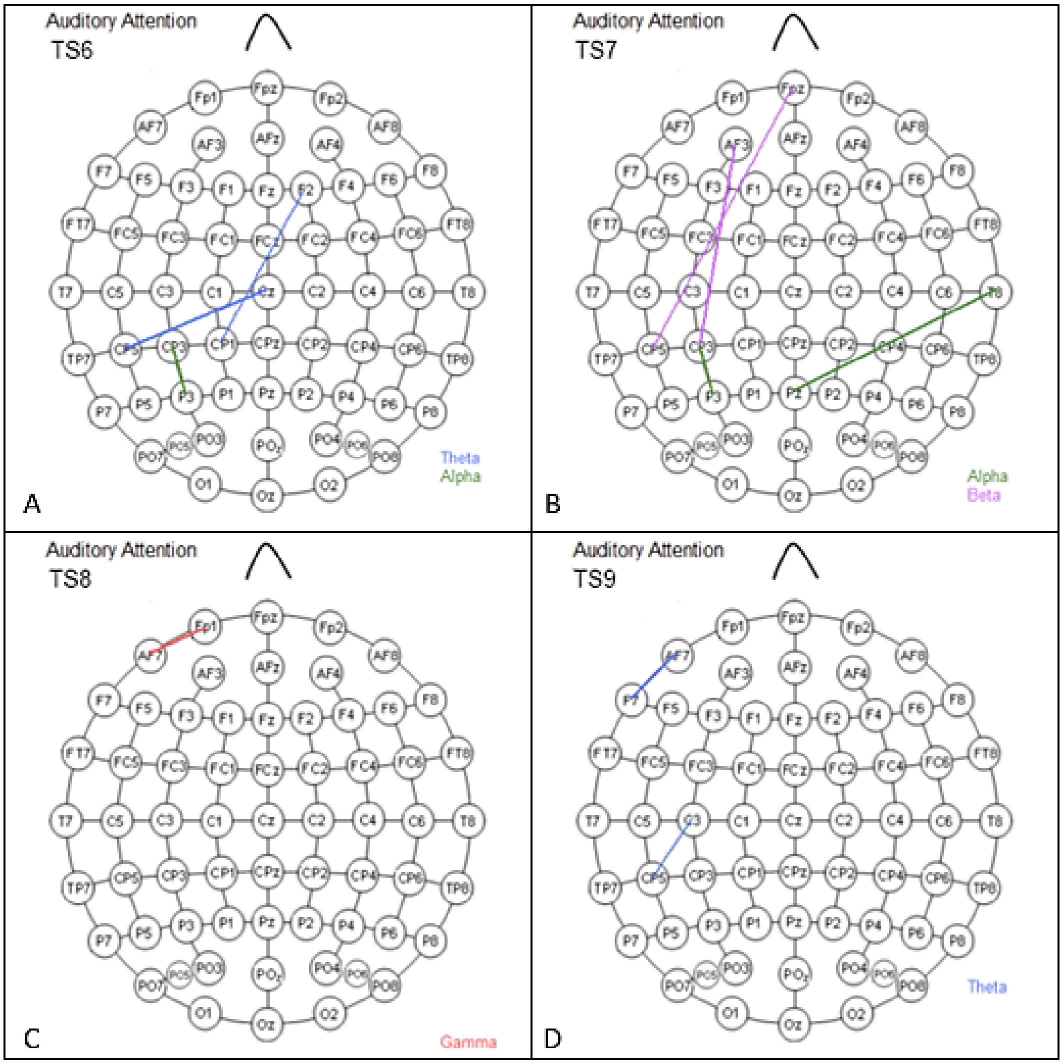

Figure 4.16: SCPs for Auditory condition TS6 to TS9

The connectivity in the segments TS6 to TS9 are sparse, but still show varied active functional connections in the Theta, Alpha, Beta and Gamma ranges (Figure 4.16).

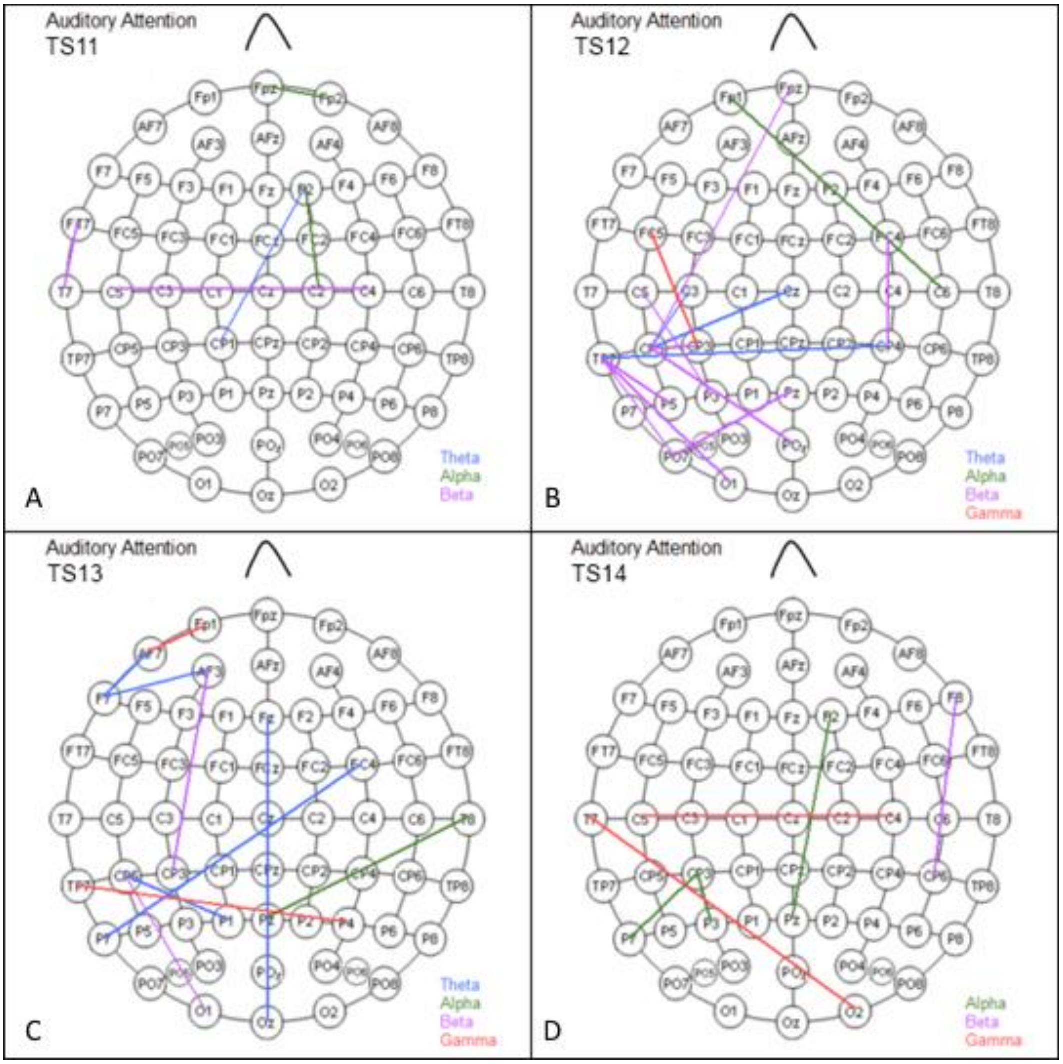

Figure 4.17: SCPs for Auditory condition TS11 to TS14

Figure 4.17 show those connections in the time segments after stimulus set presentation which became active again and are common with those depicted in Figures 4.15 and 4.16. These common connections could be responsible for holding task relevant features in mind after cue presentation and again utilized for task performance after stimulus set occurs.

The main channels involved in these common connections before and after stimulus presentation are depicted in the Figure 4.18 below. These depict the top ten active channels in each condition from all frequency bands. As previously seen in the plots for main channels for the auditory and visual conditions, the temporal, central and frontal channels, mainly on the left side, are active in auditory condition and frontal and occipito-parietal channels mostly on the right side are active in the visual attention condition.

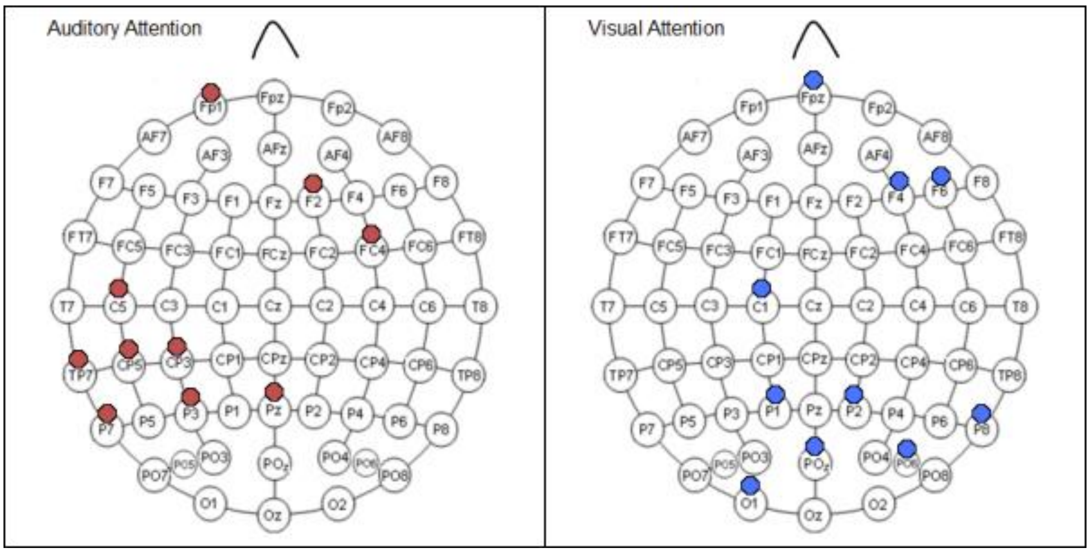

Figure 4.18: Main channels for Auditory and Visual attention

A recent EEG study used a similar crossmodal attention task to study differences in spectral responses between typically developing children and those with ADHD (Mazaheri, Coffey-Corina et al. 2010). They found that cues indicating oncoming visual stimuli lead to a reduction of posterior Alpha activity while Theta activity showed no significant differences. Here Theta and other functional frequency bands show changes according to task demands. A major difference with this study is that here spectral coherence between electrodes is calculated at 100 ms intervals while that study used a pre and post cue interval of

1 s each. It is likely that since functional connections are being modulated at a fast rate, when using a longer time segment, some of these changes might cancel out.

Another study considered attention effects of eye opening and simple auditory tones on EEG (Sharova, Boldyreva et al. 2009). On eye opening frequency modulations were seen in the posterior locations and mostly in the Alpha band, while tones caused changes in the frontocentral regions on the left side. Other frequency bands like Theta and Delta also showed some changes. Since in that study the comparison was made between a baseline condition, with no stimulus, and an attention causing stimulus, some findings might not directly match those of this study. Furthermore a time segment of about 5 s and eighteen channels were used in that study while this one attempts to analyze quicker dynamics at 100 ms intervals in all unique channel pairs of a sixty-two electrode montage.

Maps for highly connective electrode locations was also plotted for the individual subjects to observe the variability. This could help guide electrode locations even more precisely and optimally for each subject, so that fewer number of electrodes can be used while developing an application. The comparative maps from four subjects (Figure 4.19) shows that though the individual maps are different from each other but in general the main cortical locations for each condition remains fairly same as the grand average map shown in Figure 4.18.

