Research Paper

Brain Functional Correlates of Intelligence Score in ADHD Based on EEG

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ABSTRACT

Introduction: It has been shown that intelligence as a general mental ability is related to the structure and function of the brain regions. However, the specificity of these regional dependencies to the intelligence scores in the typical and atypical developed individuals needs to be well understood. In this study, we hypothesized that neural correlates of IQ should not have a fixed pattern rather they must follow a dynamic pattern to compensate for the functional deficits caused by a neurodevelopmental disorder. Therefore, electroencephalography (EEG) correlates of normal IQ in various subtypes of attention deficit hyperactive disorder (ADHD) were compared with a group of healthy controls.

Methods: Sixty-three ADHD subjects comprising combined, inattentive, and hyperactive individuals diagnosed by a psychiatrist using structural clinical interview for DSM-V, and 46 healthy controls with similar normal IQ scores were recruited in this study. The subjects' EEG data were then recorded during an eye-closed resting condition. The subjects' intelligence level was measured by Raven's standard progressive matrices. Then, the association between IQ and the power of the EEG signal was computed in the conventional frequency bands. Subsequently, topographical representations of these associations were compared between the groups.

Results: Our results demonstrated that the association between IQ score and EEG power is not the same in various ADHD subtypes and healthy controls.

Conclusion: This finding suggests a compensatory mechanism in ADHD individuals for changing the regional oscillatory pattern to maintain the IQ within a normal range.

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Highlights

- There is a significant relationship between intelligence scores and electroencephalography (EEG) power;
- The dynamic of the brain activities in addition to the specific brain structure plays a great role in intelligence
- There is probably a compensatory mechanism in attention deficit hyperactive disorder (ADHD) individuals to change the regional oscillatory pattern to maintain the IQ in the normal range.

Plain Language Summary

Intelligence is a general mental ability, which includes planning, reasoning, comprehension, abstraction, and learning. This ability is produced by brain structure and functions, which could be traced by neuroimaging techniques. EEG is one of the most popular used method and it is presented a correlation with intelligence. ADHD as a neurodevelopmental disorder could influence the pattern of brain activities. In this study, a significant relationship between IQ score and EEG power in the ADHD individuals was observed suggests the existence of a compensatory mechanism to hold a suitable cognitive performance (IQ) in the ADHD subjects.

1. Introduction

Intelligence is a general mental ability, which includes planning, reasoning, comprehension, abstraction, and learning (Gottfredson, 1997). Therefore, intelligence scores may be used to predict one's performance (Haier & Jung, 2008). This cognitive ability is produced by brain structure and functions, which could be traced by neuroimaging techniques. In this regard, neuroimaging studies have mainly presented a region-specific pattern of anatomy as well as activities associated with the intelligence score. In terms of structure, with the advent of magnetic resonance imaging (MRI) studies, researchers have found a strong association between intelligence and grey matter density (Narr et al., 2006). For example, an association between intelligence and grey matter density has been reported in the basal ganglia (Dietrich, 2004), hippocampus (Deary et al., 2010), fusiform (Deary et al., 2010), posterior region (Heilman et al., 2003), Parietal and frontal (Thatcher et al., 2008; Thatcher et al., 2007) and dorsolateral prefrontal cortex (DLPFC) (Cabeza & Nyberg, 2000). Other studies associated global properties of the structural brain network with general intelligence (Fischer et al., 2014). Similar to structural studies, functional studies also suggest a network for intelligence (Jung & Haier, 2007). In this context, about the relationship between intelligence and the function of the brain, a variety of psychophysiological measurement methods ranging from positron emission tomography (PET) (Kane & Engle, 2002; Gray et al., 2003), functional magnetic resonance imaging (fMRI) (Geake & Hansen, 2005; Burgess et al., 2011; Tang et al., 2010) and electroencephalography (EEG) (Neubauer et al., 2005; Anokhin et al., 1999) has been employed. Of the all above-mentioned methods, EEG is one of the most popular used method because it is cheap, portable, and easy to wear, and has a high temporal resolution (Reis et al., 2014) and it is proper to use in the applied studies. EEG presented a correlation with intelligence (Mundy-Castle, 1958). Recent studies have demonstrated that highly intelligent individuals allocate fewer resources and recruit minimum task-relevant brain areas when performing an easy task, while they allocate more resources and recruit several brain areas when the task demand is high. In contrast, low intelligent individuals do not use different resource allocation strategies during easy and hard tasks (Kang & Lee, 2015).

In general, the association of IQ scores and EEG properties have been studied using the power or amplitude (Klimesch, 1999b; Giannitrapani & Liberson, 1985) (Martín-Loeches et al., 2001), and the functional connectivity networks extracted with coherence and phase delays (Thatcher et al., 2005; Thatcher et al., 2007). Moreover, the brain works in a frequency-specific manner; therefore, the association between IQ scores and EEG parameters has also been investigated in the conventional frequency bands as well. The conventional frequency bands in EEG include delta (slowest), theta, alpha, beta, and gamma (fastest) bands. These frequency bands have a critical role for performing the cognitive tasks (Klimesch et al., 1993; Moretti, 2015). In addition, cognitive disabilities have also been related to changes in the neural oscillatory pattern (frequency-specific activities). For instance, an increase in task demand increases the theta power and causes more synchronization in this band. In contrast, an increase in a task demand decreases the alpha power and causes desynchronization in this band (Schacter, 1977) (Webster, 1978) (Marosi et al., 1999) (Fogel et al., 2007). EEG waves are caused by large numbers of neurons firing in synchrony. Synchronization behavior of EEG signals is important for decoding information processing in human brain.

In terms of the IQ index of EEG, it has been shown that alpha power is the most closely correlated with IQ score (Stankova & Myshkin, 2016). In addition, high-IQ individuals present higher modularity in their brain functional connectivity network (FCN) and have different patterns of activations between short-range and long-range connections in the FCN (Hearn et al., 2016) (Song et al., 2008). The above-mentioned studies have mainly focused on normal individuals.

Neurodevelopmental disorders, such as attention deficit and hyperactive disorder (ADHD) could influence the pattern of brain activities. For instance, studies have reported greater frontocentral theta activity, lower beta activity, and higher theta/beta ratio in ADHD subjects compared to healthy controls (Clarke et al., 2001b; Loo et al., 2010) (Bresnahan & Barry, 2002) (Arns et al., 2013) (Loo et al., 2010). However, there is inconsistency in the previous studies on the effect of IQ on EEG power in ADHD. For instance, Clark et al. reported that IQ does not affect the EEG power in ADHD individuals compared to their matched control subjects (Clarke et al., 2006) While Chabot and Serfontein (1996) showed that there is a different oscillatory pattern in EEG of ADHD children with high and low IQ. They suggested that children with low IQs show lower alpha and beta bands (Chabot & Serfontein, 1996). Other studies have also highlighted the importance of IQ on any potential group's differences in ADHD with high and low IQ (Kitsune et al., 2015). Therefore, it seems that studies should try to control the effects of IQ on their data. In this study, we hypothesized that neural correlates of intelligence should not have a fixed pattern rather it must follow a dynamic pattern to compensate for the deficits caused by the disorder.

