Role of Parietal Cortex's Alpha Wave in Numerosity: Numerical Processing or Visual Attention?

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ABSTRACT

There are numerous fMRI studies showing privilege roles of parietal brain in numerical processing. However there are few studies on relationships between temporal dynamics of the parietal brain and performance of the numerical processing. In this study taking advantages of high temporal resolution of EEG, both linear and nonlinear characteristics of the parietal brain during performing an approximation on non-symbolic numerosities (called dot estimation task (DET)) were analyzed in 14 healthy female adolescents. Absolute power (AP) and relative power (RP) at alpha band as linear characteristics and fractal dimension (FD) (showing irregularity and complexity of dynamics) at alpha band as a key nonlinear characteristic were computed during the DET task. The results showed there is not a significant correlation between the dynamical characteristics of the left parietal and the performance of the subjects; whereas in the right parietal AP and FD at alpha band during the DET task showed a strong correlation with the subjects' performance. The higher alpha FD and AP in the right parietal, the more accurate approximation. A linear regression was performed to quantify the relationship between the approximation performance and the FD and AP values at alpha in the right parietal. Consequently the right parietal plays a more important role in approximation and performing non-symbolic numerosities tasks compared with the left parietal. Furthermore it was shown that during the approximation task, the higher complexity (FD) of the alpha dynamics comes with the higher alpha activity (AP) in the right parietal.

KEYWORDS

Absolute/Relative power, Alpha activity, Dot estimation task, EEG, Fractality, Parietal lobes.

1.1 INTRODUCTION

Parietal brain plays a privilege role in calculation, arithmetic operations, and quantity and numerical magnitude processing (Carreiras, Carr, Barber, & Hernandez, 2010; Davis et al., 2009; Rosenberg-Lee et al., 2011; Santens, Roggeman, Fias, & Verguts, 2010; van Harskamp & Cipolotti, 2001). The role of left and right parietal areas (especially horizontal segment of the intraparietal sulcus and posterior superior parietal lobule) in arithmetic operations and numerical processing has been investigated in many fMRI-based studies. Some fMRI studies reported an equal contribution of the right and left parietal to addition, subtraction, and simultaneous non-symbolic numerosities (Andres et al., 2011; Dormal, Andres, Dormal, & Pesenti, 2010). Some studies reported the right parietal lateralization in numerical comparison and sequential non-symbolic numerosities (number of elements in a collection) (Chochon, Cohen, van de Moortele, & Dehaene, 1999; de Smedt, Holloway, & Ansari, 2011; Dormal, Andres, Dormal, & Pesenti, 2010; Holloway, Price, & Ansari, 2010; Piazza, Pinel, Bihan, & Dehaene, 2007). Also there are some studies reported the left parietal activation is more important than the right parietal activation during multiplication and also symbolic number processing (Bugden, Price, McLean, & Ansari, 2012; Chochon, Cohen, van de Moortele, & Dehaene, 1999).

Although fMRI has higher spatial resolution, the higher temporal resolution of EEG gives us the greater opportunity to investigate temporal nonlinear and linear brain dynamics. Hence in this study, in order to investigate temporal dynamics of brain during numerical processing, the authors use the EEG. And since numerous studies have shown alpha frequency of EEG is involved in numerical processing (Glass, 1968; O’boyle, Alexander, & Benbow 1991), the alpha band dynamics was considered for the analysis in this research. Glass (1968) showed reduced alpha band activity of parietal lobes in numerical processing. Earle & Pikus (1982) showed higher alpha power of parietal lobe during difficult arithmetic tasks (successive addition and multiplication) relative to a simple counting task. In another study Earle (1985) showed as difficulty of arithmetic problems is increased from low to moderate levels, relative left parietal activity is increased significantly, but as the difficulty is increased to higher levels, the alpha asymmetry of the parietal brain is reduced. However he didn't find any significant correlation between the alpha asymmetry and the behavioral performance. Harmony et al. (1999) showed the decreased EEG activity at 12.46 Hz in left parietal is related to retrieval of arithmetic facts. However it's not completely clear that there is any correlation between alpha waves of parietal lobes and the behavioral performance in numerical processing, neither approximated no exact numerical processing.

In order to avoid effects of retrieving arithmetic facts and high-loading memory in the numerical processing, we use a simple approximation task (called Dot Estimation Task (DET)), instead of more complicated tasks such as arithmetic operations. DET implicates approximation of non-symbolic numerosities. Absolute and relative powers as key characteristics of linear dynamics and fractal dimension as a key characteristic of nonlinear dynamic are applied to alpha band EEG during DET task to investigate relationships between electrical activity of brain involved in the estimation and the behavioral performance (the estimation error).

