Analysis of Spectral Features of EEG during four different Cognitive Tasks

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Abstract - Cognition is a group of information processing activities that involves the visual attention, visual awareness, problem solving and decision making. Finding the cognitive task related regional cerebral activations are of great interest among researchers in cognitive neuroscience. In this study four different types of cognitive tasks, namely tracking pendulum movement and counting, red flash counting, sequential subtraction, spot the difference is performed by 32 subjects and the EEG signals are acquired by using 24 channels RMS EEG-32 Super Spec machine. The analyses of the EEG signal are done by using well known spectral methods. The band powers are calculated in the frequency domain by using the Welch method. The task- relaxes relative band power values and the ratios of theta band power/ beta band power are the two variables used to find the regional cerebral activations during the four different cognitive tasks. The statistical paired t test is used to evaluate the significant difference between the particular tasks related cerebral activations and relaxation. The statistical significance level is set at $p < 0.05$. During the tracking pendulum movement and counting task, the cerebral activations are found to be bilateral prefrontal, frontal, right central and temporal regions. Red flash counting task has activations in bilateral prefrontal, frontal, right central, right parietal and right occipital lobes. Bilateral prefrontal regions are activated during the sequence subtraction task. The spot the difference task has activations in the left and right prefrontal cortex. The unique and common activations regions for the selected four different cognitive tasks are found to be left and right prefrontal cortex. The pre frontal lobe electrodes namely Fp1 & Fp2 can be used as the recording electrodes for detailed cognitive task analysis were cerebral activations are observed when compared with the other cerebral regions.

Keywords: Cognitive task, Electroencephalography, Spectral analysis, Band power, Theta/Beta ratio

I. INTRODUCTION

Cognitive task studies are one of the major areas of research in neuroscience. Cognitive task is a group of mental activities that involves the visual attention, visual awareness, problem solving and decision making. When the subject performs different types of cognitive tasks, according to the cognitive task demand, the activations in the cerebral region varies. Finding the cerebral activation regions is popularly done by using electroencephalography (EEG), functional magnetic resonance imaging (FMRI), positron emission tomography (PET), single photon emission computed tomography (SPECT), and near infrared spectroscopy (NIRS). EEG is a non invasive technique and, most commonly used for cognitive task related analysis [1]. EEG signals consist of frequencies in the four bands [2] [3] namely Delta (0.5-4Hz), Theta (4-8Hz), Alpha (8-13Hz), Beta (13-30Hz). When more information is required about the neurophysiology of the electrical activity of the brain then the individual frequency bands in the EEG signals are analyzed in detail [4]. Power spectral analysis is a well-known standard method for the analysis of EEG signals [5]. According to the previous studies [6] using spectral band power they have shown during visual stimulus processing relative delta band power decreases. When the subject has visual attention and tendency for cognitive load during cognitive tasks, there is a decrease in relative theta band power. During attention, demanding cognitive load condition [7] they found an increase in relative alpha and beta band power. The purpose of this work is to find changes in the magnitude of power in various frequency bands of EEG signals at different electrode sites during task and relaxation periods associated with the execution of four different types of cognitive tasks namely Tracking pendulum movement and counting, Red flash counting, Sequence Subtraction and Spot the difference. The objective of this work is to determine the unique associated cortical regions for all the four types of cognitive tasks. When these four different cognitive tasks are used for cognitive research, only the electrodes in the common activation regions can be selected as the recording electrodes for detailed analysis.

II. MATERIALS AND METHODS

A. Mental Tasks Description

Four mental tasks are performed, during which the EEG signals are recorded.

1) Task1- Tracking pendulum movement and counting: In this task, the subject is given a visual cue consisting of a moving pendulum on the computer screen. The subject is asked to fix his/her gaze on a particular point in the path of the pendulum and is asked to count mentally, the number of times the pendulum crosses that particular point. The pendulum will oscillate for a predefined number of times during the trial period of 10 seconds.

2) Task2- Red Flash Counting: In the center of the computer screen flashes are presented. The flash changes its colour randomly either red or blue. During the trial duration of 10 Sec a target of 4 to 7 red colour and distractors of 8 to 5 blue colour flashes are presented randomly. Here the subject task is to mentally count the total number of times red color comes up.

3) Task3- Sequential Subtraction: During each trial a four digit number is presented and the subject is asked to subtract mentally 9, 8 and 7 sequentially. For example- XXXX - 9 = Answer – 8 = Answer - 7 = Final Answer. In each trial the four digit number is changed, but the subtrahend remained the same. The main objective of this task is to keep the mind occupied with mental arithmetic.

4) Task4 – Spot the difference: Here the presented visual cue has a set of two similar images with slight differences and the subjects are asked to spot the difference mentally. The given image sets contain a moderate level of difficulty. 3 different image sets are used in a random manner for this task. Similarly 8 trials are done.

In all the 4 tasks, during the inter trial relaxation duration, a smile picture is displayed and the subject is asked to mentally relax during the inter trial relaxation duration.