Therefore, in this study, EEG was recorded from three ADHD subtypes and a control group in eye closed condition. Then, the correlation of EEG spectral bands using estimates of absolute and ratio with IQ and significant differences within groups were computed at a specific brain region. We also estimated the whole pattern of association at each absolute frequency band. Details of the experimental design and data analysis are explained in the next section.

2. Materials and Methods

A schematic of the experimental design is presented in Figure 1.

Subjects

One hundred nine boy participants comprising 22 combined (age=9.13±0.99, IQ=103.13±11.02), 27 inattentive (age=8.62±1.30, IQ=104.37±10.22), 14 hyperactive (age=9.42±1.74, IQ=107.5±9.27), and 46 healthy controls (age=9.41±1.42, IQ= 102.39±10.83) were recruited in this study. All subjects were right-handed and there were no significant differences in age and IQ between the groups (Table 1). The diagnostic assessment was performed by a psychiatrist and a senior clinical psychologist using the Persian version of the Structural Clinical Interview for DSM-V (SCID). Average DSM-V symptom scores of inattentive, hyperactive, and combined were 7.0±1.3, 8.2±2.9, and 6.3±1.3, respectively. Children with brain damage, neurological disorder, and epilepsy as well as children who consume stimulants or were under neurotherapy were excluded. The research protocol was approved by the Iran University of Medical Science Ethics Committee and all parents signed informed consent.

IQ scores

All participants completed Ravan's standard progressive matrices (SPM) test. This multiple-choice test is used to assess abstract reasoning and nonverbal ability (Raven, 2000b). It has also been considered to be the best measure of spearman's g factor (Reynolds & Brown, 1984) and intelligence (Raven, 2000a).

EEG data recording and analysis

EEG data were recorded during an eyes-closed resting state for 4 minutes while children were seated on a comfortable chair. All subjects were asked to sit relax and try not to blink. The EEG data were registered using a 19-electrode Mitsar amplifier (www.mitsar-medical.com) with a sampling rate of 250 Hz. Electrodes were placed on the scalp using a standard 10-20 montage (Fp1, Fp2, Fz, F3, F4, F7, F8, Cz, C3, C4, T3, T4, T5, T6, Pz, P3, P4, O1, and O2) with the average of ear channels used as reference and FPz as the ground electrode. Electrode impedances were kept below 5 kΩ. After recording, a self-written program using Matlab (https://www.mathworks.com) and EEGlab functions (https://sccn.ucsd.edu/eeglab/) was used to process the data. Standard pre-processing included band-pass filtering (1-40 Hz), segmenting the data into epochs of 1-second duration, automatic rejection of disturbing channels using probability (artifact rejection was carried out using both to single electrodes and the collection of all electrodes), spectrum (thresholds are expressed in terms of amplitude changes relative to baseline in dB), and kurtosis (technically called the four first cumulates of the distribution) of the signal interpolation of rejected channels by averaging its spherical neighbors, removing unreliable epochs, and referencing to the average. Subsequently, the pre-processed EEG data were transformed to the frequency domain using Fast Fourier Transform (FFT), and the absolute power of the data was then calculated in Delta (1-4 Hz), Theta (4-8 Hz), Alpha (8-13 Hz), Alpha1 (8-10), Alpha2 (10-12), and Beta (13-30Hz) frequency bands. After that, the power ratio was estimated for the theta/beta and theta/alpha frequency bands.

Statistical analysis

Pearson's correlation was calculated using the score of SPM and the spectra of each frequency band. Spectral power was calculated in absolute and ratio style from the cleaned data. Then p- the values of each correlation score were considered and significant associations were recognized by putting a threshold of 0.05 for the p-values. This analysis was performed using the statistical analysis toolbox of MATLAB 2015 (www.mathworks.com). Then, the group comparison of correlation values was performed using the cocor package (Diedenhofen & Musch, 2015).

3. Results

Detailed information on significant results ($P<0.05$) for absolute and ratio power are presented in Tables 2-7 and Figures 2-6, and the whole pattern analysis is shown in Table 8 and Figure 7. Correlation maps were scaled between -1 and 1. Only significant correlations ($P<0.05$) were plotted. The hot color indicates a positive and cold color shows a negative correlation.

Association between EEG power spectrum and IQ score

Absolute power

Figure 2 and Table 2 present the significant correlation between absolute power and intelligence in ADHD subtypes and healthy control groups. the combined ADHD group showed significant positive correlations between IQ scores mainly at P4 in the alpha band, and at Fp1, C3, and T5 in the beta band. Negative correlations in this group were also found between IQ score and delta power at F8, and theta power at Cz. The inattentive ADHD group showed a significant positive correlation between IQ and delta power at F3 and alpha power at P4. A negative correlation in this group was also observed between IQ score and delta power at C4, and theta power at T3. ADHD-hyperactive/impulsive group showed a positive correlation between IQ score and theta power at Cz and a negative correlation between IQ score and delta power at T3, and alpha power at C4. The healthy control group did not show any negative correlation between IQ and EEG bands, while positive correlations were observed between IQ score and theta power at F3 and F7, and apha1 power at T5 and O1.

The association between ratio power (theta/alpha, theta/beta) and intelligence score is presented in Table 3 and Figure 3. The ADHD-combined group showed negative correlations between IQ score and theta/alpha at Cz, and O2 as well as theta/beta at F3, and Cz areas. The inattentive ADHD group revealed a positive correlation between IQ score and theta/beta at Fp2, and a negative correlation between IQ score and theta/alpha at P4. The hyperactive ADHD group and the healthy control group did not show any significant correlation between IQ score and the above-mentioned power ratios.

Differential patterns of the association between IQ scores and EEG power spectrum in ADHD subtypes and healthy control groups

Topographical differences in the association between IQ score and absolute power in various frequency bands in ADHD subtypes were compared with the healthy control group (Table 4 and Figure 4). Compared to the healthy control group, ADHD-combined cases showed increased alpha power at P3 and decreased delta at F8 and Fz, and theta at F3 and Cz, and alpha1 power at F3, C4, T4 locations. ADHD-inattentive cases revealed increased theta power at F8 and T3, increased alpha power at P4, and decreased beta power at P3. In addition, ADHD-hyperactive cases also showed decreased theta power at F8 and Fz, decreased alpha power at T5, and decreased power of the lower alpha band at F4 and C4 areas.