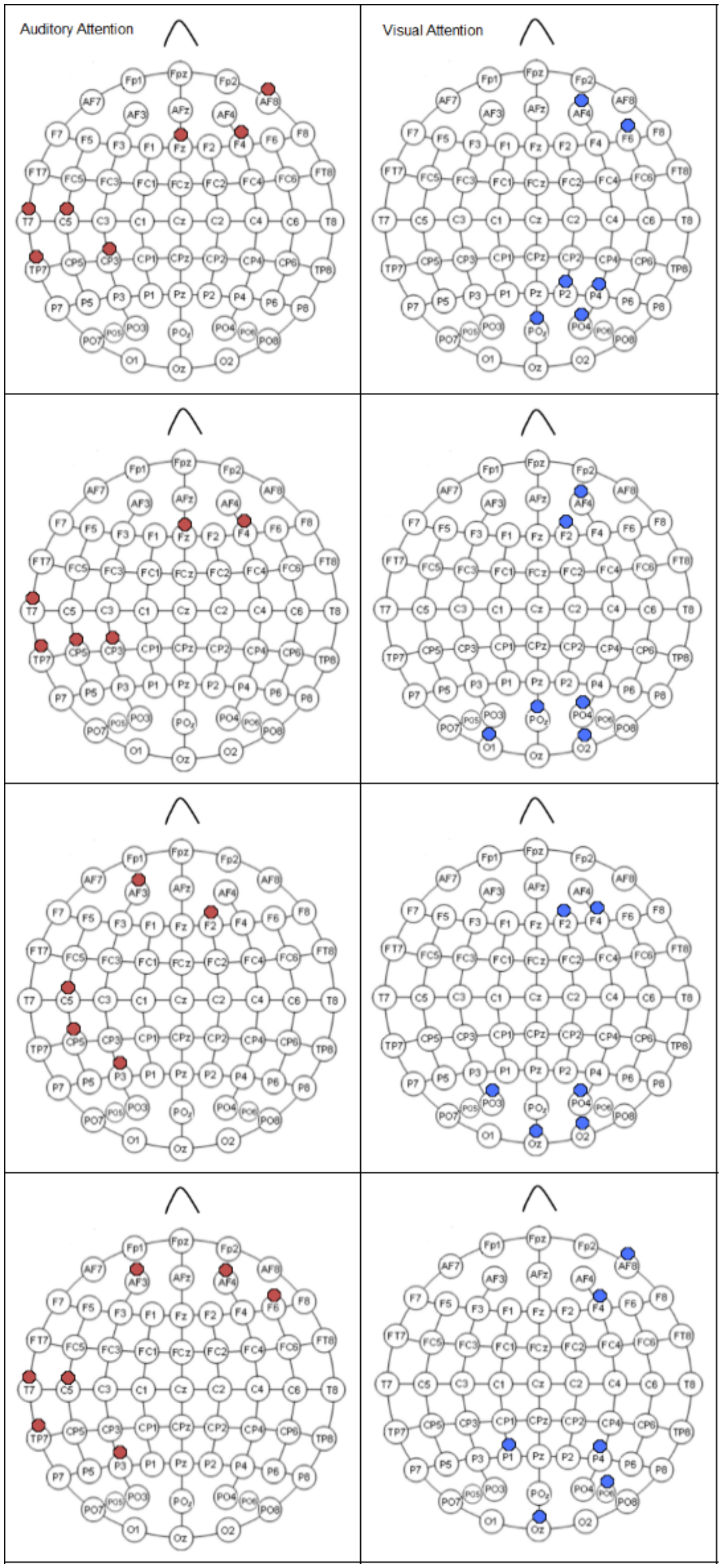

Figure 4.19: Main locations for Auditory and Visual attention for four subjects

4.4 Concluding Remarks

An EEG Event Related Coherence based method has been used to study the connectivity dynamics of visual and auditory intermodal attention. The Inter-Electrode Event Related Coherence values estimate the functional connectivity between all channel pairs in the main frequency bands Theta, Alpha, Beta and Gamma at 100 ms intervals linked to cue and stimulus presentation. Statistically significant differences ($p < 0.01$) are found by analyzing and comparing these connectivity patterns in the two attention conditions, which helps in a better understanding of the complex interactions happening during intermodal attention tasks. This method gives a way to objectively estimate functional connectivity during attention states and could be easily used to differentiate them. Results using this method provide information on scalp EEG locations which are most active in a particular state, as well as the frequency bands in which most interactions are taking place. Since the neural dynamics are studied in 100 ms time segments, this method can depict the changing surface connectivity patterns while task performance with good time resolution.

A seemingly simple cognitive task requiring a participant to focus on either the auditory or visual sensory modality requires various brain regions to act in concert and transfer of information to take place with precise timing. Working memory is needed to maintain the relevant task commands in mind and prepare for the appearance of a particular stimulus either in the visual or auditory domain depending on the cue. Attention and working memory are said to be based in the temporal and frontal cortex regions. After presentation of the stimuli set, recognition needs to be made, whether the set contains the correct target in the relevant sensory modality and this leads to a button press response, if it is a valid target. This action happens by commands from the motor cortex. Thus by estimating functional connectivity between different EEG channels, this complex process can be studied. The results clearly show that at different time segments, various connections between channels become active in diverse frequency bands. This further emphasizes the importance of processing connectivity data in small event related time segments in all the major frequency bands.

When the common connections are compared before and after the presentation of stimulus sets, those relevant connections can be isolated which might be responsible for initially maintaining the target features in mind and then eventually used to process the target once stimuli are presented. This further reduces the number of relevant connections which need to be monitored to differentiate these states, as well as adding to our understanding of this complex cognitive process of switching and maintaining attention on one of the sensory modalities.

A summary of the main findings are listed below.

1. Consistent differences in connectivity patterns were seen between auditory and visual attention conditions in Theta, Alpha, Beta and Gamma bands.
2. These patterns change in different time intervals during cognitive task performance, emphasizing the need to study these processes at shorter time intervals.

3. In the auditory attention condition, the left centro-parietal EEG locations are more active.
4. In visual attention, right parieto-occipital locations are showing numerous interactions.
5. In both conditions, the right frontal locations are active, though the exact surface location is different for both these connections. This could indicate that there is some differentiation in the frontal cortices when dealing with these two sensory modalities.
6. Functional interactions in Theta, Alpha and Beta bands are more involved in auditory attention compared to the visual modality.

5 Study on Emotional Modulation of Attention

5.1 Introduction

Emotions inherently play a major role in our lives and can affect our cognitive abilities in various ways. High emotional content in a stimulus makes it "catch" our attention and eventually makes it easier to remember. Our emotional state does not stay constant and varies with time depending on external and internal factors. The way external events and stimuli are handled depends to a great extent on the internal state. Any neutral stimulus can be ignored easily when one is in a positive mood, while the same stimulus can become irritating if the mood is already negative. Thus same kind of stimuli can be processed differently due to internal emotional states.

The interaction of subcortical regions with higher cortical regions leads to a modulation of responses depending on emotional states. As previously stated, different brain regions communicate with each other through synchronization of their oscillations. Thus by detecting alteration in functional connectivity between various EEG electrodes, these dynamics could be captured and studied.

Emotions can be initiated by various factors, like seeing certain pictures, listening to emotional sounds, remembering past emotional events, watching emotional videos, etc. One standardized way to produce emotions in experimental subjects is by the use of the IAPS (International Affective Picture System) database. This database contains images, which have been rated on the valence-arousal scale, and tested in various studies which show that they are successful in inducing emotional states in experiment participants. The sound stimuli from

Schirmer's work (Schirmer, Striano et al. 2005) were used as emotional probe events while emotional states were induced using IAPS images. By monitoring the changes in connectivity response to the sound stimuli in relation to emotional state, this study intends to study the effect of emotional states on attention.

5.2 Experiment Protocol and Participants

This protocol is designed to assess the effects of emotional states on our ability to pay attention to different kinds of emotional stimuli. This is like probing the mind to detect its internal condition. A schematic of the blocks and stimuli is shown in Figure 5.1.

In this experiment design, neutral and emotional images from the IAPS (International Affective Picture System) are used to induce a particular emotional state in the subject. For this experiment three types of image groups were chosen from the IAPS database – Low arousal and positive valence, Neutral picture (having both arousal and valence somewhere in the middle) and High arousal and negative valence group. These three groups are used in three different blocks of the experiment – Positive block, Neutral Block and Negative block respectively with some rest period of 5-10 min in between (lower part of figure).

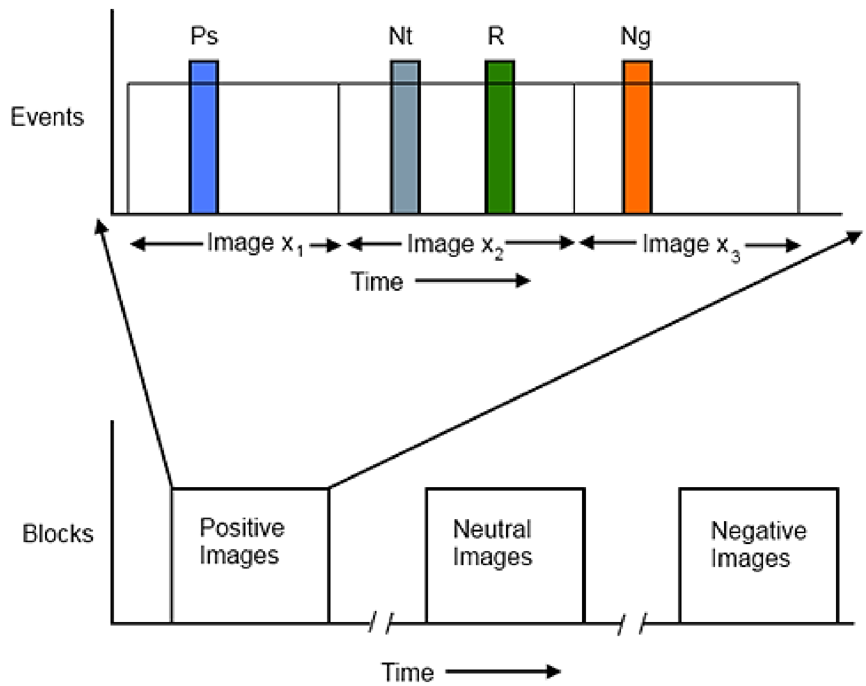

Figure 5.1: Emotion Protocol Schematic

The order in which these three blocks are presented is counterbalanced between different subjects. The images are displayed on a computer screen in front of the subject who are supposed to keep looking at the images while doing the auditory task. The images change every 2.5 seconds. In the different blocks the subject is required to do the same sound stimuli recognition task.

For the sound stimuli recognition task, three sound stimuli were used in which "dada" was being spoken by a female voice in happy, neutral and angry tones (upper part of figure). The subject is asked to press a button on the keyboard when he hears the neutral "dada". The sound with a happy intonation is marked as Ps, that with a neutral intonation is Nt, followed by a response R and the sound with an angry intonation is marked as Ng. The order of presentation of these sounds within every block is pseudorandom and an equal number of each type of sound is presented (70 each). The sound is presented at an interval of 500 ms after the image changes. This sound stimulus remains for about 500 ms after which the subject might press the response button. The image stays on the screen for about 2.5 s total and is then replaced by another picture from the same group. This keeps the subject engaged in the task and gives us a way to assess whether the subject was paying attention to the task or not. It is hypothesized that the same sound stimulus will be processed differently in the three blocks, because the emotional state of the subject has been changed because of the images. After the completion of the experiment the subject is asked to rate the images used in the experiment giving his ratings for the arousal and valence aspects of each image. This helps in determining whether these ratings match with the original IAPS ratings of the images and indirectly indicate if these images were successful in arousing the specific emotional state in the experiment.

Ten healthy male volunteers (M=20.5 yrs, SD=1.65) were selected for the study after screening of interested participants from the University student population. These participants had normal or corrected to normal vision and no history of neurological or psychiatric disorders. Participants were briefed on the intent and procedure of the experiment and signed informed consent forms before the experiment. The University Ethical Review board approved the study.

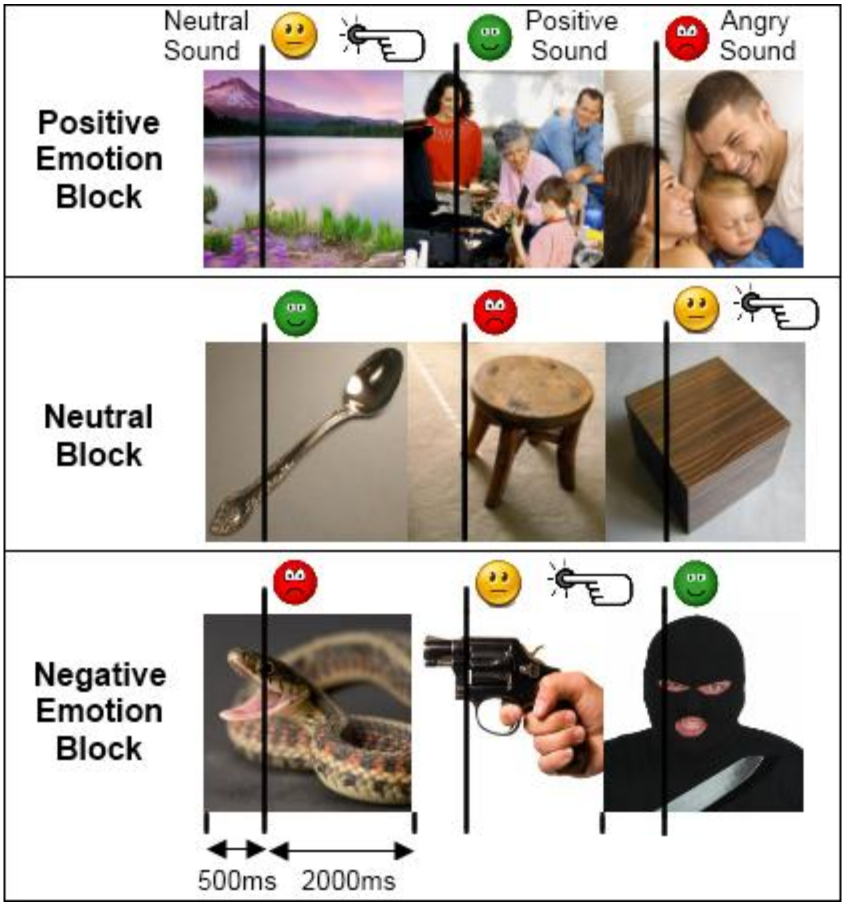

Figure 5.2: Protocol Design

5.3 Data Processing

The Inter Electrode Event Related Coherence (IE-ERC) method is applied to each sound in each experiment block. The neutral block is considered a control block. Each sound is processed separately and the connectivity in response to that sound in different emotional states is calculated. For the negative emotional sound, the connectivity values in the neutral block are subtracted from that in the positive emotional block to give the effective connectivity for positive block. Similarly effective connectivity in negative emotional block is calculated by subtracting the connectivity values in the neutral block in response to this sound from the values in the negative block. This process is done for all ten subjects and averages are calculated from all trials for each subject. These effective connectivity values in positive and negative blocks are then compared statistically using separate left and right sided paired t-test by comparing averaged data between subjects. This comparison shows the functional connections between electrodes which were more active in one of the emotional blocks in comparison to the other in response to this same negative emotional “dada” sound. Similarly the connectivity responses to the positive emotional “dada” sounds are compared separately. The Time Segments show number of activated connections from the presentation of the sound stimulus till 500 ms after that. Each time segment represents data of 100 ms blocks and is labelled as TS1 to TS5. The surface connectivity profiles are plotted for each time segment and the five major frequency bands of Delta, Theta, Alpha, Beta and Gamma.