B. Visual Cue Protocol

Each task is performed for 8 trials, according to the protocol shown in figure. 1. During the inter trial relaxation duration, subjects are asked to relax with eyes open, gaze fixed on a particular point in the visual display monitor without any overt body movements. In between the task duration, the subjects are asked to relax and if needed body movements can be done.

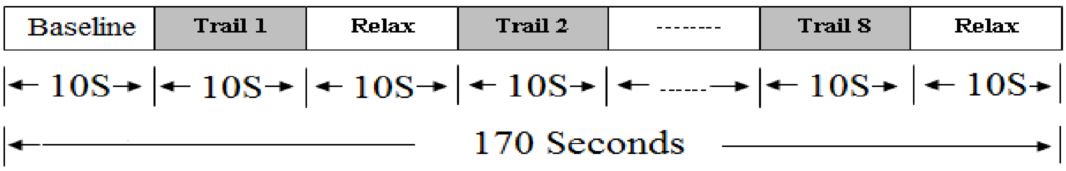

Fig. 1. Visual cue for cognitive task

Similarly, four tasks are performed and EEG signals are acquired. The duration of the whole experimental protocol starting from electrode placement and acquiring EEG with the visual cue is about 45 minutes. The environment within the laboratory is kept quiet during the entire recording so that the subjects are not disturbed by others.

C. EEG Data Collection

1) Subjects: The EEG data are acquired from 32 subjects. All the subjects are right handed in the age group of 21-24. Out of 32 subjects, 20 subjects are male and 12 subjects are female. All the subjects are either undergraduate or postgraduate student volunteers. All the subjects are normal, free from any medication and without any disorder in central nervous system.

2) EEG recording: EEG signals are recorded using RMS EEG-32 Super Spec (RMS INDIA) with the sampling frequency of 256Hz/channel. The electrodes are placed using International standard 10-20 lead configuration. EEG is recorded with reference electrodes in the left and right ear lobe. The EEG data are recorded from Fp1, Fp2, F3, F4, C3, C4, P3, P4, O1, O2, F7, F8, T3, T4, T5, and T6 with reference to respective ear lobes. The subjects are instructed to sit in the chair comfortably and rest their hands on the thigh. No body movements are made during the performance of the tasks and eye blinks are kept as minimum as possible. The skin electrode contact impedance is measured and kept below 10kΩ. EEG signals are filtered between 0.5 to 70Hz and a 50Hz notch filter is used to remove power line interference and EMG filters to remove the muscle artifacts.

D. Feature Extraction

The acquired EEG signal is band pass filtered with the band from 0.5 Hz to 30 Hz. The acquired signal contains the information required for further analysis. EEG signal analyses are done by extracting parameters in time and frequency domain. Spectral analysis is a frequency domain analysis. Spectral analysis is a well established method [4] for the analysis of EEG data. In each channel, for every 10s (2560 samples) of EEG data the features are extracted, thereby providing 8 relax and 8 trials states for a particular task. Further analyses are done with the calculated features. The common four bands of EEG signal [2] [3] δ (0.5-4 Hz), θ (4-8 Hz), α (8-13 Hz) and β (13-30Hz) are extracted by employing Butterworth band pass filter. For each channel after splitting up the signal into four specific bands, the absolute power of each band is calculated by using a Welch method [8] [9]. Using Hamming window of 2s (512 samples) width and 1s (256 samples) overlaps the periodogram is created. From the periodogram of each segment, the power spectral density is calculated and it is averaged to find the absolute band power values. The absolute band power is converted to dB for further analysis.

Relative band power is calculated for each band as a percentage of total EEG activity in the band 0.5-30 Hz [11].

$$RDP = Power\ of\ \delta / (Power\ of\ \delta + \theta + \alpha + \beta) \quad (1)$$

$$RTP = Power\ of\ \theta / (Power\ of\ \delta + \theta + \alpha + \beta) \quad (2)$$

$$RAP = Power\ of\ \alpha / (Power\ of\ \delta + \theta + \alpha + \beta) \quad (3)$$

$$RBP = Power\ of\ \beta / (Power\ of\ \delta + \theta + \alpha + \beta) \quad (4)$$

RTP /RBP ratio [10] [11] is also used as metrics to find the regional cerebral activation in addition to the relative band power analysis. When there is a cognitive load, the theta power is expected to decrease and beta power to increase. In the Theta/Beta Ratio during cognitive information processing the numerator decreases and denominator increases and so the net ratio decreases when compared to the eyes open relaxed condition.

III. RESULTS

The typical EEG recordings during cognitive task1 and relaxation periods are shown in figure 2 and figure 3 respectively.

