Proceedings of 2013 ICME
International Conference on Complex Medical Engineering
May 25 - 28, Beijing, China

EEG Mean Power and Complexity Analysis during Complex Mental Task

Hafeez Ullah Amin, Aamir Saeed Malik*,
Nasreen Badruddin
Centre for Intelligent Signal and Imaging Research (CISIR)
Department of Electrical and Electronics Engineering
Universiti Teknoloogi PETRONAS
31750 Tronoh, Perak, Malaysia
*aamir_saeed@petronas.com.my

Weng-Tink Chooi
Advanced Medical and Dental Institute (AMDI)
Universiti Sains Malaysia
Pulau Pinang, Malaysia

***Abstract* - The aim of this study was to investigate the association between EEG measures (mean power and sample entropy) and complex mental reasoning task (IQ test). Six healthy university students participated voluntarily in the experiment. EEG was recorded at resting states (eye open and eye closed) and during performing IQ test and analyzed over 12 regions across the scalp. EEG mean power measure of delta and theta frequency significantly (p<0.025) discriminated the IQ test from resting states at frontal regions and alpha frequency at parietal, occipital and parieto-occipital regions. Highly reduced mean power of beta frequency was found during IQ test at parietal, occipital and parieto-occipital regions as compared to frontal regions. Results of Sample Entropy (SE) showed high complexity in EEG signal during IQ test than resting state eye closed. Our findings showed high cortical activation and increased EEG complexity during IQ test than resting states.**

Index Terms – EEG frequency band, Mean power, Sample entropy, and IQ test.

I. INTRODUCTION

Power spectrum and Sample entropy (SE) are independent measures of EEG signal. They could discriminate the brain behavior in different states. Although MRI [1] has also been used in studying brain behavior using various mental tasks but we concentrate on EEG because it is low cost and experiments can be performed out of laboratory environment too [2, 3]. Power spectrum indicates the strength of synchronous neural activities in cortex, while SE estimates the regularity of the EEG signal. Recent research studies investigated EEG frequency bands during cognitive tasks. Several studies reported changes in EEG frequency bands paralleled with mental stress [4], creative thinking [5], mental arithmetic task [6], working memory [7, 8] and intelligence test [9]. High theta activity in intelligent individuals and upper alpha correlation with cognitive tasks has explored by [10]. Another study reported high theta and alpha power in brighter individuals, and suppressed alpha in averaged ones [11].

Nonlinear EEG time series analysis has been of great interest to many researchers. Entropy measures have been showed as a strong tool to analyze EEG time series and estimate the signal regularity [12]. Richman and Moorman [13] presented a method "Sample Entropy" as a new statistics quantifying regularity of time series. Theoretically, it is based on the conditional probability, which is estimated as the ratio of the unconditional probabilities of the two sequences matching lengths "m", and "m+1".

R.J. Sternberg presented the theory, nature and measurement of intelligence [14]. It is defined as general cognitive problem solving skills or mental ability involved in reasoning, perceiving associations, learning or calculation etc. Individuals who are strong in analytical and cognitive abilities are conventionally viewed as smart and intelligent. Several psychological tools are available to judge the general cognitive ability and measure the IQ. Raven's Advance Progressive Matrices (APM) test is a psychological standardized cognitive ability test, which is used to measure an individual's higher order general mental ability. It is designed to discriminate among individuals of "superior intellectual ability" [15]. Normally, it is used as a selection methodology for high stakes situations such as defense training, research, and medical education [16].

The aim of this study was to investigate the association between EEG measures (mean power and sample entropy) and mental reasoning task (IQ test). More specifically, power spectrum and entropy measures were used to study the changes in brain electrical activity in IQ test and in resting states. Rests of the sections are organized as: section II presents the experimental design and data recording; section-III describes the findings of mean power and sample entropy; section-IV provides the discussion; and section-V gives conclusion.