5.4 Results and Discussion

5.4.1 Picture Ratings

The original mean (SD) IAPS ratings (Valence=V, Arousal=A) for the images used in the Positive block were V=7.34(0.29) and A=3.57(0.37), while that given by the participants in this study were V=6.29(0.57) and A=4.20(1.17). For the Negative block the IAPS ratings were V=1.68(0.19) and A=6.73(0.41) and the participants in this study rated them as V = 2.39(0.62) and A=6.11(0.74). The ratings given by the participants in this study were close to their original ratings, thus implying that the images had the intended effect on the participants.

5.4.2 Number of Activated Connections

Three different types of sounds were used in the experiment. Since the neutral sound was used mainly to keep subjects engaged in the task by responding to it, henceforth only the results for happy and angry intonation sounds are discussed. It is seen that each sound stimuli is processed differently in the various emotional states and this gives rise to functional connectivity differences between the EEG electrodes. An Activated Connection in Positive emotional state means a functional connection between any two electrodes, which was statistically stronger in the Positive state compared to the Negative state at $p<0.01$ across ten participants. Similarly an activated functional connection in Negative Emotional state means those channel pairs which were more active in this state compared to the Positive state.

The results discussed below are those functional connectivity changes which were statistically significant ($p<0.01$) across all ten subjects. The overall number of activated connections (aggregated from TS1-TS5 and in Delta, Theta, Alpha, Beta and Gamma frequency bands) remained higher in the positive emotional states for each sound. For the Angry intonation sound they were 497 and 285 and for the happy intonation sound 548 and 273 in the positive and negative emotional states respectively. These total numbers of activated connections show that during the positive emotional state many more electrode pairs show functional connections in response to both these sounds. The pattern of increase and decrease in activated connections along Time Segments is dependent on each sound and frequency band. The trend of number of activated functional connections (AFC) for Happy and Angry intonation sounds in both emotional states for Alpha and Beta band is shown in Figure 5.3.

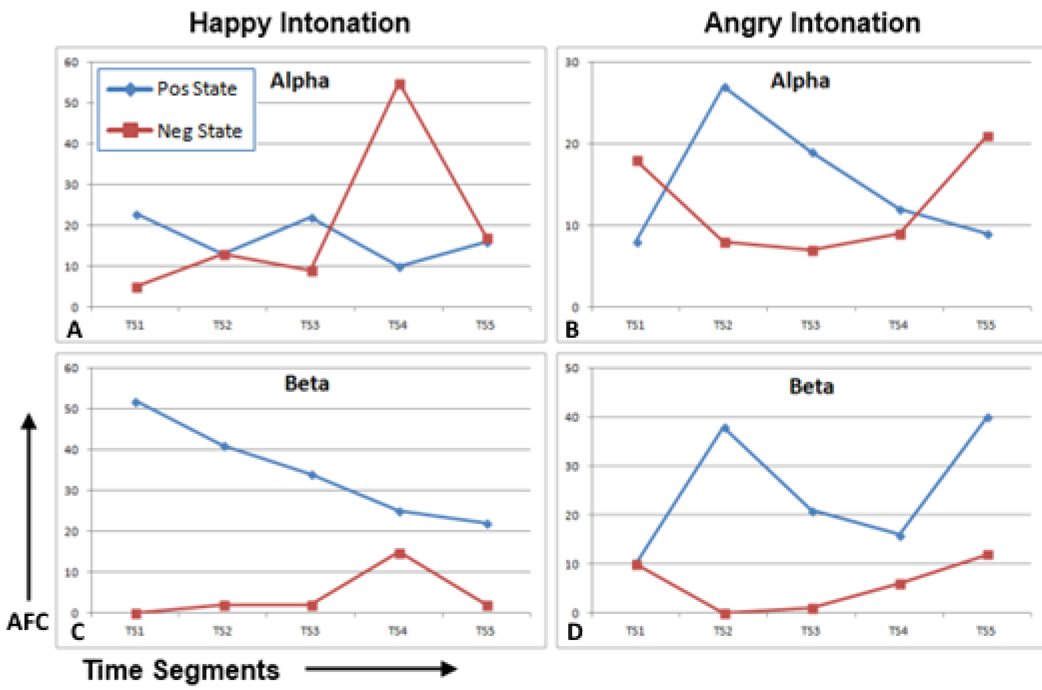

Figure 5.3: Trend of number of AFCs in Alpha and Beta bands ($p<0.01$)

Figure 5.3-A shows the AFC trend for the sound stimulus with happy intonation in positive and negative emotional states in the Alpha frequency band. It can be observed that in the positive emotional state, the number of AFCs shows little variation with time, but in the negative state there is an increase in Alpha connectivity in the fourth time segment (TS4). The AFC trend for the angry intonation sound in Alpha band is shown in Fig 5.3-B and depicts an initial high number of AFCs in TS2 in positive emotional state, compared to a relatively opposite trend in the negative emotional state. Observing the activated connections at short intervals thus shows clear distinction when the same sound stimulus is processed in dissimilar emotional states. The number of AFCs in the

Beta band remains high for both these sounds in the positive emotional state compared to the negative state. This also shows that functional connectivity in specific frequency bands are modulated in different ways by a change in internal emotional state.

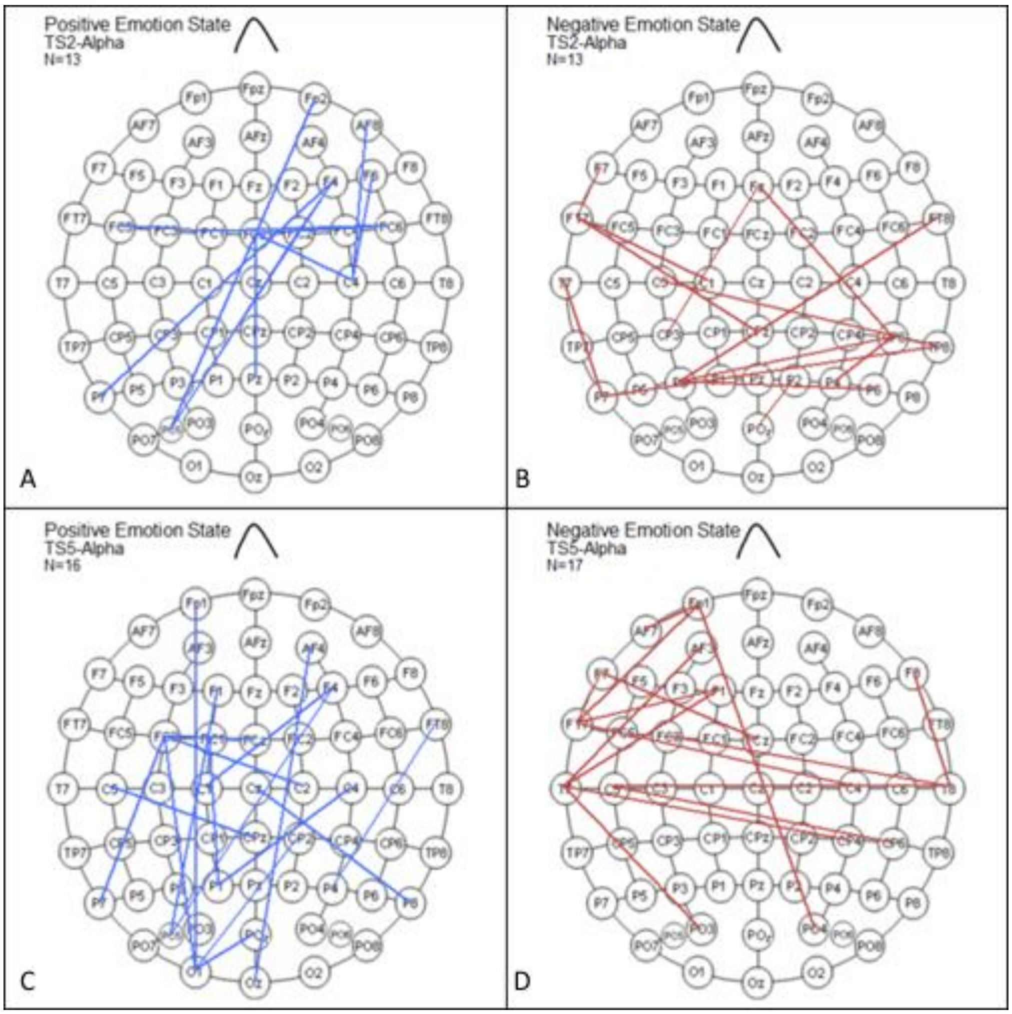

Figure 5.4: SCP for Happy intonation sound in Alpha band (p<0.01)

A Surface Connectivity Profile (SCP) can depict the relevant functional connections for studying the locations and active channel pairs. Figure 5.4 presents the SCP for happy prosody stimulus in the Alpha band in time segments 2 and 5 (TS2 and TS5). In TS2 and positive emotional state (5.4-A), the right frontal and some left parieto-occipital locations are seen to interact while in the same time segment during the negative state (5.4-B) centro-parietal locations are more active in addition to few frontal and temporal locations. The SCP in TS5 contrasts that in TS2 and shows that at short intervals functional connections can be observed even within the same frequency bands. In the positive emotional state (5.3-C) central frontal and occipital channels are active while in the negative emotional state (5.3-D), left fronto-temporal and right central locations are forming connections along with some parieto-occipital locations. In a recent study, a decrease in prefrontal-parietal interactions in the Beta band was associated with more emotional involvement and less cognitive control (Reiser, Schulter et al. 2012). Here Alpha band also shows a similar pattern with more prefrontal-parietal interactions during positive emotional state, which are absent during the negative state. This could indicate that during a negative emotional state the cognitive control mechanisms could be weakened while processing emotional sounds. It should also be reiterated that Beta band connectivity remained low in all time segments in the negative emotional state for both emotional sounds as shown in Figure 5.3.

5.4.3 Changes dependent on Emotional states

After finding significant connectivity differences for each sound in the Positive and Negative emotional state, a search was done to find those connections which were common for a particular state. If we find that a functional connection is active between two electrodes in the positive emotional state for both happy and angry intonation sounds, it might mean that those functional connections are state dependent and thus can be used to estimate the internal emotional state of the participant. Similarly those functional connections can be found which are specific for the negative emotional state. The results below are those statistically significant differences which were found across the ten participants.

The coherence responses to the Happy and Angry sound stimuli in Positive emotional state were compared to find any functional connections which were commonly activated during this state in all five time segments. There were 92 such connections which were active in the frequency bands Delta (12), Theta (4), Alpha (17), Beta (35) and Gamma (24). For the Negative emotional state, there were 36 functional connections common to both the Happy and Angry sounds – Delta (24), Theta (5), Alpha (6), Beta (1) and Gamma (0).

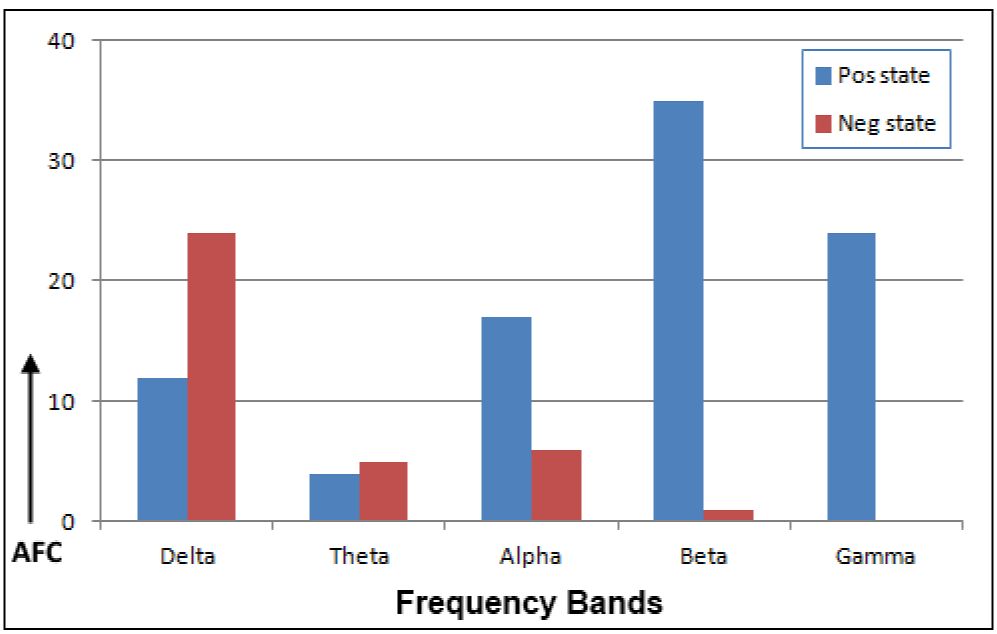

Figure 5.5: Frequency distribution of state specific connections ($p<0.01$)

In the Positive emotional state a larger number of functional connections are active compared to the Negative state and most of these interactions are taking place in the upper frequency bands – Beta and Gamma (Figure 5.5). The number of Alpha interactions is also relatively high in this state. During the negative emotional state the Delta band is mainly active, while the upper range bands Beta and Gamma show hardly any interactions common between the two sound stimuli. This implies that in a particular emotional state not only is the number of functional connections made are different in response to these sound stimuli, but their distribution in the EEG frequency bands is also distinct. A recent review of the Delta band has implicated it in homeostatic and motivational functions (Knyazev 2012), while some other studies suggest that oscillations in this band from the subcortical region help modulate the functioning of the higher frequency bands of the cortex (Putman 2011).