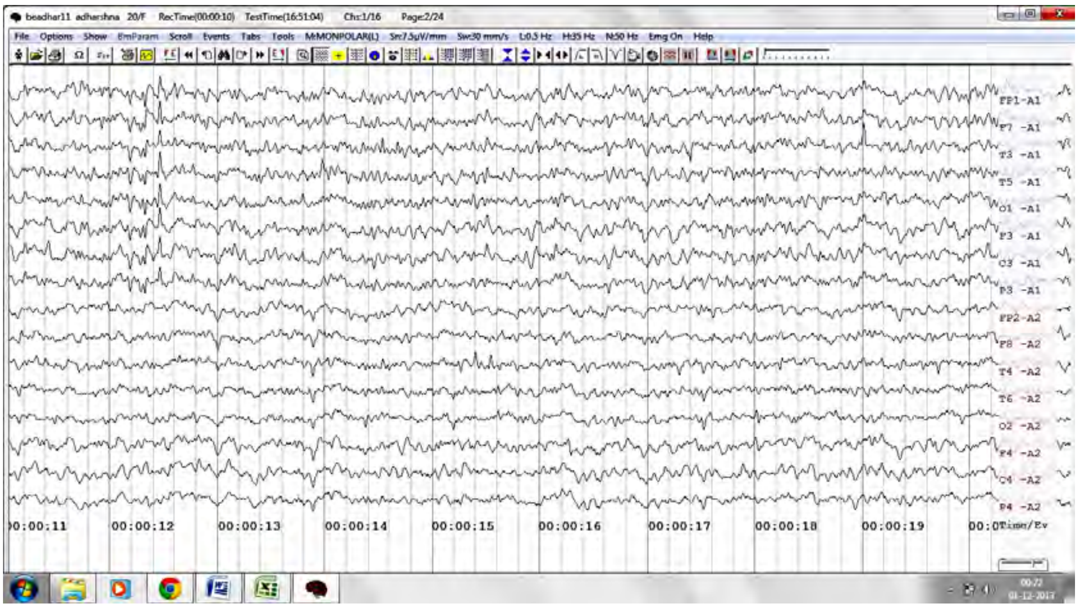

Fig 2. EEG signals during cognitive task1

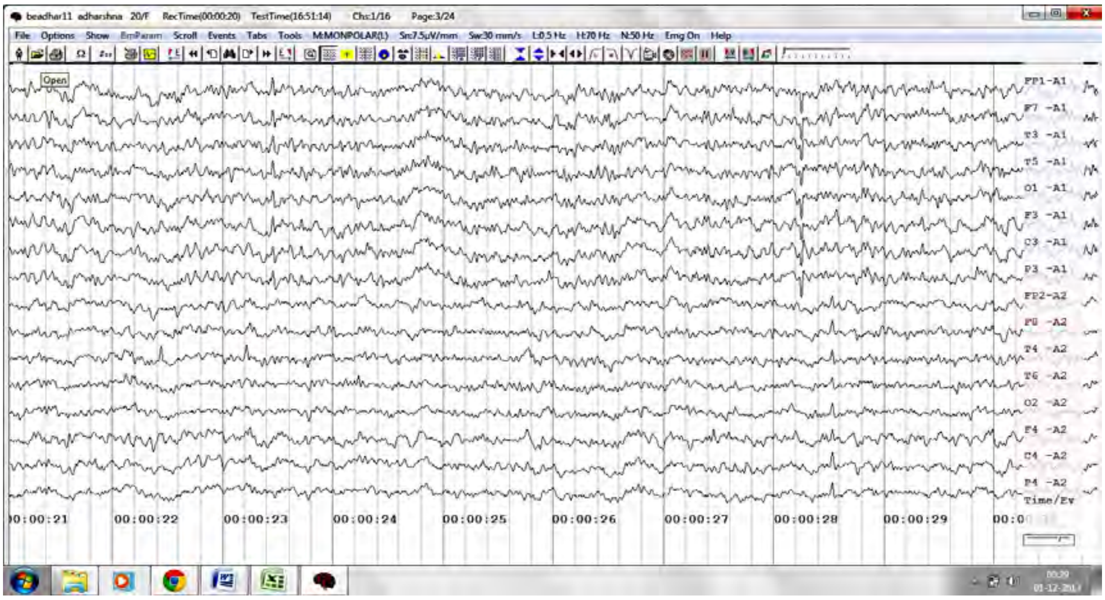

Fig. 3. EEG signals during relaxation after cognitive task1

The analyses of the band power are based on the average of 32 subject's data. The four different band power variations are studied in all the 16 electrode sites, namely Fp1, F3, F7, C3, T3, T5, P3, O1, Fp2, F4, F8, C4, T4, T6, P4, O2 in the International standard 10-20 lead system in the monopolar configuration. The different band power of the EEG signals, namely Delta band power (DBP), Theta band power (TBP), Alpha band power (ABP) and Beta band power (BBP) during different cognitive tasks (at relaxation and task phase) are analyzed and found the corresponding cerebral activation regions. Statistical significance between task period and relaxation period is tested using the paired student test, at $p< 0.05$ using the absolute band power values. Table-1 shows the statistical results during the four different cognitive tasks.