Subsequently, a comparison between the patterns of ADHD subtypes was also performed and the results are shown in Table 5 and Figure 5. Elevated alpha 2 power at F7 and Cz, decreased delta power at F8 and T6, and

Table 1. Demographic characteristic of each group

Variables	COM (n=22)	IN (n=27)	HY (n=14)	HC (n=46)	F	sig
Age	9.13±0.99 (8-11)	8.62±1.30 (7-10)	9.42±1.74 (7-12)	9.41±1.42 (7-11)	2.07	0.109
Intelligence score	103.13±11.02 (92-115)	104.37±10.22 (94-115)	107.5±9.27 (98-117)	102.39±10.83 (91-114)	0.9	0.444
Handedness	All right handed	All right handed	All right handed	All right handed		

Abbreviation: COM: Combined; IN: Inattentive; HY: Hyperactive; HC: Health control

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Table 2. Significant association between intelligence and absolute power

Power	Subjects							
	Ch	COM (n=22) (r, p)	Ch	IN (n=27) (r, p)	Ch	IN (n=14) (r, p)	Ch	HC (n=46) (r, p)
Delta	F8	-0.501, 0.017*	F3	0.406, 0.035*	T3	-0.554, 0.04*	---	---
			C4	-0.383, 0.048*				
Theta	Cz	-0.44, 0.04*	T3	-0.449, 0.019*	Cz	0.610, 0.02*	F7	0.295, 0.046*
							F3	0.333,0.024*
Alpha	P4	0.445, 0.037*	P4	0.431, 0.025*	C4	-0.608, 0.021*		
Alpha1	---	---	---	---	---	---	T5	0.311, 0.035*
							O1	0.311, 0.035*
Beta	Fp1	0.440, 0.04*	---	---	---	---	---	---
	C3	0.435, 0.043*						
	T5	0.439, 0.041*						
Beta2	---	---	Fz	-0.389, 0.045*	---	---	---	---

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Abbreviation: Ch: Channel number; F: Frontal; C: Central; P: Parietal; O: Occipital; T: Temporal; Fp: Prefrontal; COM: Combined; IN: Inattentive; HY: Hyperactive; HC: Health control.

*Sig=0.05, **Sig=0.01

Table 3. Significant association between intelligence and ratio power

Power	Subjects							
	Ch	COM (r, p)	Ch	IN (r, p)	Ch	HY (r, p)	Ch	HC (r, p)
Theta/alpha	cz	-0.428, 0.047*	P4	-0.441, 0.021*	---	---	---	---
	O1	-0.524, 0.012*						
Theta/ beta	F3	-0.518, 0.014*	Fpz	0.387, 0.046*	---	---	---	---
	cz	-0.516, 0.014*						

Abbreviation: Ch: Channel number; COM: Combined; IN: Inattentive; HY: Hyperactive; HC: Health control

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*Sig=0.05; **Sig=0.01

Table 4. Comparing correlation among ADHD subtypes at absolute power

Power	Ch	COM versus IN p	Ch	COM versus HY p	Ch	IN versus HY p
delta	F8	-0.874, 0.0021**	---	---	---	---
	T6	-0.725, 0.013*	---	---	---	---
theta	O1	-0.753, 0.009**	Cz	-0.105, 0.001**	F8	0.681, 0.048*
alpha	---	---	C4	1, 0.003**	T5	0.79, 0.007**
	---	---	T5	0.63, 0.03*	---	---
Alpha1	T4	-0.604, 0.042*	---	---	F4	0.704, 0.04*
Alpha2	F7	0.642, 0.03*	---	---	---	---
	Cz	0.68, 0.019*	---	---	---	---
beta	---	---	Fp2	0.733, 0.04*	O1	0.67, 0.04*
	---	---	F3	0.773, 0.02*	---	---
	---	---	O1	0.73, 0.04*	---	---

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Abbreviation: Ch: Channel number; F: Frontal; T: Temporal; O: Occipital; C: central; Fp: Prefrontal; COM: Combined; IN: Inattentive; HY: Hyperactive

*: sig=0.05; **: sig=0.01

decreased theta power at O1 were observed in ADHD-combined cases as compared to the ADHD-inattentive group. Moreover, the ADHD-combined group showed increased alpha power at C4 and T5, increased beta power at Fp2, F3, and O1, and decreased theta power at Cz compared to the ADHD-hyperactive group. In addition, the ADHD-inattentive group was also compared to the ADHD-hyperactive group and presented increased theta

Table 5. Comparing correlation between ADHD subtypes and control at absolute power.

Power	Ch	COM versus HC r, p	Ch	IN versus HC r, p	Ch	HY versus HC r, p
Delta	Fz	-0.529, 0.04*	---	---	---	---
	F8	-0.578, 0.022*	---	---	---	---
Theta	F3	-0.676, 0.01*	F8	0.681, 0.004**	Fz	-0.729, 0.022*
	Cz	-0.554, 0.03*	T3	-0.504, 0.034*	F8	-0.712, 0.026*
Alpha	P4	0.598, 0.021*	P4	0.503, 0.015*	T5	-0.909, 0.001**
Alpha1	F3	-0.532, 0.045*	---	---	F4	-0.66, 0.03*
	C4	-0.535, 0.04*	---	---	C4	-0.68, 0.03*
	T4	-0.615, 0.02*	---	---	---	---
Beta	---	---	P4	-0.487, 0.04*	---	---

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Abbreviation: F: Frontal; C: Central; P: Parietal; T: Temporal; COM: Combined; IN: Inattentive; HY: Hyperactive; HC: Health control.

*Sig=0.05; **Sig=0.01

Table 6. Whole pattern of significant association within groups at significant EEG band

Power	Groups	Mean±SD	Sig.	Lower CI	Upper CI
Theta	COM versus HC	-0.226±0.067	0.015*	-0.421	-0.032
	HY versus HC	-0.212±0.067	0.026*	-0.407	-0.018
Alpha	COM versus HY	0.305±0.56	0.000**	0.143	0.466
	IN versus HY	0.204±0.56	0.007**	0.043	0.365
Alpha1	COM versus IN	-0.322±0.047	0.000**	-0.45	-0.185
	COM versus HC	-0.375±0.047	0.000**	-0.512	-0.238
	IN versus HY	0.337±0.047	0.000**	0.201	0.478
	HY versus HC	-0.391±0.047	0.000**	-0.527	-0.254
Alpha2	COM versus IN	0.225±0.053	0.001**	0.710	0.379
Beta	COM versus IN	0.311±0.046	0.000**	0.178	0.444
	COM versus HY	0.404±0.046	0.000**	0.271	0.537
	COM versus HC	0.236±0.046	0.000**	0.103	0.369
	HY versus HC	-0.188±0.046	0.007**	-0.301	-0.035
Beta1	COM versus HY	-0.244±0.041	0.000**	-0.363	-0.125
	COM versus HC	-0.224±0.041	0.000**	-0.343	-0.105
	IN versus HY	-0.201±0.041	0.000**	-0.32	-0.082
	IN versus HC	-0.82±0.041	0.001**	-0.301	-0.063
Beta2	COM versus HY	-0.277±0.035	0.000**	-0.378	-0.176
	COM versus HC	-0.116±0.035	0.017*	-0.217	-0.015
	IN versus HY	-0.279±0.035	0.000**	-0.381	-0.178
	IN versus HC	-0.119±0.035	0.014*	-0.22	-0.017
	HY versus HC	-0.16±0.035	0.000**	-0.262	-0.059