The active functional connections in the main frequency bands are contrasted for these two states below. Figure 5.6 shows main active connections for positive and negative emotional states in the Delta and Alpha bands. The SCP for Alpha band in positive emotional state (Fig 5.6-A) shows a larger number of connections in fronto-central and parieto-occipital regions, while in the negative state (Fig 5.6-B) there are a few active connections between frontal and central locations. Previously, Alpha band connectivity has been seen in left anterior and posterior regions in response to pleasant musical stimuli while unpleasant stimuli produced posterior midline coherence (Flores-Gutierrez, Diaz et al. 2009). This study shows that in response to the same sound stimulus, functional connectivity in Alpha band can be modulated by internal emotional state. In addition, the Delta band also shows different SCP for the two emotional states. In the positive state (Fig 5.6-C) mainly frontal locations are active with some in the parietal region, while in the negative state (Fig 5.6-D) there are extensive connections between right fronto-central locations and left temporo-parietal regions. Delta and Alpha band oscillations have been associated with the arousal aspect of emotional stimuli (Balconi, Brambilla et al. 2009) .

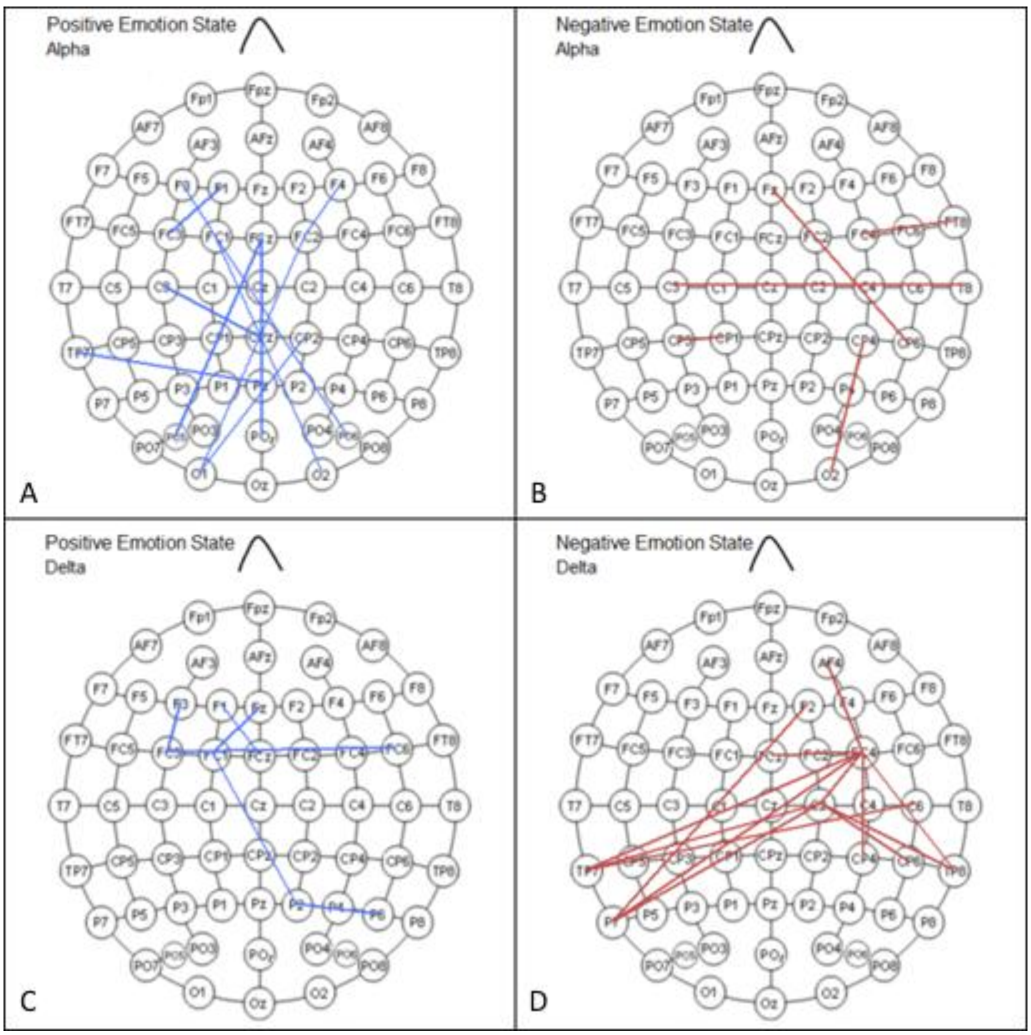

Figure 5.6: Active Connections for Positive and Negative states in Alpha and Delta bands ($p<0.01$)

Figure 5.7 displays the SCPs for connections in the Beta (Fig 5.7-A) and Gamma band (Fig 5.7-B) which were commonly active for the happy and angry prosody sounds in the positive emotional states. Both these bands show many connections between frontal, centro-parietal and occipital locations. In the negative emotional state, the Beta band only shows one connection which was common following the two sound stimuli, while the Gamma band shows no such connections. This implies that functional connectivity in response to sound stimuli is modulated by internal emotional state with positive state showing a dominance of Beta and Gamma bands, while the negative state shows activity in the Delta band.

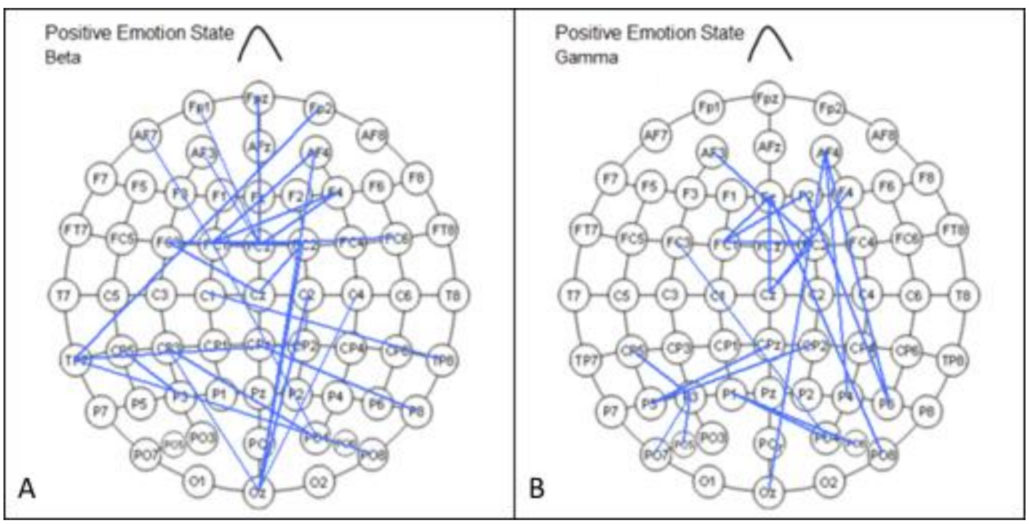

Figure 5.7: Active Connections in Beta and Gamma bands (p<0.01)

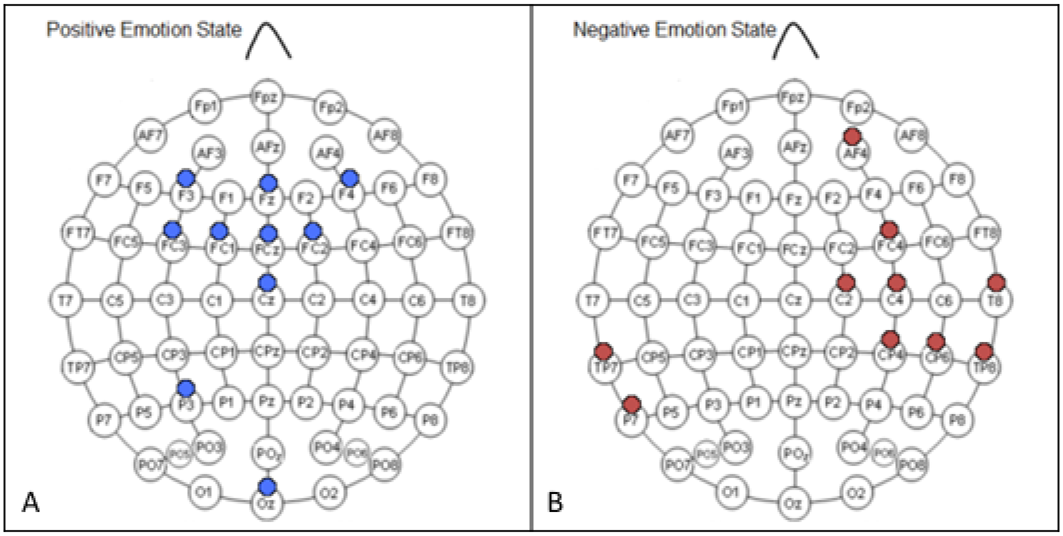

Figure 5.8: Main active channels in Positive and Negative emotional states

Figure 5.8 shows the ten main channels which are making the most number of connections cumulatively from TS1 to TS5 and in all frequency bands combined. In the Positive state (Fig 5.8-A), Frontal channels in the middle and left along with P3 and Oz are mostly active, while in the Negative state (Fig 5.8-B) central and parietal channels on the right side along with AF4, TP7 and P7 are making the most number of connections. This result mostly supports the valence lateralization hypothesis (Harmon-Jones, Gable et al. 2010).

Among the common connections found for each state, it was observed that the same connections were activated in earlier time segments after the happy sound compared to the angry intonation sound stimulus. In the negative state there were some connections in the Delta and Alpha bands which showed such shift, while Theta band showed no shift and in Beta band, some connections activated earlier after angry sound than after the happy sound. In the positive emotional state, all frequency bands, except the Theta band, showed that same connections activated in earlier time segments after the happy sound compared to the sound with angry prosody.

Electrode locations for channels making large number of functional connections was plotted for the individual subjects to observe the variability. Similar to the previous experiment on cross modality attention, here also the comparative maps from four subjects (Figure 5.9) shows close correspondence between the individual maps and the grand average map shown in Figure 5.8. Some individual variations should be expected and are observable in the maps.

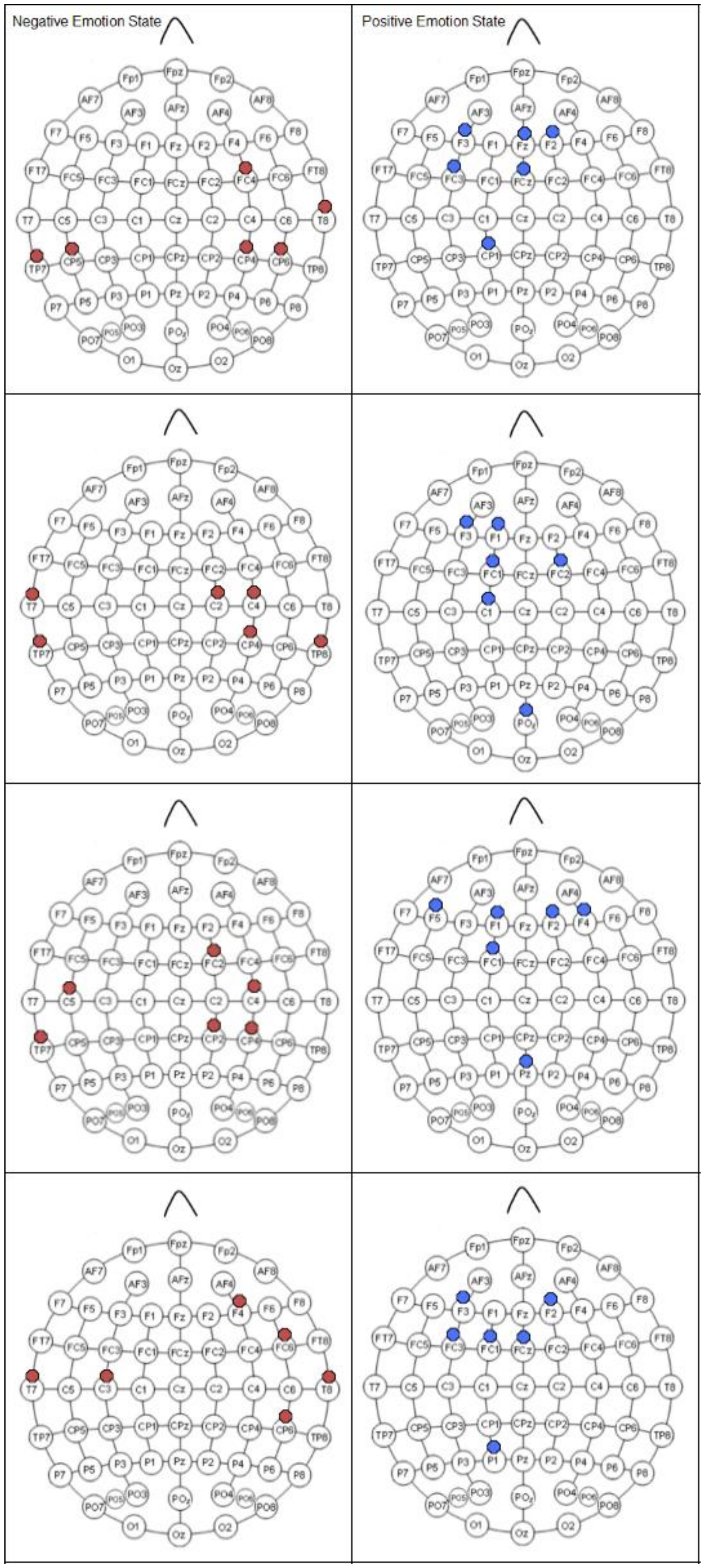

Figure 5.9: Main active channels in Positive and Negative emotional states for four different subjects

5.5 Concluding Remarks

The EEG Inter-Electrode Event Related Coherence method was used to study the brain connectivity responses to emotional sounds in different emotional states at short 100 ms intervals. This method gives detailed information on the connectivity dynamics in the form of important electrode locations, frequency bands and the time segments in which these electrode locations interact.