TABLE-1

RESULTS OF STATISTICAL PAIRED t TEST

S.No	Task	EEG Absolute Band Power	Electrodes Positions where Band power decrease	Electrodes Positions where Band power increase	Significant p values <0.05
1	Tracking Pendulum Movement & Counting (Task1)	DBP	Fp1, F3,Fp2,F4,C3,C4	T4, T6, P4	Significant
		TBP	Fp1,F3, F7,Fp2,F4,F8,T5,T6	C3,C4, O1,P3,T3	Significant
		ABP	C3,O1,O2,P3,P4,T3, T5,T6	Fp1, Fp2,F3, ,F4,F8	Significant
		BBP	P3,P4,O1,O2	Fp1, F3, F7, Fp2,F4, F8, C3, T3,T6	Significant
2	Red Flash Counting (Task2)	DBP	F3,F4,F7,F8,Fp1,Fp2	-	Significant
		TBP	Fp1,Fp2,F3,F7	-	Significant
		ABP	-	Fp1,Fp2, O1,O2,P4,T6	Significant
		BBP	-	Fp1,Fp2,O2,P4,T6	Significant
3	Sequence Subtraction (Task3)	DBP	F4,F7,F8,Fp1,Fp2	-	Significant
		TBP	Fp1, Fp2	O1,O2,P3,T5	Significant
		ABP	P4, T6	Fp1, Fp2	Significant
		BBP	F4, P4, T6	Fp1, Fp2, F8	Significant
4	Spot the Difference (Task4)	DBP	Fp1, Fp2	F8,O1,O2,P3,P4,T5,T6	Significant
		TBP	Fp1, Fp2	F3, ,O1,O2,P4	Significant
		ABP	C3,C4,F3,F4,F7,F8, ,O2,P3,P4,T3,T5,T6	Fp1, Fp2	Significant
		BBP	C3,C4,F3,F4,F7,F8, O2,P3,P4,T5,T6	Fp1, Fp2, T3	Significant

A. Task 1 Results

For task1 the relative band power difference between task and relaxation in various band powers is shown in figure 4. The positive polarity indicates that during the task, the particular band power increases when compared to relaxation and vice versa for the negative polarity. The Theta/Beta ratio in various electrode sites during task1 and relaxation is shown in figure 5. If there is cerebral activation during cognitive load, the Theta/Beta ratio decreases when compared to relaxation. From figure. 4 and figure 5 for task1, the effective bilateral activation in prefrontal, frontal, right central and temporal regions are found.