II. METHOD

A. Subjects

This research study was approved by the Research Committee of Universiti Teknologi PETRONAS (UTP) and Human Research Ethics Committee of Universiti Sains Malaysia. Six healthy university students participated in the experiment voluntarily. All subjects had normal or corrected to normal vision and were free from any hearing impairments and. All the subjects were male, right handed and their age range was between 18 to 28 years. They signed informed consent document which has a brief description of the research study in English and in Malay languages prior to start experiment. The subjects were free from any medication, neurological disorder, or other head injury that may affect the experiment results. None of them were currently using any drugs which may affect cognitive performance. Previously, they did not experience Raven's Advance Progressive Matric test (APM).

B. IQ test

Raven's APM consists of two sets of patterns. Set-I consists of 12 patterns; each pattern has a missing element that the participant needs to detect from eight available options (see Fig. 1). Set-I was used for practice. Set-II consisted of 36 patterns that had similar style and patterns as in Set-I, but more difficult and complex than Set-I. Each correct answer had score 1 and each incorrect answer had a score 0. The recommended administration time for Raven's APM is 30 to 40 minutes.

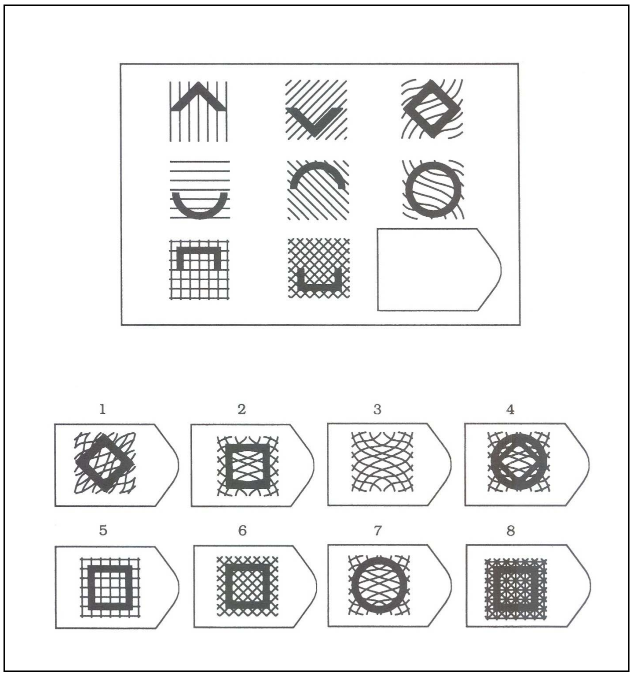

Fig. 1 Raven's Advance Progressive Matric Design

C. Experiment Procedure

Subjects were seated in a partially sound-attenuated EEG experiment room and were instructed about the experiment to perform the IQ test (Raven's APM). EEG data were recorded using 128-channel Hydro Cel Geodesic Net (see Fig. 2). The impedance of all electrodes was below 50 kΩ. The EEG recordings were referenced to Cz. The sampling rate was specified 250 samples per second. Data conditions were (a) baseline rest condition of eye-closed and eye open, (b) performing IQ test *"Raven's Advance Progressive Matric test (APM)"*. Raven's APM was implemented in E-prime software and time stamped each question for 1 minute. So, the test session was up to 36 minutes. The experiment lasted up to one hour maximum.