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Abbreviation: COM: Combined; IN: Inattentive; HY: Hyperactive; HC: Health control; CI: Confidence interval

*Sig=0.05; **Sig=0.01

Table 7. Comparing correlation among ADHD subtypes at ratio power.

Ratio power	Ch	COM versus IN r, p	Ch	COM versus HY r, p	Ch	IN versus HY r, p
Theta/alpha	O1	-0.744, 0.008**	---	---	---	---
Theta/beta	cz	-0.59, 0.035*	cz	-0.881, 0.011*	---	---

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Abbreviation: Ch: Channel number; COM: Combined; IN: Inattentive; HY: Hyperactive.

*Sig=0.05; **Sig=0.01

Table 8. Comparing correlation between ADHD subtypes and control at ratio power.

	ch	COM versus HC r, p	ch	IN versus HC r, p	ch	HY versus HC r, p
Theta/alpha	F3	-0.66, 0.012*	P4	-0.755, 0.001**	---	---
	Cz	-0.576, 0.027*	---	---	---	---
	O1	-0.78, 0.002**	---	---	---	---
	O2	-0.631, 0.017*	---	---	---	---
Theta/beta	F3	-0.772, 0.002**	---	---	Fz	-0.635, 0.049*
	C3	-0.556, 0.037*	---	---	---	---
	Cz	-0.501, 0.043*	---	---	---	---

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Abbreviation: Ch: Channel number; F: Frontal; C: Central; O: Occipital; COM: Combined; IN: Inattentive; HY: Hyperactive; HC: Health control

*Sig=0.05; **Sig=0.01

power at F7 and alpha power at T5, and lower alpha power at F4 and beta power at O1.

Topographical differences in the association between intelligence and patterns of ratio power for ADHD subtypes as well as control group are presented in Tables 6 and 7 and Figure 6. In comparison with the healthy control group, the ADHD-combined group showed decreased theta/alpha at f3, cz, o1, and o2, and decreased theta/beta at f3, c3, and cz compared to the control group. The ADHD-inattentive group also showed decreased theta/alpha at f3, and the ADHD-hyperactive group presented decreased theta/beta at f3 (Table 6 and Figure 6). In addition, the ADHD-combined group compared to the ADHD-inattentive present ed decreased theta/alpha at o1 and theta/beta at cz. A decrease in theta/beta at cz was also observed in the ADHD-combined group compared to the ADHD-hyperactive group (Table 7 and Figure 6).

In the second phase of analysis, comparisons of whole-brain patterns of the association between IQ scores and EEG power were performed to discriminate patterns of EEG power related to IQ scores in ADHD subtypes from healthy controls (Table 8 and Figure 7). The ADHD-combined group revealed the increased correlation between IQ score and whole-brain pattern of beta power, and the decreased correlation between IQ score and whole-brain pattern of power at theta and alpha1 bands. The inattentive ADHD group showed no significant differences, and the hyperactive/impulsive ADHD group showed a decreased correlation between IQ score and whole-brain pattern of power at theta, alpha1, and beta bands compared to the healthy control group.

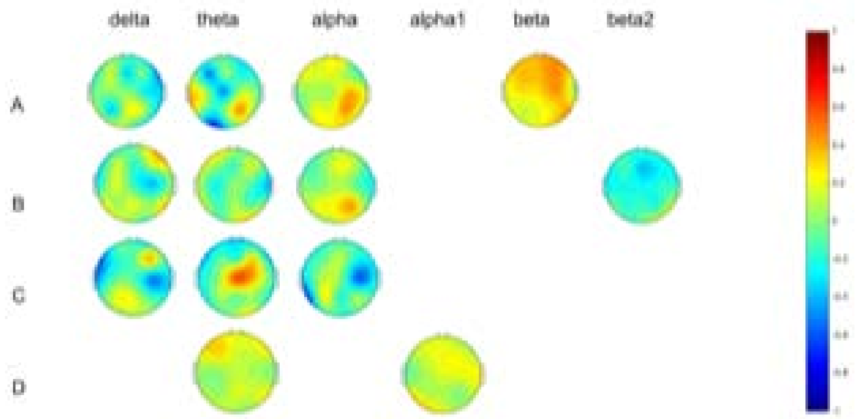

Figure 1. Topographical map of the correlation between intelligence and absolute power

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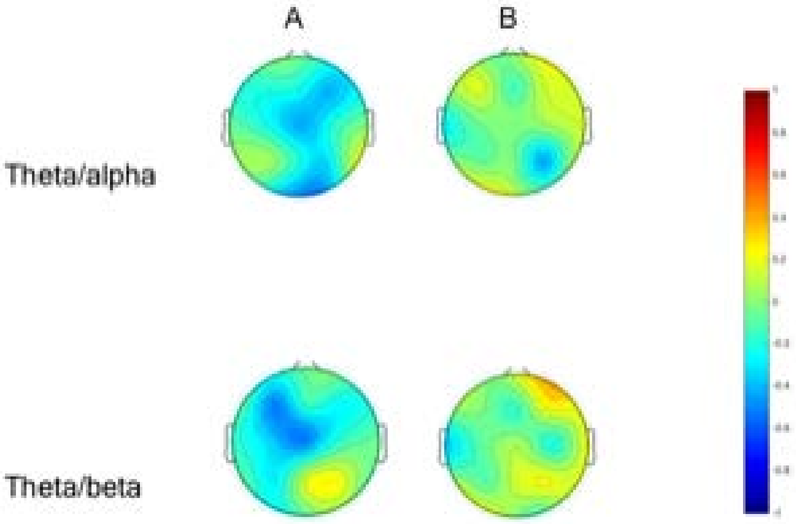

Figure 2. Topographical map of the correlation between intelligence and ratio power