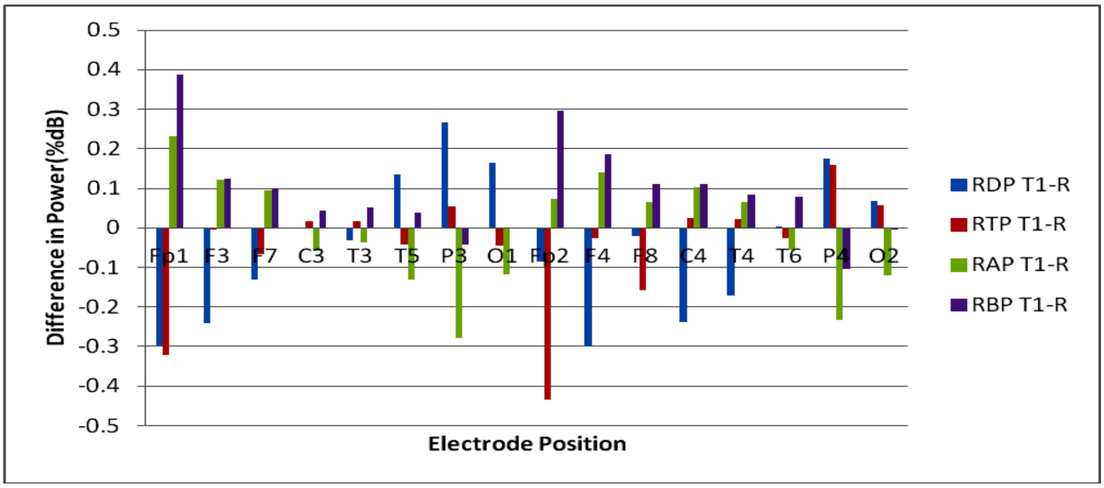

Fig. 4. Band power difference between task1 and relaxation

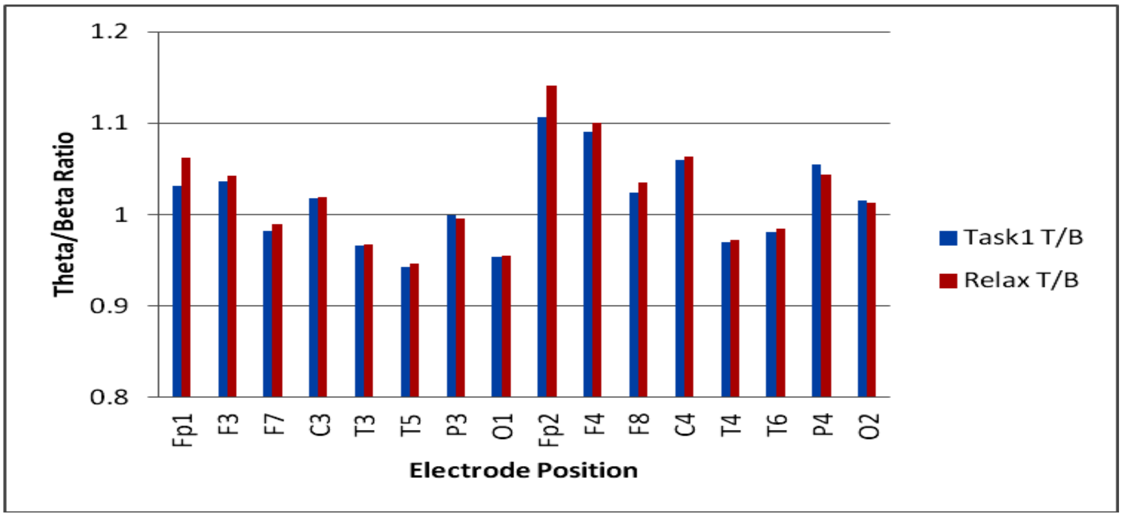

Fig. 5. Theta/Beta ratio during task1and relaxation.

B. Task 2 Results

Figure. 6 shows the difference between the band power during task2 and relaxation in various EEG signal bands. Figure. 7 shows the Theta/Beta ratio of task2 trial period and relaxation in various electrode sites. From figure 6 and 7, the cerebral activation regions for the task2 is found to be bilateral prefrontal, frontal, right central, right parietal and right occipital lobes. The electrode sites are Fp1, Fp2, F3, F4, F7, F8, C4, T4, T6, P4 and O2.