1.2 METHOD

1.2.1 Subjects

The subjects were 15 girls, aged 12-15 years (13.07 ± 1.03 years), and recruited from a middle and high school in Tehran. The subjects had no history of neurological/psychological disorders, brain injuries or seizures, and vision deficits. Their parents signed a written informed consent prior to participation. All subjects were right handed as assessed and scored through Edinburgh handedness questionnaire (range from 0 to 100 for right handedness) (Oldfield, 1971). The subjects had normal nonverbal IQ as scored more than 100 by Raven's IQ test (Raven Standard Progressive Matrices). Table 1 shows statistical characteristics (mean and standard deviation) of the nonverbal IQ and handedness scores, and ages of the subjects.

1.2.2 Stimulation: Dot Estimation Task (DET)

The task contains two blocks. The first block includes 60 images of 15-55 dots with 60 fixations. Each dots-image was presented 1000 msec. and each fixation cross image was presented for 1000 ± 100 msec. before presentation of each dots-image. There was no response from the subjects. Figure 1 shows a schematic illustration of block one. Before starting the second block of the stimulations, the subjects were asked to estimate and say number of the dots represented in each image. Therefore the second block includes dots-images (60 images of 15-55 dots), fixations, as well as response images (60 images containing the word "SAY" in the middle). Each dots-image presented 1000 msec. and each fixation cross image presented for 1000 ± 100 msec. immediately before (fixation 1) and after (fixation 2) presentation of each dots-image. Each response image was presented after each fixation 2 and the subjects had 3000 msec. to say their estimation. Figure 2 shows a schematic illustration of block two.

The estimation error of each subject was computed by averaging the estimation errors of the subjects in the trials overall the trials. A positive estimation error indicates an overestimation and a negative estimation error indicates an underestimation.

1.2.3 Psychophysiological recording

EEGs were recorded using a 32-channel PC-based system. Using an electrocap the Ag-AgCl electrodes were placed to 31 scalp locations (Fp1, Fp2, F3, F4, FC3, FC4, C3, C4, CP3, CP4, P3, P4, O1, O2, F7, F8, FT7, FT8, T3, T4, TP7, TP8, T5, T6, Fpz, Fz, FCz, Cz, CPz, Pz, and Oz) according to the international 10-20 system, referenced against linked earlobes. Figure 1 shows the loci. In this study only the right parietal (P4, CP4, TP8, and T6) and left parietal (P3, CP3, TP7, and T5) channels were subjected for further analyses. The resistance of electrode-scalp was kept below 5 kΩ. The vertical and horizontal EOG on the right eye was registered as well. With the subjects in a relaxed state, at the viewing distance of 60 cm from the monitor, sitting on a comfortable fixed chair in a quiet room, the EEGs were recorded simultaneously with the DET task. The EEGs were recorded with sampling rate of 250 Hz, filtered by a band-pass 0.1-150 Hz, and digitized in 16 digits. During the entire DET task session, the subjects were instructed to avoid body and eye movements. The EEG epochs free from eye blinking and electro-oculographic artifacts, where absolute amplitude of EOG < 70 μV, and free from movement artifacts, based on visual inspection, was selected to be included in the study. Also epochs with absolute amplitudes exceeding 100 μV at any electrode were excluded from further analyses. The subjects with less than 15 correct epochs, in each block, were excluded from further analysis. Hence in this stage one subject was removed from the study.

1.2.4 EEG analysis

The EEGs were digitally filtered in 1-70 Hz by a Butterworth band-pass filter and the electricity line interference was removed by 50 Hz notch filter. Alpha band as the most related frequency band to calculation, and attention was considered for further analyses. Then the alpha band of each EEG was extracted using 8-12 Hz band-pass Butterworth filter. Three analyses were used to extract dynamical properties of the alpha-band EEG associated with the estimation task: fractal dimension, absolute power, and relative power.

1.2.4.1 Fractal dimension

FD algorithms attempt to quantify the self-similarity of a time series, which refers to how many times similar patterns in the time series are repeated in different temporal scales (Ahmadlou, Adeli, & Adeli, 2012a). In order to compute fractality of the EEGs, Katz's Fractal Dimension (KFD) algorithm was used (Katz, 1988). This is one of the most common FD algorithms. Esteller, Vachtsevanos, Echauz, & Litt (2001) compared it with the other common FD algorithm, called Higuchi's FD (Higuchi, 1988), for estimation of FD of both synthetic time series and intracranial EEGs as experimental time series. They showed KFD is more robust to noise in comparison with Higuchi's FD, which makes it more effective for measuring FD of natural signals. Also in recent studies the KFD algorithm showed successful results in investigation of the changed brain dynamics in autism (Ahmadlou, Adeli, & Adeli, 2010), Alzheimer's disease (Ahmadlou, Adeli, & Adeli, 2011), and major depressive disorder (Ahmadlou, Adeli, & Adeli, 2012b). The algorithm of KFD has been presented in the appendix. In this way the KFD was computed for alpha-band EEG of the right and left parietal channels of each subject. Subtracting the KFDs obtained from block one from the corresponding KFDs obtained from block two resulted in 8 KFD values related to the 4 right parietal and the 4 left parietal channels at alpha band. This subtraction was done in order to investigate the approximation process more specifically.