1. Functional connections in lower frequency Delta band were observed to be more active during the negative emotional state, while the higher frequency Gamma and Beta bands showed more connectivity during the Positive emotional state in response to both types of emotional sound stimuli. This shows that the same type of sound stimuli are processed in variable ways depending on the internal emotional state.
2. Few connections were found to be commonly active in a particular state in response to both the happy and angry intonation sound stimuli.
3. Among these common active connections, there was dominance of Delta frequency band in the negative emotional state and of Gamma and Beta bands in the positive state.
4. In the positive emotional state, frontal locations in the midline were mostly active while in the negative state right frontal locations were interacting.
5. Many of the common connections for a particular state were activated in earlier time segments following the happy prosody sound compared to the angry sound stimulus.

6 Study on effect of Mind Wandering on Attention

6.1 Introduction

Attention is an integral cognitive ability which underlies and supports many other mental functions like memory. While a person is not focused on any external task, there is a tendency of the mind to wander into Task Unrelated Thoughts (TUTs) or Stimulus Independent Thoughts (SITs). If in such a mind wandering state, a person is supposed to suddenly respond to a cognitive demand, there is a decrease in their performance. The activity of the Default Mode Network of the brain is highly correlated with the occurrence of these thoughts and thus is detrimental to external task performance. This study aims to explore the use of EEG connectivity markers to determine whether Default Mode Network and mind wandering affect attention demanding tasks. Inter-Electrode Event Related Coherence gives us a way to estimate connectivity between various EEG electrodes at 100 ms time segments during cognitive task performance.

6.2 Experimental Protocol and Participants

An experiment protocol requiring an attention and memory task performance interspersed with resting was used to collect EEG data. A schematic of the protocol is shown in Figure 6.1. The experiment started with a Resting period, which lasted 18 s, where the subject was instructed to sit quietly while focusing his gaze on a white cross sign presented at the center of the LCD screen. In the Task phase – four trials of a memory task were presented on the same monitor. Each trial lasted 4s and showed one to eight colored squares on the screen for 500 ms, which the subject was supposed to memorize. This was the Stimulus Encoding phase (S) and was followed 1 s later by a color probe, consisting of one colored square. This is the Retrieval or Probing phase (P), where the subject matches the current color probe to his memory and responds accordingly. If the subject had seen this color in the Encoding phase, he is supposed to press the response (R) button 1 on the keyboard, denoting Yes, while if that color was not presented in the encoding phase, he presses 2, indicating No.

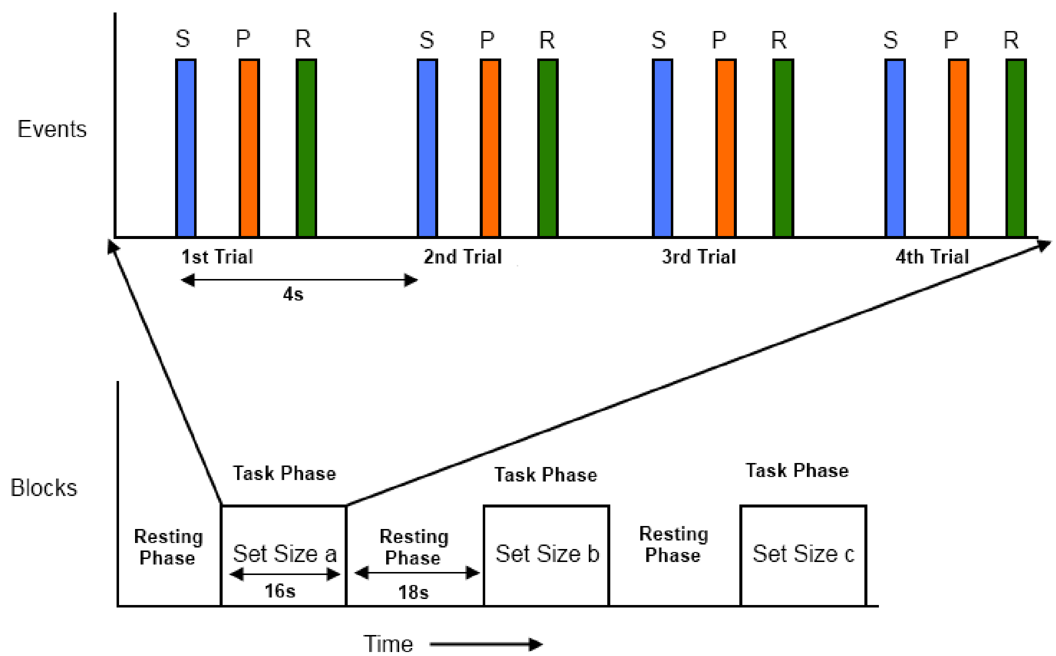

Figure 6.1: Visual Short Term Memory Protocol

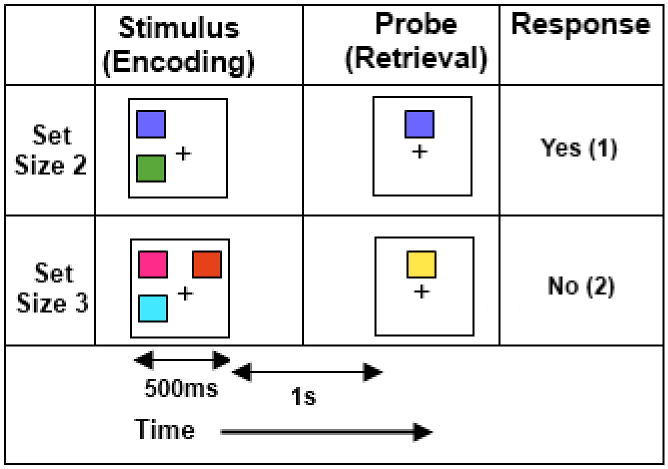

Figure 6.2: VSTM stimulus response

Figure 6.2 shows one trial each for Set size 2 and 3, the former requiring a "Yes" response, while the latter requiring a "No". The Set size (SSz) or the number of colored squares initially shown in the Encoding phase was one, two, three, four, six or eight – thus varying the workload of the attention and memory task. Each subject was presented with 8 blocks of the memory task for each Set Size, thus the total number of trials for each Set Size was 32 (8x4), since each Task phase consisted of 4 trials. The total number of trials for all Set Sizes was thus 192 (32x6).

During each Task phase, when the first trial starts, the participant is in Resting phase, during which there is an increase in SITs. Thus the 1st trial of each Task phase can be affected by interference from the Default Mode Network (DMN). Chuah et al had used the same protocol in an fMRI study and showed that DMN regions like Precuneus and Posterior Cingulate were indeed activated during the Resting phases compared to Task phase (Chee and Chuah 2007). Once the Task phase starts, the participant is able to focus more on the task and thus the later trials are processed with more attention. By comparing the first and the third trial it would be possible to see whether there is a difference in the connectivity profiles for these trials and thus evaluate how the DMN detrimentally effect the first trial.

Ten healthy male volunteers (M=20.5 yrs, SD=1.65) were selected for the study after screening of interested participants from the University student population. These participants had normal or corrected to normal vision and no history of neurological or psychiatric disorders. Participants were briefed on the intent and procedure of the experiment and signed informed consent forms before the experiment. The University Ethical Review board approved the study.

6.3 Data Processing

EEG data is collected while 10 healthy subjects perform the task. Bandpass filter from 1 Hz to 45 Hz is applied and any epochs with excessive artifacts are excluded from analysis. Each epoch with memory task performance is extracted from Stimulus presentation up to 400 ms after Probe presentation. This helps in studying the Encoding process and the Retrieval processes. IE-ERC method is applied to find functional connectivity differences between the first and the third trials. Behavioural measures like accuracy and response times for the memory task are also compared between the first and third trials.

6.4 Results and Discussion

6.4.1 Accuracy and Reaction Times

The behavioural measures of accuracy and reaction times for different set sizes and trials show variations which support the notions about the memory task and also the interference of mind wandering on this task. The Accuracy for different Set Sizes (SSz) and Trials (1st to 4th) are shown in the Figure 6.3. As expected the Accuracy declines as Set size increases, since the normal working memory is said to have the capacity of about four to seven items for most people (Todd and Marois 2004). This shows that as set sizes increase and participants have to memorize a larger number of colors their ability to perform the task decreases. The accuracy differences between the first and the third trials show a varying relationship for different set sizes. For Set size 1 and 6, the accuracy is higher for the first trial, while for Set sizes 2, 3 and 4 it is more for the third trial. This mostly supports the notion that the first trial will suffer detrimental interference from mind wandering since just before this trial the participant was in Resting phase of the experiment.

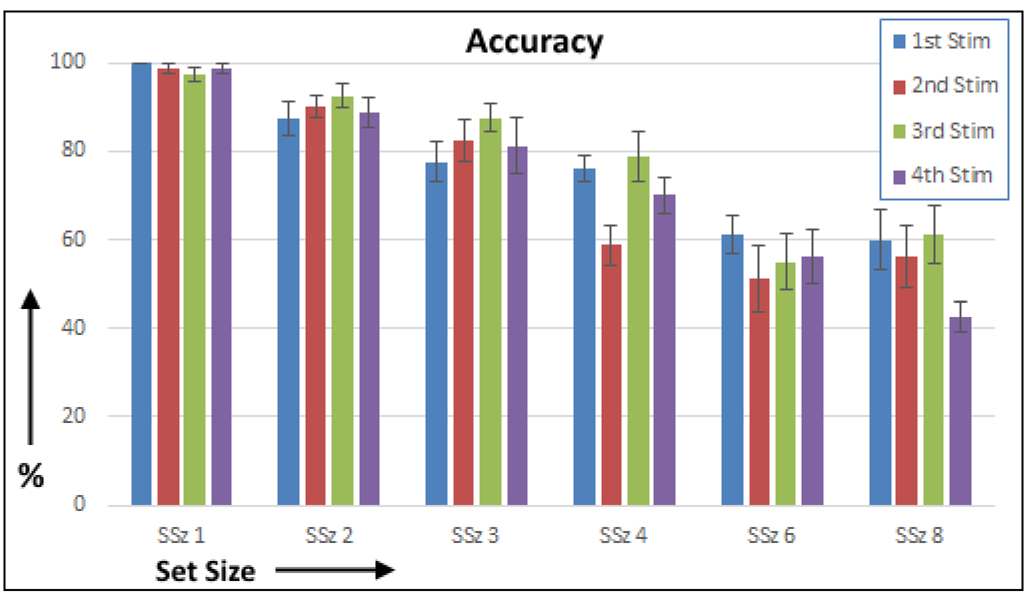

Figure 6.3: Accuracy for Trials and Set Sizes (Average of ten participants)

Figure 6.4 depicts the trend in Reaction times for various Set sizes and Trials.