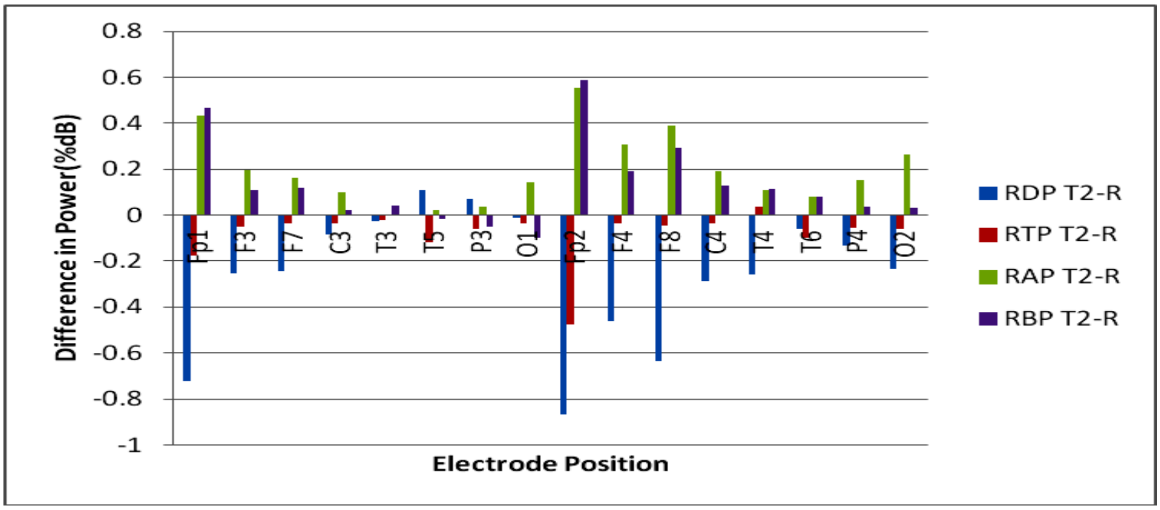

Fig. 6. Band power difference during task2 and relaxation

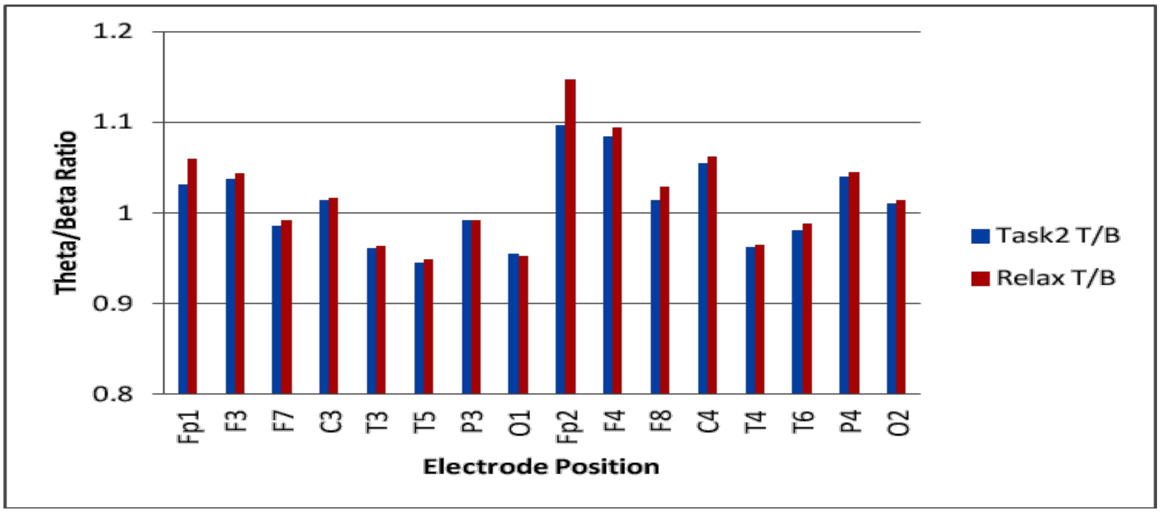

Fig. 7. Theta/Beta ratio during task2 and relaxation

C. Task 3 Results

For task3 the relative band power difference between task and relaxation in various band powers are shown in figure 8. During the task3 relative theta band power increases in all the electrode sites except in Fp1 and Fp2. The Theta /Beta ratio is less only in Fp1 and Fp2 during task3 period when compared to relaxation. Figure. 9 shows the Theta/Beta ratio of the task 3 trial periods and relaxation in various electrode sites.

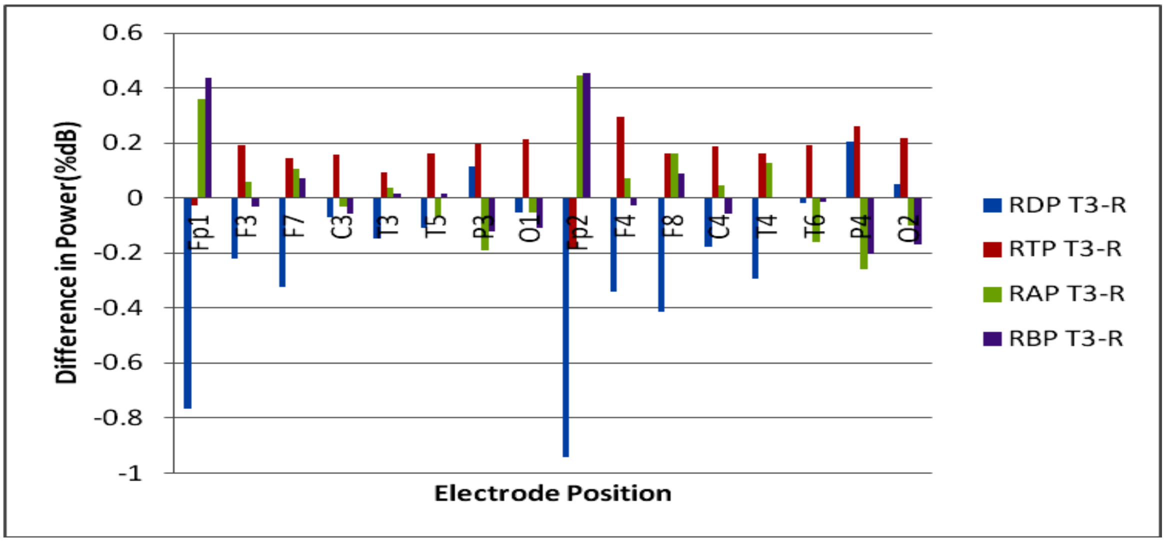

Fig. 8. Band power difference during task3 and relaxation

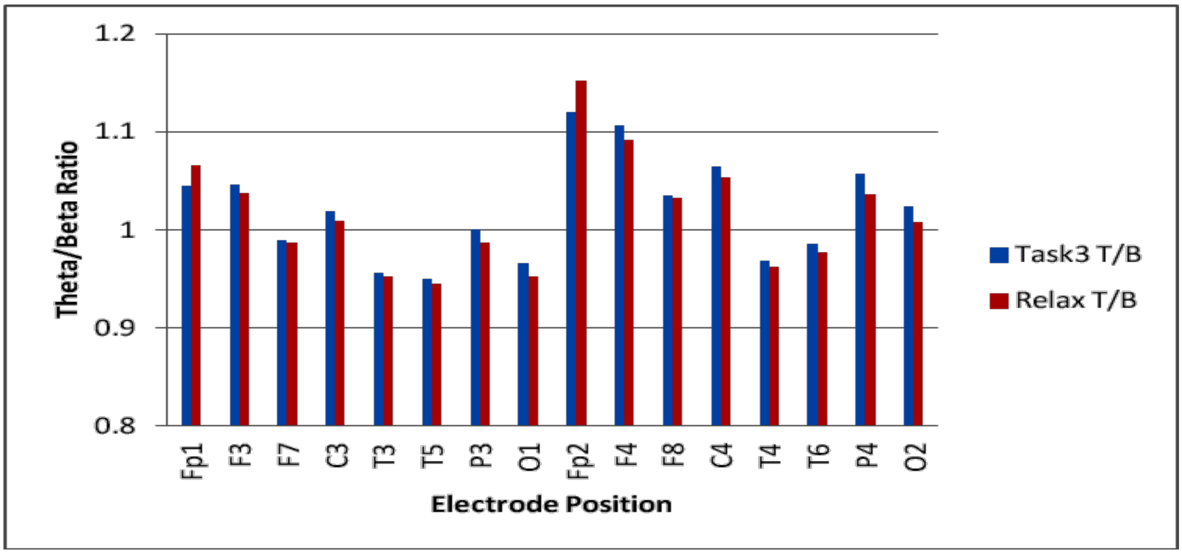

Fig. 9. Theta/Beta ratio during task 3 and relaxation.