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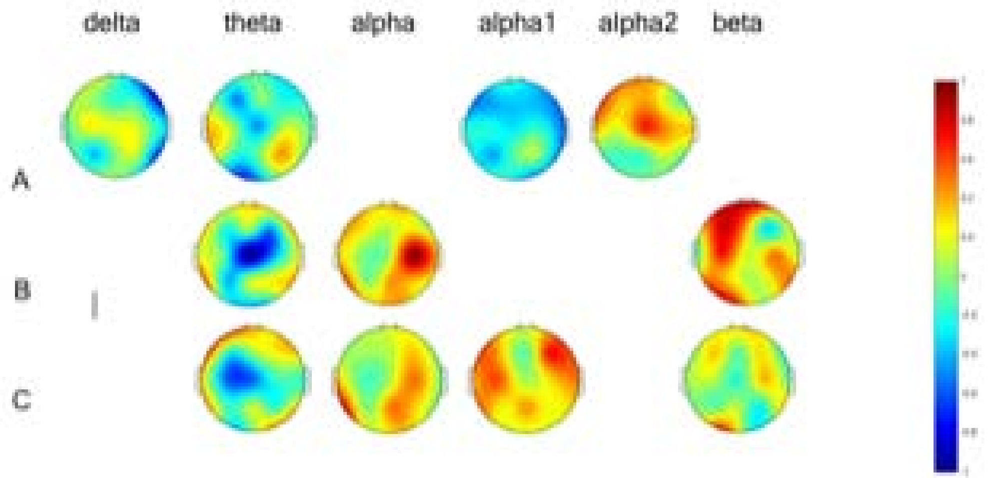

Figure 3. Topographical map of comparing the correlation of ADHD subtypes at absolute power

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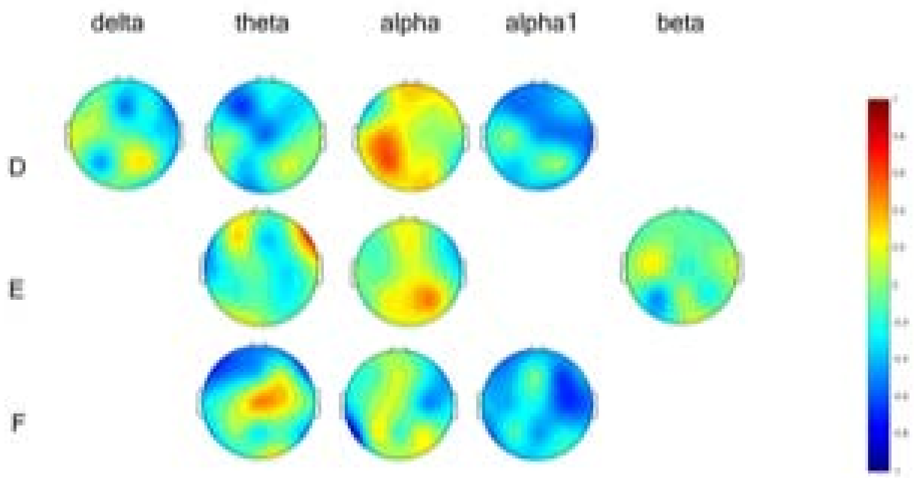

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Figure 4. Topographical map of comparing the correlation of ADHD subtypes compared to healthy controls at absolute power

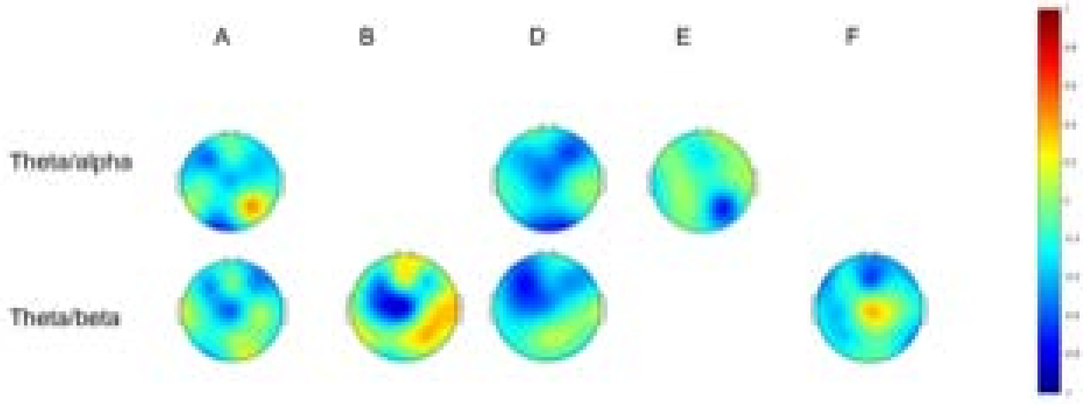

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Figure 5. Topographical map of comparing the correlation of ADHD subtypes and ADHD subtypes compared to healthy controls at ratio power

In addition, comparisons of ADHD subtypes also showed that the combined ADHD group compared to the ADHD-inattentive group presented an increased correlation between IQ score and whole-brain pattern of power at alpha2 and beta bands, while the correlation decreased at alpha1. The combined ADHD group compared to the hyperactive ADHD group showed an increased correlation at alpha and beta bands. The inattentive ADHD groupcompared to the hyperactive ADHD group showed an increased correlation between alpha and alpha1 and IQ scores.

4. Discussion

The present study primarily investigated the association between brain functions based on absolute, and ratio power of EEG, and IQ scores in various individuals within a normal range of IQ. The association pattern was then compared between three ADHD subtypes and