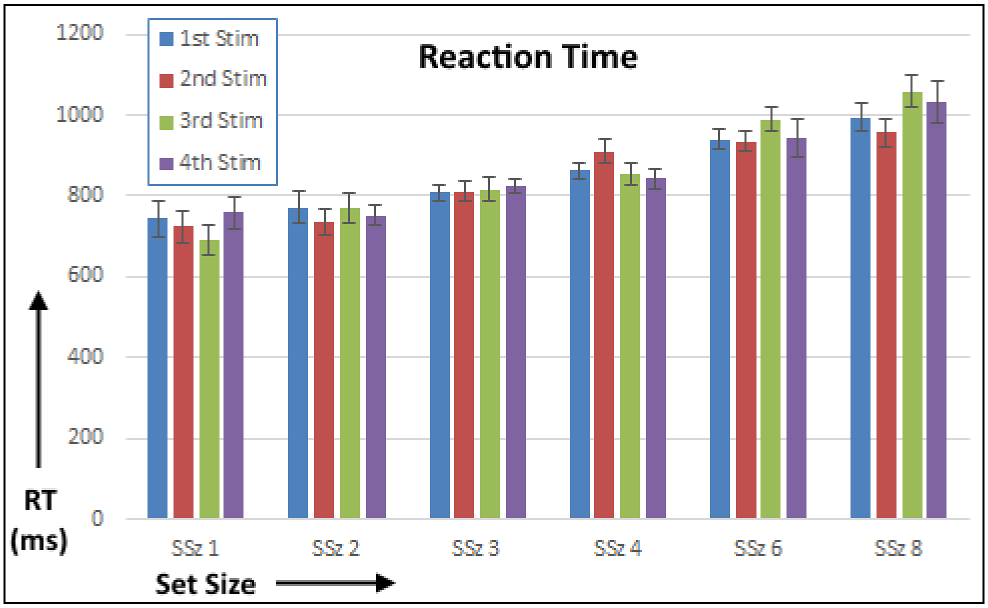

Figure 6.4: Reaction Times for Trials and Set Sizes (Average of ten participants)

Since a longer reaction time would mean a worse performance, the trend is opposite of that seen in accuracy with larger Set sizes showing longer reaction times. Furthermore, the reaction times were marginally longer for the first trial in set sizes 1, 2, 3 and 4 and for set sizes 6 and 8 it was longer for the third trial. This could indicate that the ability to perform a trial after being in a resting phase might depend on the workload of the task. The data for Set sizes one, two and three were combined together, as during this workload, the participants were mostly able to maintain minimum 80% accuracy. Figure 6.5 shows the trend of accuracy and reaction times for the combined data of set sizes one, two and three (SSz1-3) with blue lines, compared with those of combined data of set sizes four, six and eight (SSz4-8) shown in red lines. Accuracy data is depicted with line markers.

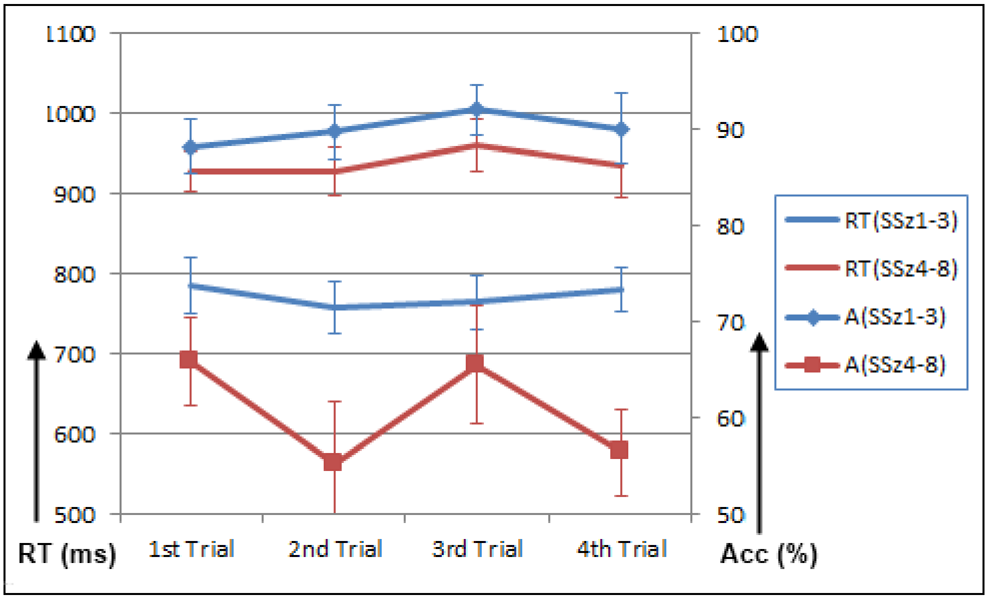

Figure 6.5: Accuracy and Reaction times for combined data (Average of ten participants)

Accuracy for SSz1-3 is higher for the third trial compared to the first trial, while reaction times show a reverse trend. This could mean that even with a longer reaction time in the first trial, the participants are not able to maintain a high accuracy rate, which could be due to the effect of switching from the Resting to the Task phase. In the third trial since the participants have already switched their attention to the cognitive task, they are able to have a high accuracy rate with a shorter reaction time. SSz4-8 shows nearly the same accuracy for the first and third trials, though the reaction times are higher for the third trial compared to the first, which could mean that the higher accuracy is achieved with a longer reaction time for the third trial. Another interesting feature is that for the SSz4-8, the accuracy for the second and the fourth trials are much lower than the first and third trials, which could indicate that with this high memory load the performance in the even order trials suffers to maintain reasonable performance in the odd order trials.

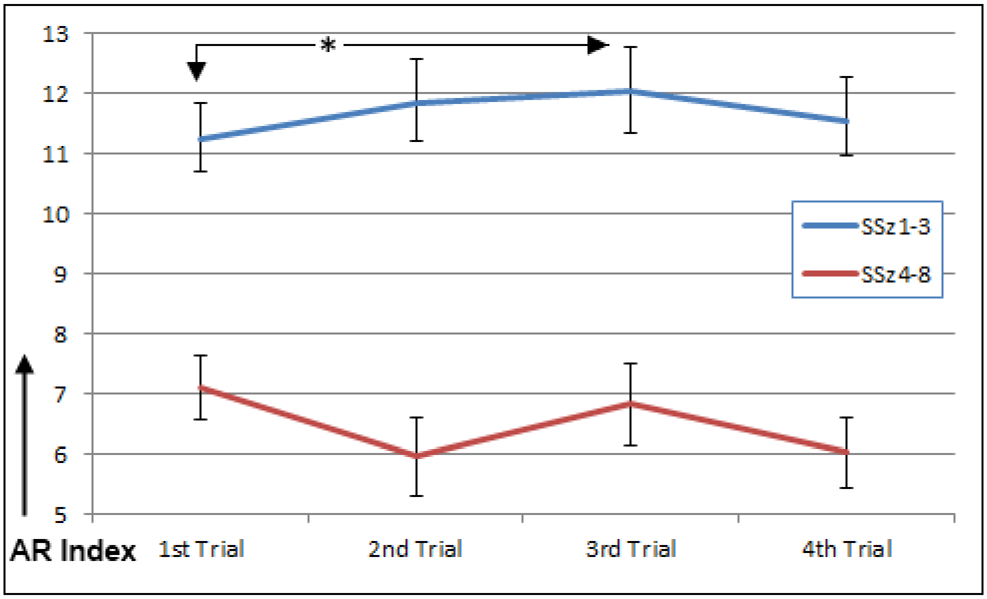

Figure 6.6: Accuracy/RT for Normal and High Memory load (* p=0.057)

Since a high accuracy can be maintained by compensating with a longer reaction time, Accuracy-Reaction Time Index (AR Index) is calculated by dividing accuracy with reaction times. A similar measure was used to assess effect of mental fatigue due to sleep deprivation in an Auditory Working Memory Vigilance Task. This metric showed very high test-retest reliability as an objective measure of mental fatigue (Tyagi, Shen et al. 2009). A higher AR Index would mean good performance as it would depend on a higher accuracy rate and a shorter reaction time, thus combining these two metrics. The AR Indices for the Normal (SSz1-3) and High (SSz4-8) memory load is depicted in Figure 6.6. It shows a steady increase in AR Index from first to third trial in the SSz1-3 and a drop again in the fourth trial. For the SSz4-8, it shows a high value in the first and third trials, with a drop in second and fourth trials.

Based on the behavioural measures, only the combined data from the Normal memory load condition, including set sizes one, two and three are used for connectivity analysis.

6.4.2 Activated Functional Connections in Encoding and Retrieval

The EEG epoch of the first trial from all task phases for the Set sizes one, two and three is compared with those from the third trial using paired t-test at $p < 0.01$ across ten participants. Connectivity differences are sought at this significance level between corresponding pairs of Inter-Electrode Event Related Coherence values to estimate those functional connections which were more active in one condition compared to the other. There are 1261 connections which were consistently more active in response to the first trial, while there were 776 active connections more active after the third trial. Figure 6.7 shows the relative numbers of these activated connections which were active in different bands. For the first trial, most connections are active in the Beta and Gamma ranges, while for the third trial, the Theta band is more active. Theta band has been associated with memory and attention functions and a preponderance of Theta oscillations in the third trial could mean a more efficient memory function since the participant is more focused on the task (Düzel, Penny et al. 2010).

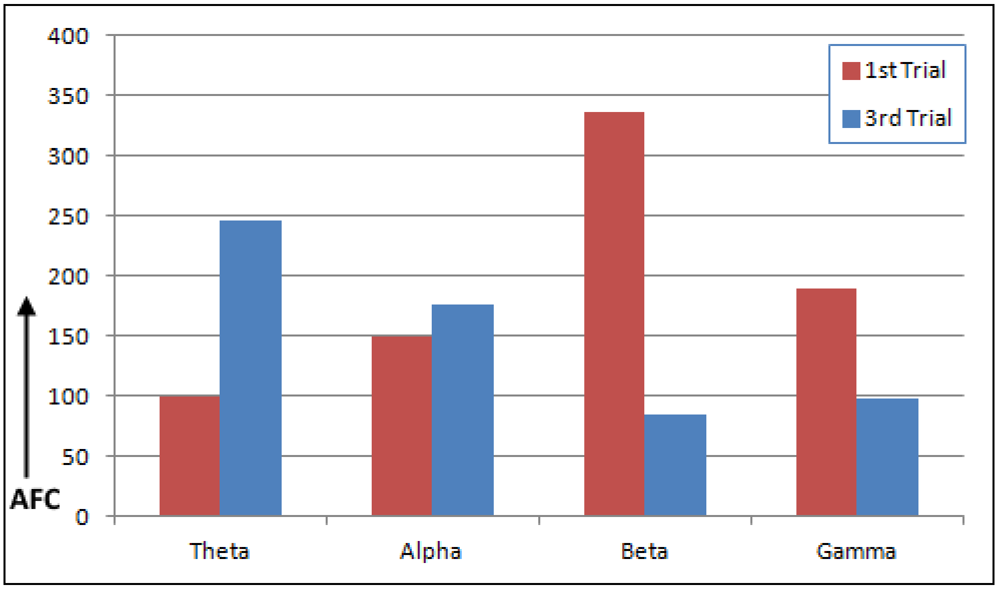

Figure 6.7: Distribution of Activated Functional Connections (AFC) in various frequency bands for 1st and 3rd Trials ($p<0.01$)

6.4.3 Common connectivity in Encoding and Retrieval

The cognitive task consists of two basic parts – the Encoding phase where the participant memorizes the colors of the stimulus blocks, and the retrieval part where the subject recalls the colors and matches it with the presented probe to make a response. Since the connectivity differences represent a neurophysiological marker for underlying brain processes, a search was made to seek those connections which were common both during the Encoding and the Retrieval phases for the two trials separately.

Figure 6.8 shows the main connections for the first and third trials in the Theta and Alpha frequency bands. In the Theta band, for the first trial (Fig 6.8-A), there are active connections between parieto-occipital electrodes which are shorter range, while in the third trial (Fig 6.8-B), long range connections between frontal-occipital and temporal-central regions are active. This could indicate that long range connections between occipital region which processes visual stimuli and the frontal regions responsible for attention and decision making could be important for better performance in a memory task.