From figures 8 and 9 the cerebral activation regions for the task3 are bilateral prefrontal.The corresponding electrode sites are Fp1and Fp2.

D. Task - 4 Results

Figure. 10 shows the difference between task 4 and relaxation in various EEG signal band powers. Figure. 11 shows the Theta /Beta ratio of the task 4 periods and relaxation in various electrode sites. From figure 10 and11 the activation regions for task 4 are bilateral prefrontal.The corresponding electrode sites are Fp1and Fp2.

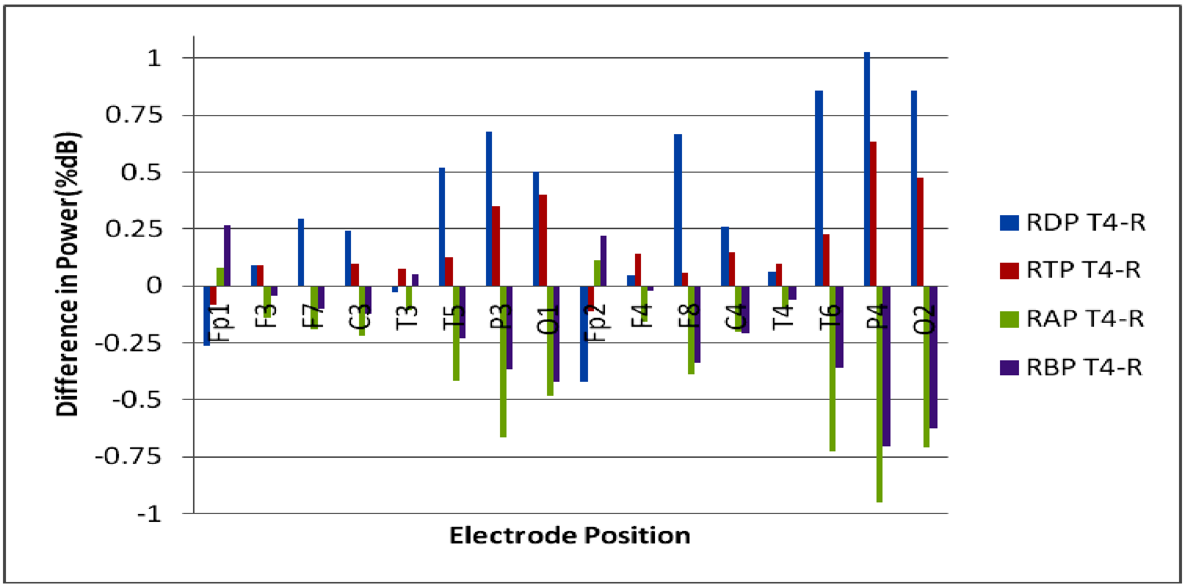

Fig. 10. Band power difference during task4 and relaxation.

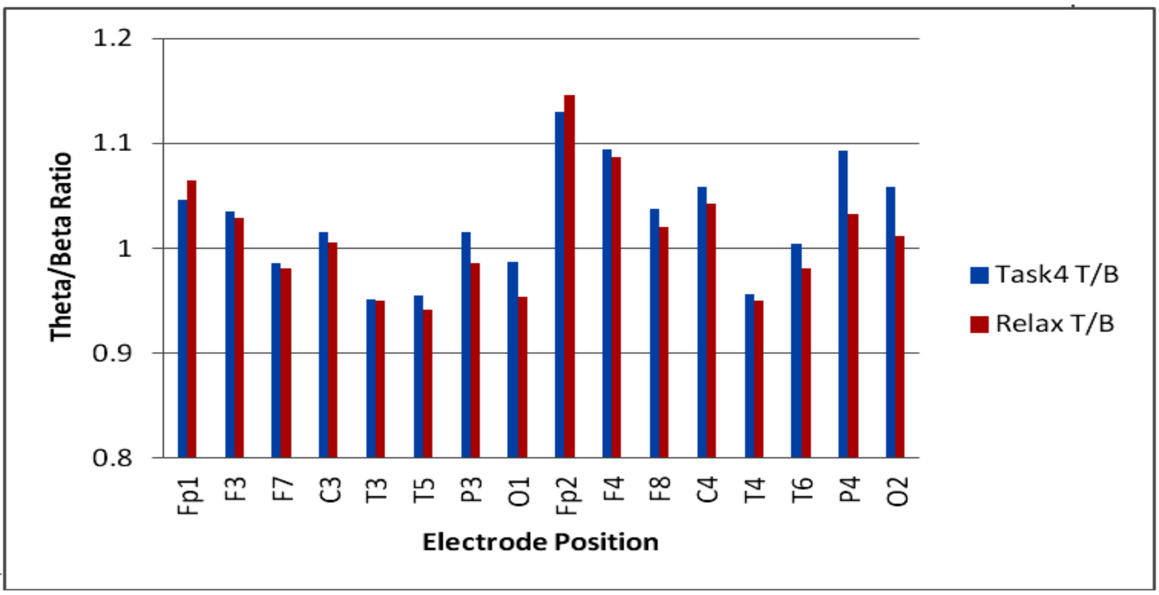

Fig. 11. Theta/Beta ratio during Spot the difference task and relaxation.