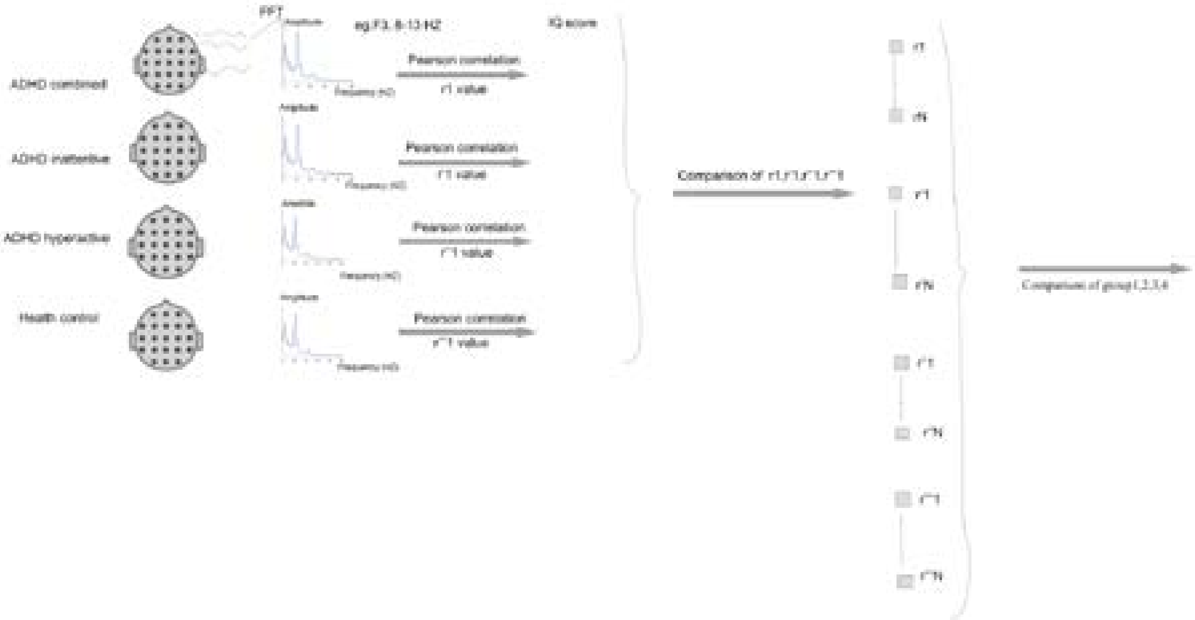

Figure 6. Schematic of experimental design

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At relative power, positive correlations in combined group were obtained at F3, F7, T3, C3, Cz, C4, P4 in alpha2 as well as Fp2, F3, F2, F8 in beta. Negative correlations were seen in T6 in delta and Cz, F3, O1 in theta. Inattentive group had positive association at T3, C4 in beta and negative association at C3 in beta1. Hyperactive group did not show any negative correlation while positive correlation was seen at Cz in theta and O2 in alpha2. Control group had not positive correlation but negative correlation was gained at T5, P3 at beta2.

Table 9. Significant association between intelligence and relative power

Power	Ch	COM (n=22) (r, p)	Ch	IN (n=27) (r, p)	Ch	HY (n=14) (r, p)	Ch	HC (n=46) (r, p)
Delta	T6	-0.528, 0.014		---	---	---	---	---
Theta	F3	-0.548, 0.008		---	---	---	---	---
	cz	-0.461, 0.031		---	cz	0.595, 0.025	---	---
	O1	-0.629, 0.002		---	---	---	---	
Alpha2	F7	0.522, 0.011						
	F3	0.543, 0.007						
	T3	0.465, 0.025						
	C3	0.430, 0.041		---	O2	0.569, 0.034	---	---
	cz	0.466, 0.025						
	C4	0.429, 0.041						
	P4	0.443, 0.034						
Beta	Fp2	0.429, 0.046	T3	0.466, 0.014				
	F3	0.507, 0.016						
	Fz	0.435, 0.043			---	---	---	---
	F8	0.469, 0.028	C4	0.417, 0.031				
Beta1	---	---	C3	-0.401, 0.038	---	---	---	---
Beta2	---		---	---	---	---	T5	-0.309, 0.036
							P3	-0.293, 0.048

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Abbreviation: Ch: channel number; F: Frontal; C: Central; P: Parietal; O: Occipital; T: Temporal; Fp: Prefrontal; COM: Combined; IN: Inattentive; HY: Hyperactive; HC: Health control

(Sig=0.05)

a healthy control group. The absolute and ratio powers were calculated in the conventional EEG frequency bands, including delta, theta, and alpha with sub-bands alpha1 and alpha2, and beta. Then, the association between IQ score and EEG powers was compared within the groups. Calculation of the absolute power index provides a reliable method to differentiate clinical and normal groups (Dumermuth & Molinari, 1987). This study also represented theta/alpha and theta/beta power ratios because these ratio powers can differentiate ADHD individuals from healthy controls (Clarke, et al., 2002).

The association between IQ score and EEG power has shown cognitive implication, which is discussed here. In our healthy control group, the association between IQ score and EEG bands showed a pattern of lateralization, more significant in the left hemisphere (frontal, temporal and occipital regions). Several studies have associated the left hemisphere with intelligence and working memory (Basso, et al., 1982) (Paulraj, et al., 2018) (Basso, et al., 1981). Our findings in the healthy control group also showed a significant association between IQ score and EEG power at theta and alpha bands, which is nicely fit with the previous studies (Klimesch, 1999a), (Yılmaz, et al., 2014). The association was mainly observed in the frontal and temporal regions. The frontal region is involved in many functions, such as cognition, emotional behavior, memory, and language (Mundy-Castle & Nelson, 1960) and the temporal region has been shown to associate with the vocabulary score of the Wechsler test (Dobbins & Russell, 1990) and arithmetic score as well (Inouye, et al., 1993).

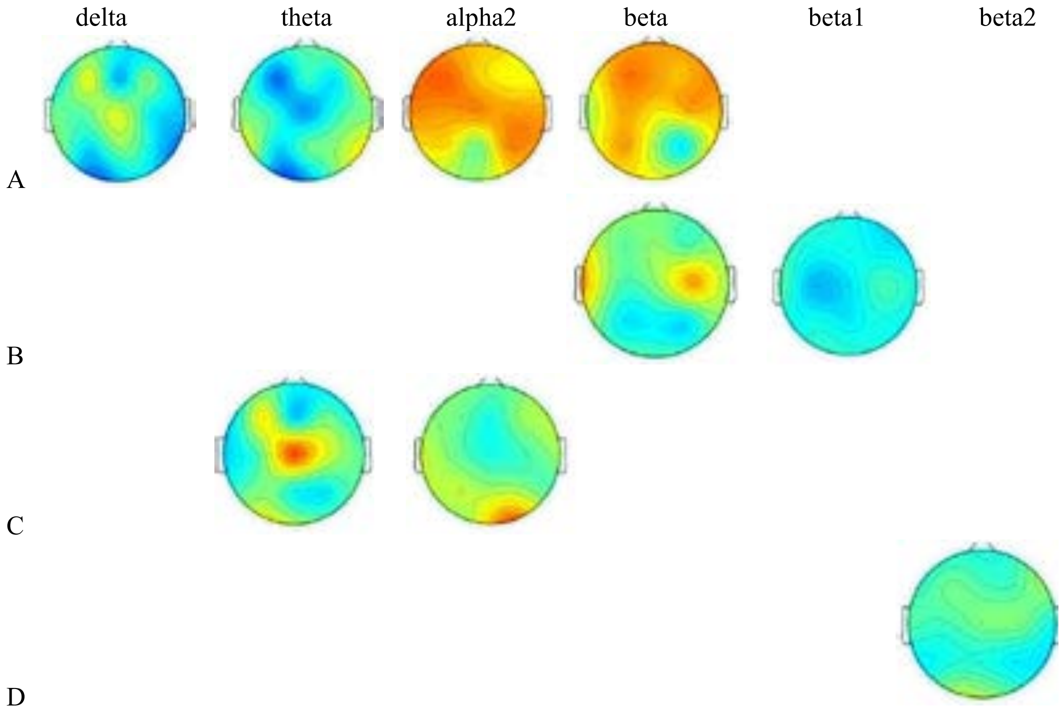

Figure 7. Topographical maps of correlations between relative power and IQ in eye close condition for ADHD subtypes and control groups. A: combined; B: inattentive; C: hyperactive; D: control.