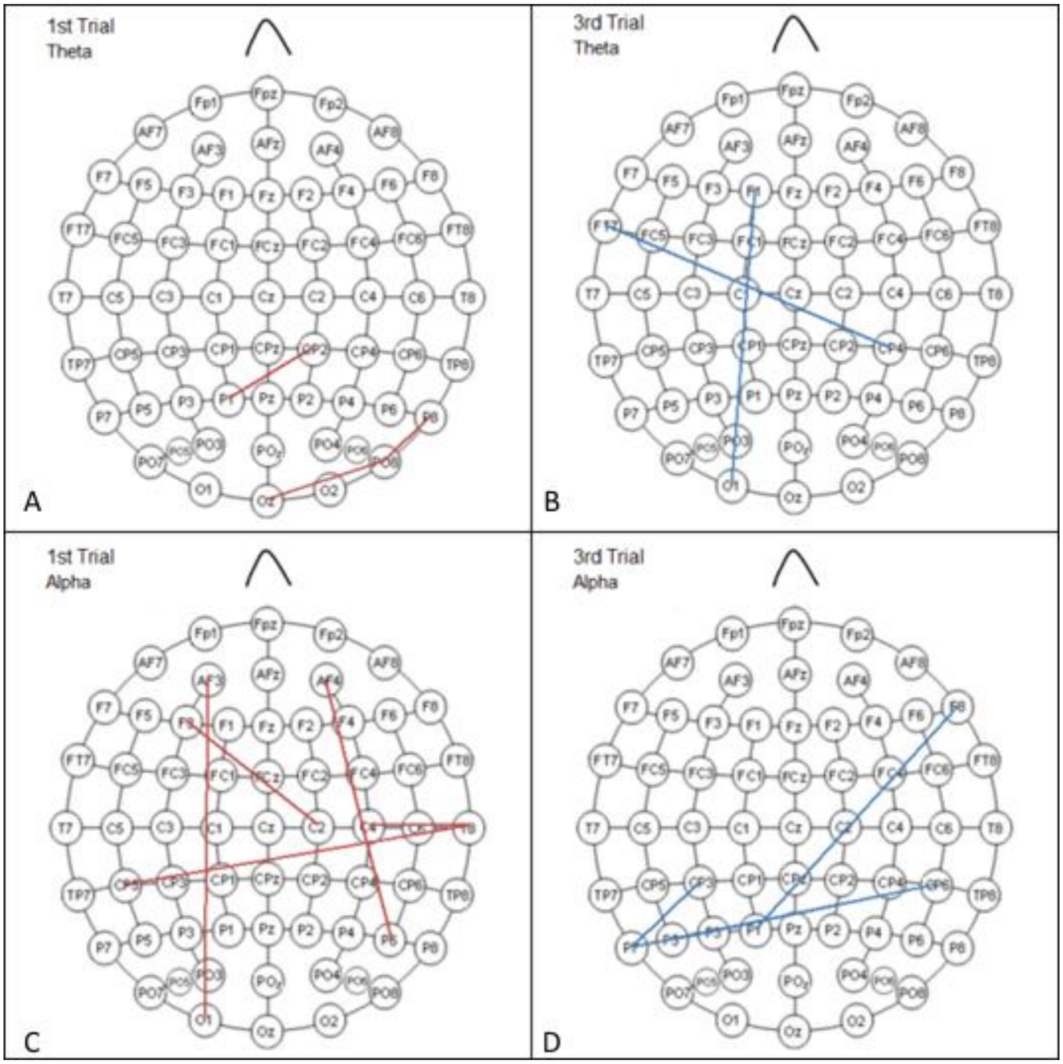

Figure 6.8: Main connections in Alpha and Theta bands (p<0.01)

Surface Connectivity profiles in the Beta and Gamma bands are shown in the Figure 6.9 for the first and third trials. The number of connections active in the first trial is higher than those in the third trial, which might seem counter-intuitive at first. However, this could signify that in the third trial when participants are more focused on the task, they might need a fewer number of connections to do this task. In the first trial, when the participant is first exposed to the memory task after being in the Resting phase, it will require more effort to perform that task and these connections in the Beta and Gamma range might point to such an increased effort.

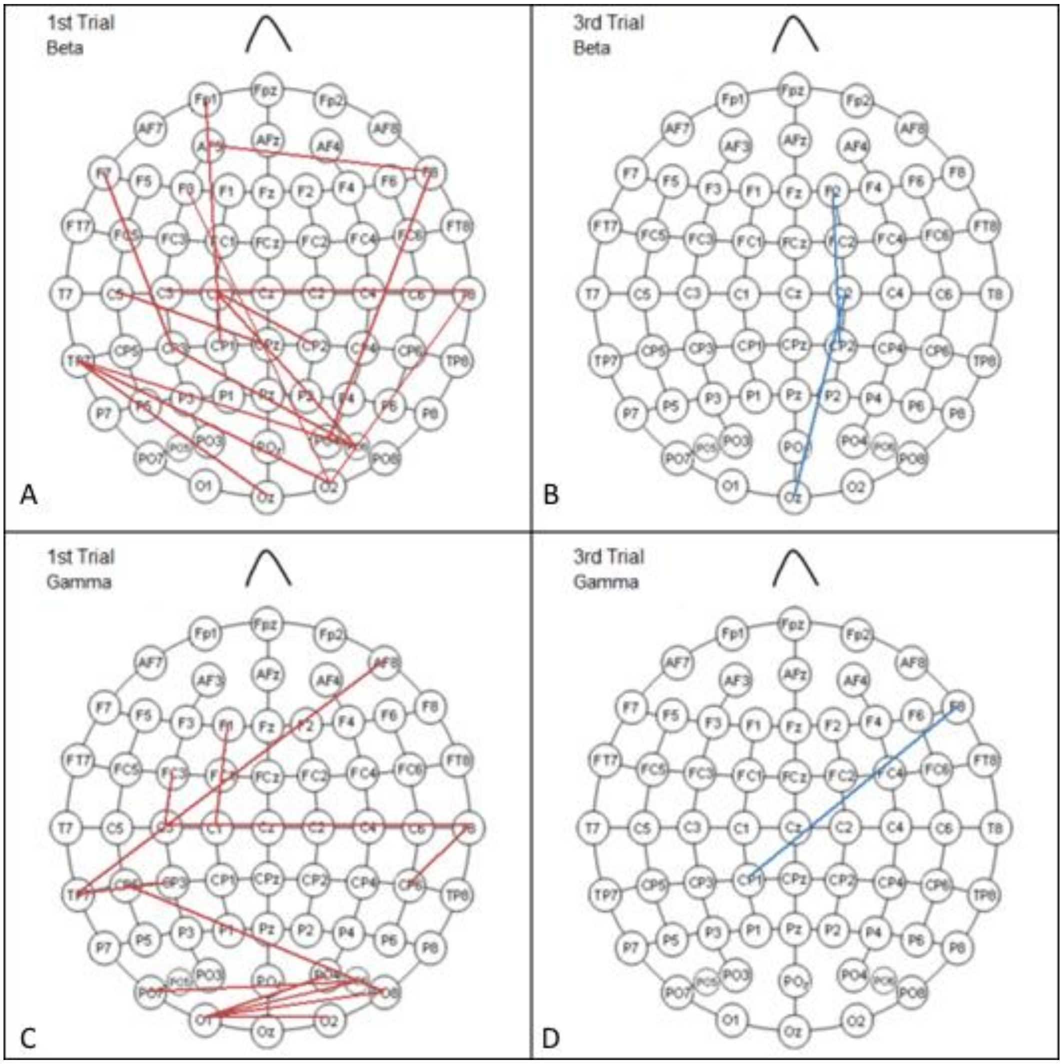

Figure 6.9: Main connections in Beta and Gamma bands (p<0.01)

There were a few channel pairs which were seen to be activated a multiple times for each condition. These are contrasted in Figure 6.10.

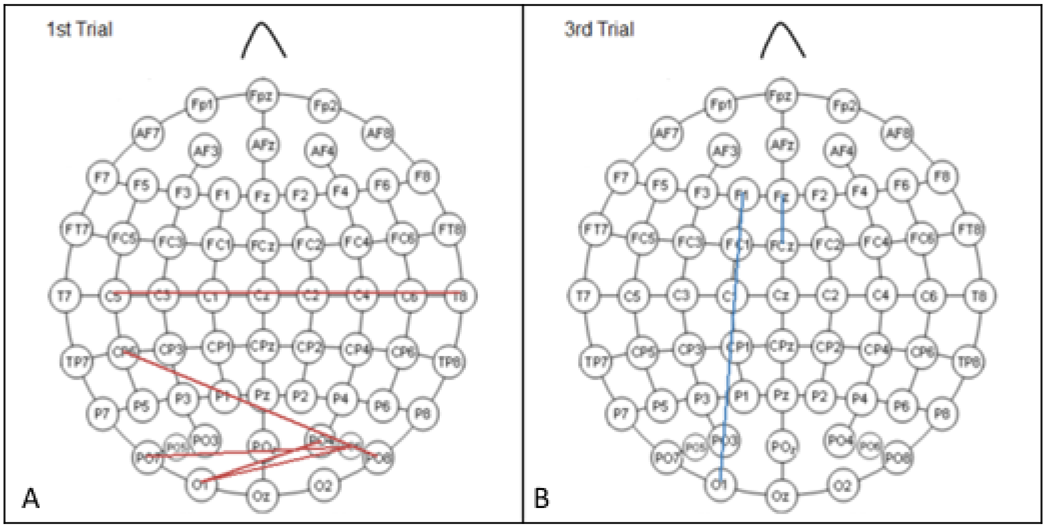

Figure 6.10: Main active channel pairs

In the first trial (Fig 6.10-A) there are cross hemispheric connections between central and parieto-occipital locations which were active. In the third trial (Fig 6.10-B) however, fronto-occipital channel pairs were activated at multiple times and in different frequency bands.

The main active channel pairs for four individual participants are plotted in Figure 6.11. They do show that not all the same channel pairs as shown in Figure 6.10 are activated, however the main areas and clusters of channels remains mostly similar to the combined results. This supports the notion that it would be preferable to optimize the channels for individual participants to get better results, once applications need to be developed using these features and classification.

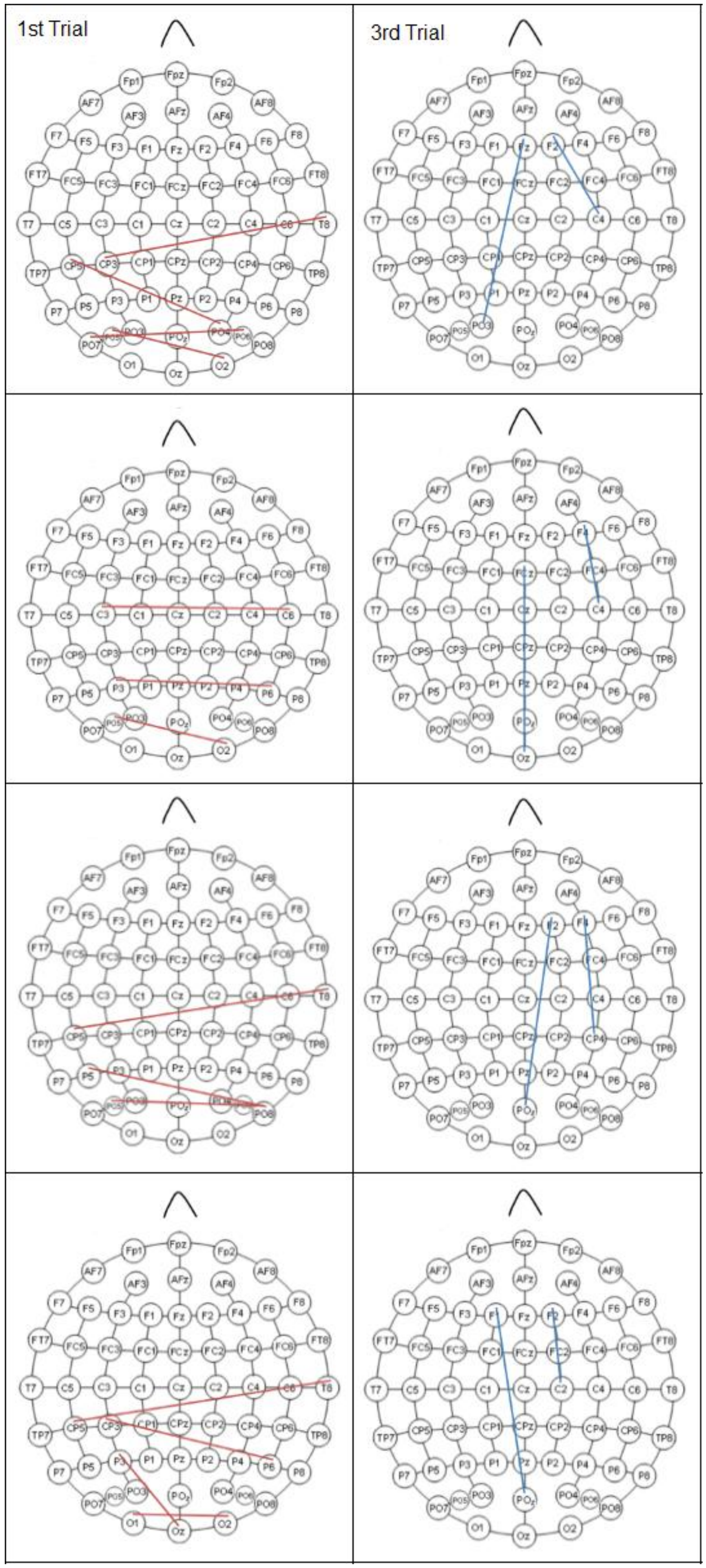

Figure 6.11: Main active channel pairs for four individual participants

6.5 Concluding Remarks

Mind wandering occurs when a person is not engaged in a goal directed external task. Such Stimulus Independent Thoughts (SIT) could lead to impairment in task performance. A study was conducted where participants conducted a Visual Short Term Memory task interlaced with resting intervals. It was hypothesized that the first task trial after the resting interval would be affected more by interference from SITs compared to the third trial when the participant is already engaged in the task. Behavioural measures of accuracy and reaction time confirmed this and IE-ERC method was applied to study the functional connectivity differences between the first trial and the third trial. The main findings are listed below –

1. Accuracy decreased with larger set sizes while reaction time steadily increased.
2. The Accuracy-Reaction Time Index was higher for the third trial compared to the first trial in the combined set sizes 1, 2 and 3 (p=0.057). The AR Index for combined set sizes 4, 6 and 8 showed no statistically significant difference between the first and the third trials.
3. The above difference in performance metrics indicates that the interference of mind wandering on VSTM is set size dependent.
4. The functional connectivity analysis of combined data from set sizes 1, 2 and 3 (SSz1-3) showed a dominance of Beta and Gamma band interactions after the first trial and of the Theta band after the third trial.