From the results the important findings are that different cognitive tasks are having different cerebral activation regions and the common and unique cerebral activation regions for all the four cognitive tasks are found to be bilateral prefrontal cortex regions. Suitable electrodes for detailed analysis are Fp1 and Fp2.

IV. DISCUSSION

Using the spectral band power analysis on EEG signals the active cerebral regions during the four different cognitive tasks are evaluated. There are significant activations in the specific cerebral regions according to the type of cognitive task performed. According to the previous studies [6] [10] when the subject performs a particular task which involves visual information processing and attention, they showed relative δ and θ decreases whereas relative α and β band power increases when compared to eyes open relaxation. In [11] a previous study showed that the Theta/Beta ratios being less during continuous cognitive task performance or cognitive load when compared to eyes open relax condition.

Tracking pendulum movement and counting task (Task1) involves visually recognizing the movement and visual attention for counting [12]. From the table –I for task1 in all the four frequency bands in EEG, paired t test showed a significant variation ($p<0.05$) in the absolute band power between task and relax in, Fp1, Fp2, F3, F4, C3, T6 electrode sites. The significant cerebral activation in the Fp1, Fp2, F3, F4, C3, T6 electrode sites shows decrease in RDP, RTP during cognitive information processing or cognitive load when compared to relaxation. RAP and RBP increase during the trial period of task1 which has cognitive load and decreases during relaxation. In this study, the results found are in line with the previous studies of pendulum movement, visual recognition of non stable postures [12]. They have used pendulum movement as control experiment and found during the active observations of the pendulum movements, there are enhancements in the signal power in all the frontal regions with maximum in F4 regions. During the trial period, visual recognition of movement and visual counting are involved so the theta power increases and beta power decreases, which causes the Theta/Beta ratio to decrease. The theta/beta ratio decreases during task1 period when compared to the eyes open relax in the Fp1, F3, F7, Fp2, F4, F8, C4, T6 which indicates the active participation of these regions during the task period.

Red flash counting tasks (Task2) have a high cognitive demand for rapid color discrimination and identify only red flashes for counting from the distractors. Task2 shows significant cerebral activations in the bilateral prefrontal, frontal, right central, right parietal and right occipital lobes. The electrode sites are Fp1, Fp2, F3, F4, F7, F8, C4, T4, T6, P4 and O2. From table–1 Fp1, Fp2, F3, F4 show significant activations during task when compared to relax in all the frequency band powers with $p<0.05$. Visual discrimination and counting the red color flash shows the involvement of working memory. The spatial information processing is done in the right hemisphere [14] of parietal and occipital regions and arithmetic of counting the flashes has the activation in frontal and prefrontal regions. In this study during task2 trial period, the theta/ beta ratio shows a pattern of decrease in 14 out of 16 electrodes when compared to the eyes open relaxation.

A calculation task, such as sequential subtraction involves number processing [13] and manipulations which depend on the short term and long term memory. Paired t test for Sequence subtraction (Task3) task showed significant activations in Fp1 and Fp2 regions in all the absolute band powers when compared to relaxation. In the literature [13] the researchers found subtraction task has either bilateral or left prefrontal cortex involvement. Arithmetic operations that involve number processing and manipulations require working memory. In general, working memory has activation in the prefrontal cortex [15]. In the current study the bilateral prefrontal cortex regions are activated during sequence subtraction tasks [13] and the results of the relative theta/beta ratios in Fp1 and Fp2 are consistent with the reported literature indicating a decrease in ratio values during task3 (cognitive load condition) [11] compared to relax.

Spot the difference task (Task4) involving comparison of two images side by side which needs visual attention to find the differences requires visual awareness [14]. Significant ($p<. 0.05$) cerebral activations during task period when compared to relaxations are observed in Fp1and Fp2.The visual attention and visual awareness are part of the working memory activity. When cognitive tasks are performed which involves working memory shows activation in the prefrontal cortex. It is also observed a decrease in theta/beta ratios in Fp1 and Fp2 regions.

V. CONCLUSION

EEG data are recorded in 32 subjects while performing 4 mental tasks. From the raw recorded EEG data, absolute band powers for the 4 bands, namely Delta, Theta, Alpha and Beta are successfully extracted. From the absolute band power, relative band power values are calculated. Analysis is performed on this data and it is evidently seen that while performing four different cognitive tasks the electrodes Fp1 and Fp2 record more activity when compared to the other electrode sites. The common activation regions for the selected four different cognitive tasks are found to be prefrontal cortex. So while cognitive task analysis more importance can be given to the pre frontal lobe electrodes where more cerebral activations are observed compared to the other cerebral regions. Also preparation of the subject scalp is more easy and convenient since the electrodes are placed on the forehead. In future, further information can be arrived using nonlinear analysis.

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