D. Data Analysis

The EEG at each electrode site i was recorded as a time series $x_i^{(k)}$ per trial *k*. Thus, the whole data can be denoted as, $X^{(k)} = [x_1^{(k)}, x_2^{(k)}, x_3^{(k)}, ..., x_{Ne}^{(k)}]^T \in R^{Ne \times Ns}$ where *Ne*=128 is the no of electrode sites, and *Ns*=250 represents sampling frequency. Data were filtered using 0.1-48Hz band pass filter. ICA was applied for artifacts removal, and fast Fourier Transform was used to estimate power spectral density (μV^2) and mean power per region. The electrodes were grouped over 12 scalp regions as: Prefrontal (PF): (9, 22, 14, 15, 21), Anterior Frontal (AF): (23, 3, 34, 12, 26, 2, and 16), Frontal (F): (19, 4, 24, 124, 27, 123, 33, 122, 32, 1, 14, 21, 15, and 11), Central (C): (30, 105, 36, 104, 41, 103), Parietal (P): (60, 85, 52, 92, 51, 97, 64, and 95), Temporal (T): (45, 108, 44, 114, 45, 108, 34, 116, 38, 121), Occipital (O): (70, 83, and 75), Fronto-Central (FC): (13, 112, 29, 111, 28, 117, 6), Centro-Parietal (CP): (37, 87, 42, 93, 47, 98, 55), Tempo-Parietal (TP): (58, 96, 46, 102, 57, 100), Fronto-Temporal (FT): (34, 116, 38, 121), and Parieto-Occipital (PO): (67, 77, 65, 90). Friedman test and Wilcoxon signed ranked test were used for statistical analysis.

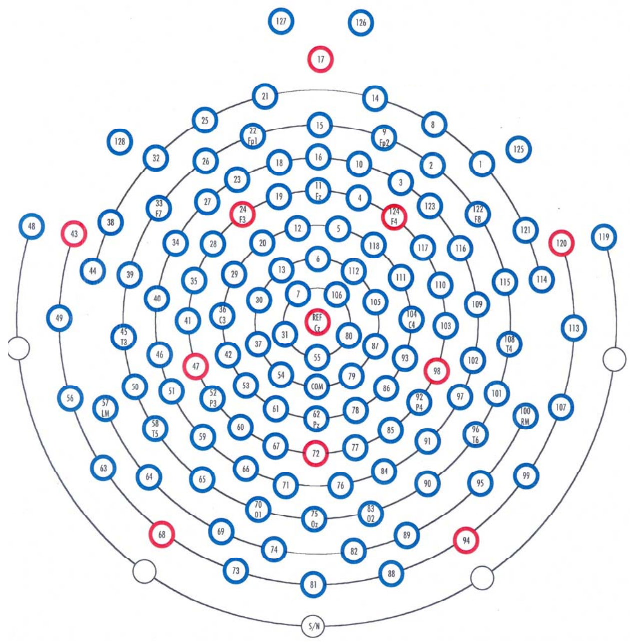

Fig. 2 Hydro Cel Geodesic 128-channel Net [17].

For calculation of SE, the following formula was applied [18].

$$SE(m, r, N) = -\ln[\frac{B^{m+1}(r)}{B^m(r)}] \quad (1)$$

Where,

m= length of sequence to be compared

r= tolerance for accepting matches (r=2*SD of x_i),

N= length of the time series

$B^m(r)$= estimated probability that two sequences match for m points

$B^{m+1}(r)$ = estimated probability that the sequences match for m+1 points

In this paper the value of m=2, and r= 0.2 × standard deviation of the original data *X(i)*. SE was calculated segment wise. The length of each segment was 500 points, which was 2 seconds in time. SE was applied on thirty seconds data of each EO and EC states, and sixty seconds data was processed of IQ test for each subject.

III. Results

A. EEG Power Spectrum

The power spectrum of frequency bands delta (0.5-3Hz), theta (4-7Hz), alpha (8-13Hz), Beta1 (14-20Hz), and beta2 (21-30Hz) were analyzed. The mean values of region wise EEG mean power in delta, theta, alpha, beta1, and beta2 frequencies for three states (IQ, EC, and EO) of six participants are showed in Fig. 3 to Fig. 7. The results presented significant ($p<0.025$) positive mean difference in values of delta and theta at frontal regions (PF, AF, and F) and significant ($p<0.025$) negative mean power difference in values of alpha at parietal, parieto-occipital, and occipital regions between IQ and rest states. In beta1 and beta2, the mean power values reduced at PO and O regions in IQ test, while in rest states the values were slightly increased at the same regions.