5. For those functional connections commonly found in the encoding and retrieval phases in the two conditions, there was an overall higher number of interactions seen after the first trial compared to the third trial.
6. Surface Connectivity Profiles for Theta band interactions showed a number of short range interactions after the first trial, while after the third trial, most interactions were long range. This could indicate that once engaged in the task, longer range interactions in the Theta band could enhance performance in this task.
7. SCPs for Beta and Gamma bands showed a higher number of interactions among various channels after the first trial which could indicate the increased effort required to focus on the task just after a resting interval.
8. Some functional connections were activated a multiple number of times in each condition and the SCPs show that there is a dominance of inter-hemispheric connections after the first trial while the third trial showed only a couple of interactions between the frontal and occipital locations.

7 Conclusions and Recommendations

The human brain is highly developed and performs various functions which are hard to be replicated by machines. This ability depends on various distinct parts of the brain which must communicate with each other in order to execute these functions. The EEG can measure potential changes on the scalp of individuals and can be processed to study internal mental functions with good time resolution.

Cognitive experiments were designed and conducted on healthy subjects to study three very important aspects of attention. First is the ability to pay attention to different sensory modalities which enables us to gather current information about the environment and carry out goal directed actions. Second is the emotional modulation of attention and third is the detrimental effect of mind wandering on attention demanding tasks.

Inter-Electrode Event Related Coherence (IE-ERC) was applied to study attention processes using functional connectivity biomarkers. Wavelet transform aided in calculating coherence at short 100 ms intervals and Surface Connectivity Profiles (SCP) in various time segments and frequency bands showed the channel locations which were interacting during different task phases. Statistical significance testing was done at a rigorous threshold of $p<0.01$, to find differences between functional connectivity values. The results in all the experiments showed the involvement of almost all the frequency bands, albeit at different time segments, depending on task demands.

7.1 Main Findings from the Attention Studies

Following are main findings of this work –

1. Auditory-Visual Crossmodality Attention – Some actions could primarily require attention to one sensory modality while ignoring other, thus an objective biomarker to differentiate modality specific attention could be useful in detecting and ameliorating any inadvertent lapses. In the Cross Modality Experiment participants performed a cognitive task requiring them to focus on either Auditory or Visual domain and functional connectivity estimates were derived using the IE-ERC method. Statistically significant differences were observed when participants paid attention to one or the other modality. Frontal lobes were involved in carrying out this function, but their interaction was mostly with the left temporal locations when focusing on the auditory domain, while it was with the right occipital locations when focusing on visual stimuli. A higher number of interactions in the Theta, Alpha and Beta bands were involved in auditory attention compared to Visual attention.

2. Emotional Modulation of Attention – To study the effect of attention modulation by emotional state, an experiment was conducted to modulate the emotional state of participants by using emotional and neutral images from the IAPS database while they performed a sound discrimination task. Functional connectivity analysis showed that the same sound stimulus was processed differently when the participant was in a dissimilar emotional state. Connections in the Beta and Gamma band were more active in the positive emotional state, while the Delta band was dominant during the

negative emotional state. Changes in connectivity profiles were observed at the 100 ms intervals. In the positive emotional state, frontal locations in the midline were mostly active while in the negative state right frontal locations were interacting, which is in line with theory about laterality of emotional valence.

3. <u>Effect of Mind wandering on Attention demanding Memory task</u> – Finally, the effect of mind wandering on the ability to perform attention demanding tasks was studied. Mind wandering tends to occur when one is not focused on an external task and it could have serious and deleterious consequences if there is a lapse of attention in industrial, military or aviation scenarios. The experiment participants performed a short term memory task which was interspersed with resting intervals. The memory task consisted of four subsequent trials of varying difficulty. The accuracy and reaction time measures confirmed the hypothesis that the first trial of the memory task was affected to a greater extent than that third trial. Since during the first trial the participant has to switch from internal mentation to the external task, this causes a decrease in task performance. However by the time the third trial occurs, the participant has focused on the task and thus the performance improves. IE-ERC method was used to study the connectivity changes occurring during this task performance. Overall a high number of interactions in the Theta range were seen during the third trial compared to the first one. A higher number of interactions in the Beta and Gamma band were present after the first trial and might indicate the

increased attention effort that was required for task performance. Furthermore long range interactions between frontal and occipital locations were seen to be active during the third trial which might indicate a greater degree of coupling between the attention regions in the frontal cortex and the visual areas in the occipital lobe.

7.2 Contributions of this work

The objective of this work is to utilize, adapt and develop EEG functional connectivity measures to study and further our understanding of the interaction dynamics within brain regions during cognitive attention tasks. Experiments were designed and conducted to explore three very important aspects of attention – switching between sensory domains, effects of underlying emotions on attention and effects of mind wandering on memory tasks. Functional connectivity estimates between electrode channel pairs were calculated using a wavelet based method which provides good time-frequency information from the signals.

These experimental studies have shown a distinct advantage of using functional connectivity measures in short 100 ms intervals to study cognitive functions. 100 ms time segments were chosen to estimate functional connectivity because there is reasonable stability of EEG microstates (Pascual-Marqui, Michel et al. 1995, Baars 2002, Van De Ville, Britz et al. 2010). It has provided insights into the various aspects of attention including the changing connectivity profile, various functional frequency bands being involved as well as the electrode positions carrying most statistically significant information. These connections showed variations with task demands and different electrode locations were seen to interact in diverse time segments. It is known that the information processing in the brain is very fast, and this method tries to capture this fast processing by studying the connectivity changes within short time durations. It is seen that the functional connections do not remain constant for the whole duration of the task, but are modified depending on task conditions. It is also observed that different channel pairs become active during the task and their interaction also takes place in different frequency domains. The conclusions from the individual studies compare well with previous research and confirm some of the earlier findings but also provide further details on the connectivity dynamics during those tasks.

Hence, it is advisable to apply methods like these to obtain connectivity data with good time resolution and also explore the roles of all functional frequency bands at the same time when conducting cognitive studies. Caution is advised when making direct inferences about the exact brain regions contributing to the connectivity changes because of volume conduction of EEG signals. Nevertheless, the electrode channels carrying the most differentiating information can still be deduced and would be useful when optimizing to fewer channels while developing applications. The studies conducted in this work, try to draw conclusions by finding statistically significant between subjects, as this is still the most common way of analyzing data in neurophysiological studies. However when developing applications, the effects of inter-subject variability will have to be addressed in greater detail. In most applications utilizing EEG data to classify some event related features, it is common to optimize those features for each individual subject. Different subjects might use different strategies to accomplish the cognitive tasks and thus distinct areas of their brain could be activated or functionally connected to fulfil these goals. Though by performing statistics across subjects most common changes would be detectable, but it could leave out some subject specific features which indeed could be more efficient in classifying the EEG data into different conditions. Since the objective of this work was not to develop a particular application, thus the main focus was constrained to across subject significance. Even though, some plots were generated on an individual basis to compare those electrode locations which were involved in making the most number of functional connections during different tasks. These show that there are some differences between the subjects as the neural configuration of each individual could be unique, but there are some common clusters which could be observed between the subjects.

7.3 Future Work

Further work is needed in relation to assessing whether different frequency bands have a different microstate characteristic. For example - whether slower oscillations in Delta band have the same or different time related stability compared to the faster Gamma band interactions. When distinct brain regions are synchronized to process a stimulus there are both feedforward and feedback signals between these regions and phase information could be added to functional connectivity analysis to study the regions which drive these interactions and the regions that lag. Many statistically significant differences were found in connectivity between different experimental conditions and machine classification could help in developing real time monitoring systems to detect attention states as an application. This would also require investigating the subject specific features, so that more specific and efficient features could be utilized for classification. Additionally, source localization methods could also be applied to investigate the sources contributing to these connectivity changes. However adding any process will bring its own assumptions, limitations and errors.

Publications

Published

A novel auditory working-memory vigilance task for mental fatigue assessment. **Rohit Tyagi**, Kaiquan Shen, Shiyun Shao, Xiaoping Li. Safety Science, 2009. **47**(7): p. 967-972.

Submitted for Publication

An EEG Coherence Method for Differentiating Auditory and Visual Attention. **Rohit Tyagi**, Li Xiaoping (Neuroscience) *Submitted*

EEG Event Related Coherence Study of Emotional Modulation of Attention. **Rohit Tyagi**, Li Xiaoping (Neuroreport) *Submitted*

Effect of Mind Wandering on Visual Short Term Memory task performance: An EEG functional connectivity study. **Rohit Tyagi**, Li Xiaoping (Memory and Cognition) *Submitted*

Conference Presentations

Using Sounds to Differentiate Emotions: An ERP Study. International Forum on Systems and Mechatronics, Singapore, 2010.

Using EEG for Neurological Disease Diagnosis, IBN International Symposium, Singapore, 2013.

Image Attributions

1. http://upload.wikimedia.org/wikipedia/commons/d/d3/Neuron1.jpg
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Appendix 1

Wavelet based Coherence function

```
function Cohere_w = w_cohere(x,y,fs_o,Dt,t_step,fs_d,w_name,Scale)

% This function estimates and plots a wavelet-based magnitude-squared (MS)
% coherence "Cohere_w" between two time series "x" and "y" both sampled at
% "fs_o" Hz.
%
% Other required input parameters:
% * "Dt" - one half of the time interval in seconds for estimating localized
% power spectra;
% * "t_step" - time step in samples at which the coherence will be evaluated;
%
% Optional input parameters:
% * "fs_d" - the desired sampling frequency in Hz; used to downsample the
% data. If not specified, the data will not be downsampled;
% * "w_name" - the name of a complex wavelet function to be used for the
% decomposition. If nor given the complex Morlet 'cmor1-2' will be used;
% * "Scale" - maximum scale for the decomposition; it determines the lowest
% frequency contents. If not specified, the scale from 4 (the finest details)
% to 200 (the coarsest) will be used.
%
% Example:
% x = 2.4*randn(1,200) + 1*sin(0.4+0.3*(1:200)) + 0.97*sin(0.43*(1:200));
% y = 1.9*randn(1,200) + 0.85*sin(1.8+0.3*(1:200)) + 0.75*sin(1.3+0.43*(1:200));
% Ch = w_cohere(x,y,100,0.005,20,100,'cmor1-2',150);
%
% A modified version of the estimator by Li et al., 2006, "Interaction
% dynamics of neuronal populations analysed using wavelet transforms".
%
% by Gleb Tcheslavski, gleb@vt.edu, February 2010
```

% Initialization

```
switch nargin
    case 7
        Scale = 200;                %default for the optional Scale parameter
    case 6
        Scale = 200;
        w_name = 'cmor1-2';         %default wavelet name
    case 5
        Scale = 200;
        w_name = 'cmor1-2';
        fs_d = fs_o;                %default - no resampling
end

w_scale = 4:0.5:Scale;              %scale parameter for wavelet... scale 1 is the finest (HF
components); scales less than 4 contradict Nyquist-Shannon theorem
t_start = 1;                        %the first time instance to be analyzed...
```

% Downsampling

```
Q = round(fs_o/fs_d);       %downsampling factor
x = resample(x,1,Q);
y = resample(y,1,Q);

fs = fs_o/Q;                %true new sampling frequency
it = 1/fs;                  %sampling step (period)
dt = round(Dt*fs);          %a half of "digital" time step, samples
```

% Estimating "cwt"...

```
Wx = cwt(x,w_scale,w_name);            %so called cwt...
Wy = cwt(y,w_scale,w_name);

t_end = size(Wx,2)-2*dt;               %the last time instance
```

% Estimating localized "power spectra" and Wavelet coherence

```
for t_ind = t_start:t_step:t_end
    wx = Wx(:,t_ind:t_ind+2*dt);              %time localization of cwts'
    wy = Wy(:,t_ind:t_ind+2*dt);
    for s_ind = 1:size(wx,1)
        Sxx = sum(wx(s_ind,:).*conj(wx(s_ind,:)));
        Syy = sum(wy(s_ind,:).*conj(wy(s_ind,:)));
        Sxy = sum(wx(s_ind,:).*conj(wy(s_ind,:)));
        Cohere_w((t_ind-t_start)/t_step+1,s_ind) = abs(Sxy)^2/(Sxx*Syy);
    end
end
```

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Usage

1. The function calculates wavelet based coherence between two given signals. Here it means time locked epoch from two EEG surface electrodes, between which coherence is to be estimated. (x and y).
2. Other parameters are used according to the data being processed, like original sampling frequency (fs_o), down-sampling frequency (fs_d), length time segment in which power spectrum will be calculated (Dt), number of data points at which coherence will be estimated (t_step – for 100 ms, use fs_o/10). Optionally wavelet name and scale can be selected, else default values will be used.
3. In the "Initialization" section, default values are assigned to the variables, if no specific values are provided in the function.
4. In the "Down-sampling" section, the data is down-sampled if the fs_o and fs_d are different.
5. In the "estimating cwt" section, the continuous wavelet transform of both the signals x and y is calculated using the given or default parameters.
6. Finally in section "estimating localized power spectra and wavelet coherence", the coherence between the two signals is computed, which is very similar to the

correlation function. This is done from the first to the last time point of the data epoch. Then, depending on the t_step value, this data is summed into different time segments.

7. Since many different scales would correspond to a particular frequency band (say Alpha band from 7 – 13 Hz) all scales corresponding to this band are averaged together to give one value for the band.
8. Paired T-tests are done to find the statistically significant results.