Compare correlation

Results showed decreased theta at F3(p=0.02) in combined vs inattentive, Cz (p=0.001) in combined vs hyperactive and Cz (p=0.021) at inattentive vs hyperactive. Increased alpha2 was observable in many frequencies in combined vs inattentive.

Nevertheless, the pattern of association between the IQ score of the Ravan test and EEG power was completely different in ADHD individuals compared to the healthy control group. Our ADHD group showed a decreased association between EEG bands and IQ scores acquired by the Ravan test compared to the healthy control group. The Ravan test mainly estimates novel problem-solving, which is defined as solving problems that cannot be answered directly by referring to long-term knowledge but instead requires analytic or fluid reasoning (Prabhakaran et al., 1997). The network of brain regions involved in fluid reasoning is comprised of the frontopolar, middle and inferior frontal gyri, and parietal region (Rapport et al., 2008). These regions, more specifically the frontal, are also associated with working memory, which is weak in ADHD cases (Rapport et al., 2008). Therefore, decreased association between EEG bands and IQ score at frontal regions in our ADHD groups nicely fit with the deficiency of working memory and fluid reasoning acquired by the Raven test in past studies (Tamm & Juranek, 2012). In addition, our finding has implications in terms of the default mode network (DMN). This network is comprised of the medial prefrontal, precuneus, and angular gyrus (Raichle et al., 2001). DMN, which is typically activated during resting state conditions and deactivated during task performance (Broyd et al., 2009), was reported to be an underlying cause of inadequate performance in ADHD (Sonuga-Barke & Castellanos, 2007). Decreased correlation between IQ and EEG bands in our ADHD individuals compared to the healthy control group in the anterior region, plays an important role in working memory and attention (Castellanos et al., 2008), which may imply deficits in the anterior part of default mode network (DMN) in ADHD patients as reported in previous studies (Castellanos et al., 2008). In this study, the patterns of correlation between IQ score and EEG power in ADHD-combined and ADHD-inattentive were similar. This finding is corroborated by former studies, suggesting similar EEG abnormality in combined and inattentive subtypes (Clarke et al., 2001a). However, the pattern for our hyperactive ADHD cases is different from two other subtypes, which can be due to the small sample size of this group in the current study.

On the other hand, the ADHD individuals revealed a decreased association between IQ score and power of EEG at the theta band. While the association between IQ score and alpha power increased compared to the

Table 10. Comparing correlation among ADHD subtypes at relative power.

Power	Ch	COM versus IN r, p	Ch	COM versus HY r, p	Ch	IN versus HY r, p
Delta	F8	-0.642, 0.02	Fp2	0.537, 0.007	---	---
	T6	-0.764, 0.007	O1	-0.798, 0.019	---	---
	O1	-0.56, 0.03	---	---	---	---
Theta	F3	-0.615, 0.02	Cz	-0.105, 0.001	Cz	-0.58, 0.021
	O1	-0.978, 0.0003	---	---	T4	0.65, 0.027
Alpha2	Fp1	0.66, 0.02	---	---	---	---
	F7	0.69, 0.01	---	---	---	---
	F3	0.72, 0.01	---	---	---	---
	T3	0.64, 0.02	---	---	---	---
	C3	0.64, 0.027	---	---	---	---
	Cz	0.57, 0.04	---	---	---	---
	T4	0.649, 0.027	---	---	---	---
	P3	0.631, 0.031	---	---	---	---
	P4	0.672, 0.02	---	---	---	---
	T6	0.589, 0.04	---	---	---	---
Beta	F3	0.58, 0.03	---	---	---	---
	P3	0.72, 0.01	---	---	---	---

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Abbreviation: Ch: Channel number; F: Frontal; C: Central; P: Parietal; O: Occipital; T: Temporal; Fp: Prefrontal; COM: Combined; IN: Inattentive; HY: Hyperactive; HC: Health control.

(Sig=0.05)

healthy control group. This finding shows the existence of a compensatory mechanism such that decreased theta can be compensated by increased alpha in the ADHD group to keep adequate intellectual function. The combined ADHD group also showed a positive association at the beta band. It has been shown that active attention and psychomotor (Polunina & Davydov, 2006) have been related to brain activities at the beta band. Therefore, a positive association between EEG beta power and intelligence, in our findings, seems to be a logical pattern. IQ and beta power were highly associated compared to that of alpha in our combined ADHD group. We think this finding of the combined group is in the same line with Webster's theory who suggested that in the condition of serious mental activity beta replaced alpha's place (Webster, 1978).

Moreover, unlike the healthy control group, no specific lateralization pattern was found in ADHD subtypes. The recent finding may provide additional support for the presence of a compensatory mechanism such that deficiencies in the right hemisphere are compensated by the left hemisphere to have adequate intellectual performance.

Our findings of the different association between EEG bands and IQ between the healthy controls and the ADHD groups were not limited to some specific brain regions and significant differences were also observed in the global pattern extracted from the whole brain regions. Decreased theta in all subtypes of ADHD has been shown in all brain regions. The differential patterns of associations in local and global measures potentially imply that a dynamic change in the brain's regional func-

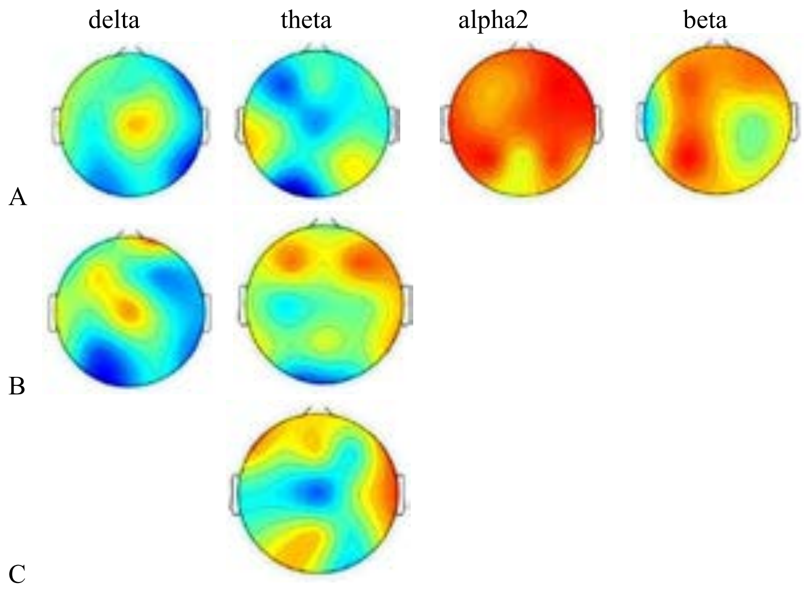

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Figure 8. Topographical maps of comparing correlations between relative power and IQ in eye close condition for ADHD subtypes. A: combined vs inattentive; B: combined vs hyperactive; C: inattentive vs hyperactive

Comparing correlation between ADHD and control showed decreased theta and increased alpha2 in combined.