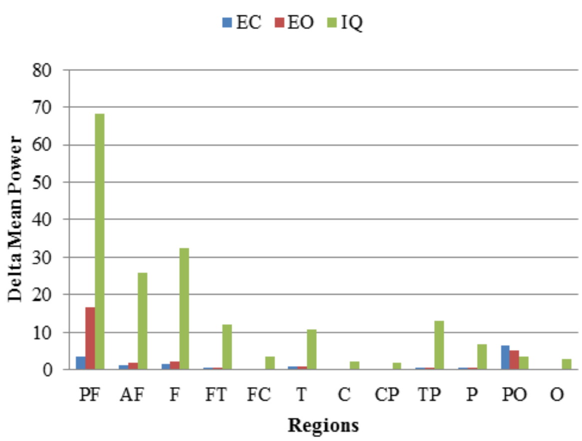

Fig. 3 EEG delta (1-3Hz) mean power for IQ, EO, and EC

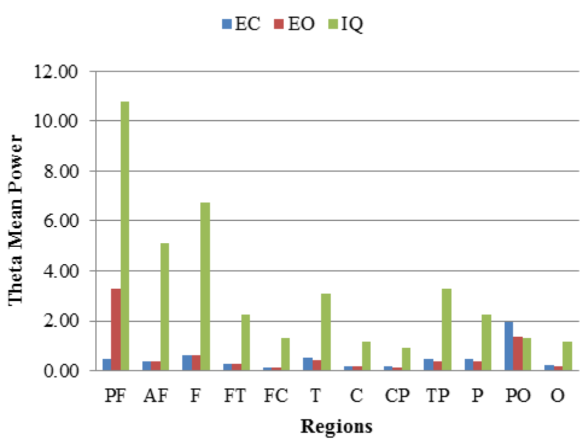

Fig. 4 EEG theta (4-7Hz) mean power for IQ, EO, and EC

B. Sample Entropy (SE)

Region wise mean SE values for IQ and EC states are showed in Fig 8. In both states the value of SE was increased at C, O, and T regions as compared to frontal regions PF and F. High SE value was found at C to PO regions in IQ than EC, but almost similar value found in PF and F.