Table 11. Comparing correlation between ADHD subtypes and control at relative power.

Power	Ch	COM versus HC r, p	Ch	IN versus HC r, p	Ch	HY versus HC r, p
Delta	fz	-0.57, 0.02	---	---	---	---
	O1	-0.64, 0.008	---	---	---	---
Theta	F3	-0.74, 0.003	---	---	---	---
	cz	-0.653, 0.011	---	---	---	---
	O1	-0.652, 0.005	---	---	---	---
Alpha2	F7	0.67, 0.008	---	---	---	---
	F3	0.65, 0.009	---	---	---	---
	T3	0.55, 0.032	---	---	---	---
	T4	0.519, 0.04	---	---	---	---
	P4	0.51, 0.04	---	---	---	---
	T6	0.59, 0.025	---	---	---	---
Beta	F3	0.55, 0.02	P4	-0.54, 0.02	---	---
Beta1	C3	-0.59, 0.01	---	---	---	---
Beta2			---	---	T6	0.71, 0.025

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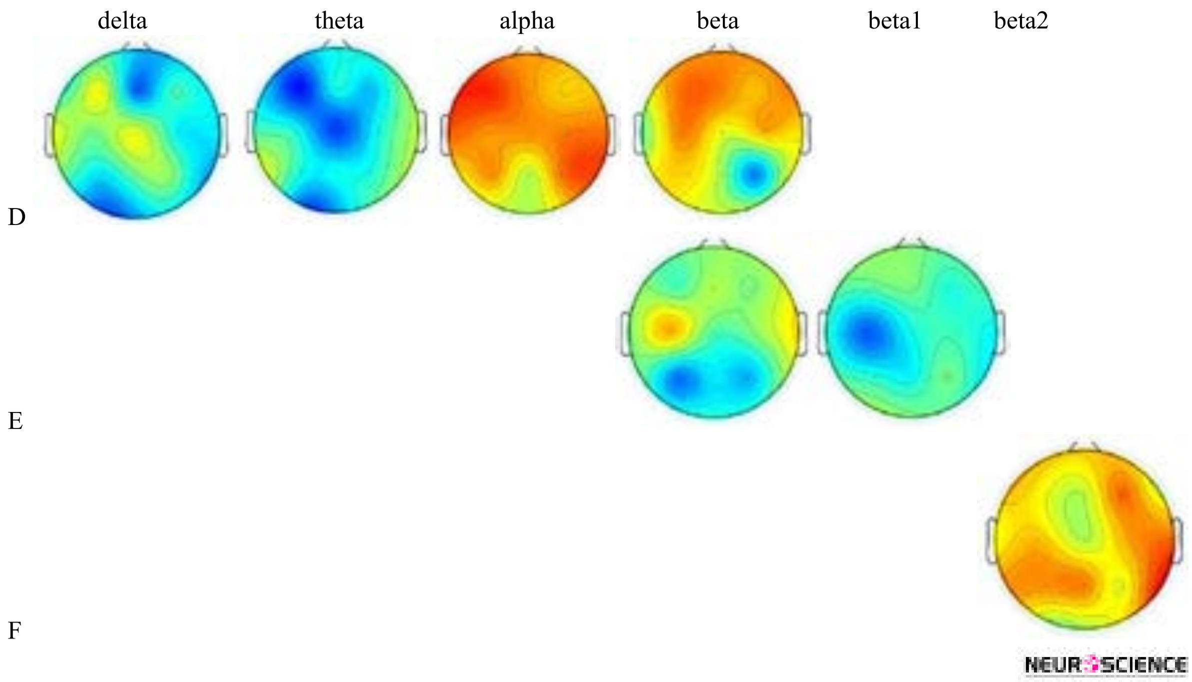

Figure 9. Topographical maps of comparing correlations between relative power and IQ in eye close condition for ADHD subtypes as compare to control group. D: combined vs control; E: inattentive vs control; F: hyperactive vs control

tions towards increasing the alpha (or beta) band activities and decreasing the laterality effect could be a compensatory mechanism to maintain a normal intelligence score in ADHD individuals.

At ratio power, our results showed a decreased theta/alpha ratio in the ADHD group (all subtypes) compared to the healthy control group. Assuming that the theta/alpha power ratio has been introduced as a criterion for intelligence (Markowitsch & Pritzel, 1985), it is expected that the theta/alpha ratio should not be different in IQ-matched individuals. While our findings put a question mark on the validity of the above-mentioned criteria for intelligence in ADHD individuals.

5. Conclusion

Significant changes observed in the score of association between IQ and EEG power in the ADHD individuals compared to the IQ-matched healthy control group suggests the existence of a compensatory mechanism to hold a suitable cognitive performance (IQ) in the ADHD subjects. We conclude that the dynamic of the brain activities in addition to the specific brain structure plays a great role in intelligence. The discrepancy of theta/alpha ratio in groups with a similar IQ score may suggest a weakness of this marker for intelligence. We hope that these findings could provide additional information to pave the way to a better understanding of the relationship between brain functions and intelligence. Extra information have been provided in tables (9-11) and figues (6-9).

Limitation

The results of this study had a number of limitations. First, it was limited to a few numbers of hyperactivity/impulsivity ADHD subjects compared to other subtypes of the ADHD and control group. Second, the study focused on the age range of 8-12 years. Because EEG activity shifts from less to high-frequency bands during maturation, a more detailed developmental analysis may provide a better insight into the relationship between intelligence and EEG oscillations. Furthermore, the study was performed in the eyes-close resting state; therefore, further investigation on the task-based EEG will be helpful to strengthen the results. Although the findings are inspiring, more studies are required to test the reliability and validity of the results.

Ethical Considerations

Compliance with ethical guidelines

The subjects were assessed after obtaining the in-formed consent signed by the parents, and the research protocol was approved by the Ethics Committee of Iran University of Medical Sciences.

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Authors' contributions

All authors contributed in designing, running, and writing all parts of the research.

Conflict of interest

The authors declared no conflict of interest.

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