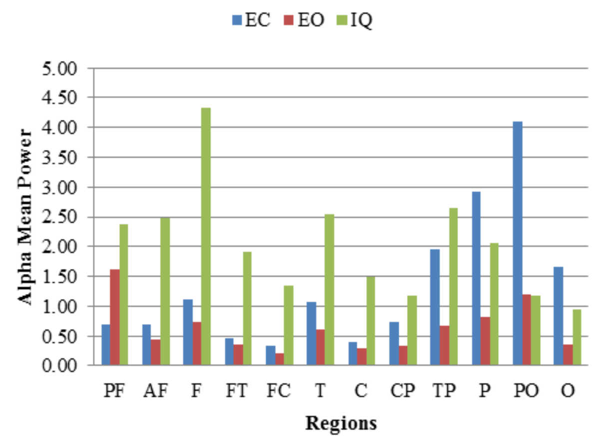

Fig. 5 EEG Alpha (8-13Hz) mean power for IQ, EO, and EC

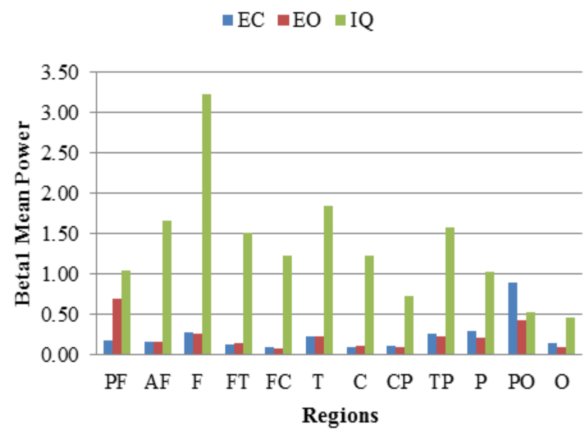

Fig. 6 EEG Beta1 (14-20Hz) power for IQ, EO, and EC

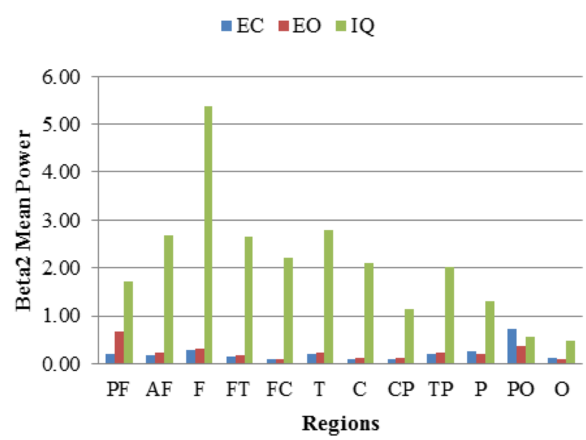

Fig. 7 EEG Beta2 (21-30Hz) power for IQ, EO, and EC

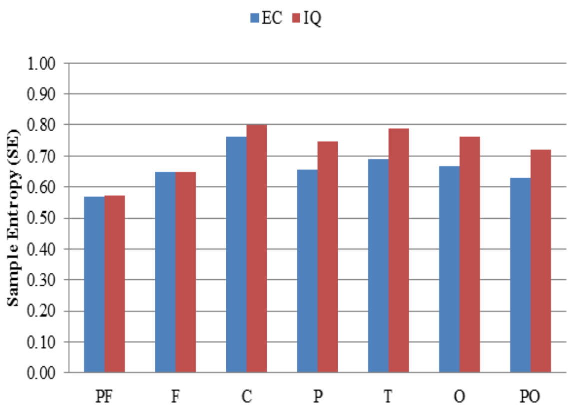

Fig. 8 Sample entropy values for IQ and EC

IV. Discussion

EEG measures brain electrical activities directly and help to study the neurobiological changes that occur during cognition. Many studies investigated the relation between EEG, cognitive tasks, and resting states. However, in this study, EEG time (SE) and frequency (power spectrum) domain measures were calculated for IQ and rest states discrimination. All four frequencies bands discriminated IQ test from rest state activation. Mental reasoning and logical thinking related increases in EEG mean power were found in delta (1-3Hz; all regions except PO) and were significant at (PF, AF, F) compared to rest state. Similar increase was also found in theta (4-7Hz). In alpha (8-13Hz) the EEG mean power was higher at region F (see Fig. 5), a clear difference at region T, and significantly ($p<0.001$) reduced at P, PO, and O regions in IQ test condition as compared to rest state EC. Further, in beta1 and beta2, high EEG mean power was found at region F in IQ, but reduced mean power value was observed at regions PO and O than rest of the regions (see Fig. 6 and Fig. 7). Overall we found increases in all four EEG bands in IQ test than rest conditions in all regions except PO where it decreased.

As Sample Entropy (SE) estimates the regularity and complexity of EEG wave, the findings of SE were increased at C to PO regions in IQ than EC state. This means that human mind system trend to uncertainty during IQ test compared to eye closed condition.

V. Conclusion

Both power spectrum and entropy measures clearly differentiated EEG behavior in the IQ test from relaxation. High delta and theta activity at frontal regions and reduced alpha and beta activity at parietal, parieto-occipital and occipital regions distinguished mental reasoning and logical thinking situation from rest conditions. Further, increased SE value at different scalp regions in IQ test reflects mental uncertain behavior during complex mental reasoning, pattern matching, and analytical tasks.

Acknowledgment

This study was funded by University Research Internal Funding (URIF: 10/2012), Universiti Teknologi PETRONAS, Malaysia.

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