1.2.4.2 Absolute and relative powers

Through Welch algorithm (using Hamming window with 50% overlap) absolute and relative power of EEG at alpha band were computed for the right parietal channels of each subject. Subtracting the APs and RPs obtained from block one from the corresponding APs and RPs obtained from block two resulted in 8 AP and 8 RP values related to the 4 right and 4 left parietal channels at alpha band.

Averaging the obtained KFD values, the absolute power (AP) values, and the relative power (RP) values overall the 4 channels in the right parietal and 4 channels in the left parietal (see figure 3) resulted in two regional values (associated to right and left parietal) for each of the KFD, AP, and RP at alpha band.

1.2.5 Statistical Analyses

Normality of the alpha KFD, AP, and RP distributions was assessed at the right and left parietal lobes using Kolmogorov-Smirnov and Shapiro-Wilk tests (using SPSS 20.0 for Windows). The relation between the estimation error, and the alpha RP, the alpha AP, and the alpha KFD of the right and left parietal lobes was analyzed using linear regression. Also in order to see the estimation error and the brain dynamics involved in the DET task have any relation with the nonverbal IQ, the dependence between nonverbal IQ scores of the subjects and the obtained alpha KFD, AP, and RP was evaluated with Pearson's coefficient of correlation.

1.3 RESULTS

Table 2 shows mean and standard deviations of the AP, KFD, and RP at alpha frequency in right and left parietal, and estimation error. The AP, KFD, and RP at alpha frequency in left parietal, in contrast with right parietal, didn't show any statistically meaningful correlation with the estimation error of DET. Table 3 shows the correlation matrix (including Pearson's coefficients and significance values) among the AP, KFD, and RP at alpha frequency in right parietal, the estimation error, and the nonverbal IQ of the subjects. The results show there is a strong correlation between accuracy of estimation and alpha KFD of right parietal activity (Pearson's coefficient = 0.838 with p-value < 0.001), between alpha KFD and alpha AP of right parietal activity (Pearson's coefficient = 0.719 with p-value < 0.005), and between alpha AP of right parietal activity and accuracy of estimation (Pearson's coefficient = 0.708 with p-value = 0.005). Figure 4 shows the diagrams of 0.05×AP-20, 250×KFD-20, and the estimation error overall the 14 subjects, where the AP and KFD are from the alpha band in the right parietal. The AP and KFD were scaled in such way (0.05×AP-20 and 250×KFD-20) in the sake of simplifying the visual comparison for the readers. Figure 5 shows the fitted line of $y=1.1145x+2.6803$, where y is 250×KFD-20 and x is the estimation error. Figure 6 shows the fitted line of

$y=0.6139x-6.8985$, where y is 0.05×AP-20 and x is the estimation error. Figure 7 shows the fitted line of $y=1.1155x-1.2643$, where y is 250×KFD-20 and x is 0.05×AP-20.

1.4 CONCLUSION

Many fMRI-based studies have revealed major roles of different parietal regions, in approximate and exact numerical processing (Kadosh et al., 2007; Salillas et al., 2012; van Harskamp & Cipolotti, 2001). However the low temporal resolution of fMRI is a limitation for studying temporal dynamics (specifically the nonlinear dynamics) of the parietal brain. In this study using EEG as a high temporal resolution tool, we investigated the relationships between dynamics of electrical activity of parietal brain and the performance of approximate numerical processing. For this purpose we used DET task as a very simple approximation of non-symbolic numerosities. Absolute power (AP), relative power (RP), and fractality (KFD) of right and left parietal lobes at alpha band, as the most related EEG frequency band to the numerical processing (Earle, 1985; Earle & Pikus, 1982; Glass, 1968), were subjected to the analysis of this study.

The behavioral results of the DET task, showed all subjects (who were female adolescents) have underestimation (negative estimation error). The results of EEG analysis didn't show any relationships between the EEG properties of left parietal lobe and the estimation error, while there are significant correlations between the alpha KFD, the alpha AP, and the estimation error. That is the less self-similarity and complexity in the right parietal activities at alpha band, the more accurate estimation. As there is a significant correlation between alpha KFD and alpha AP, it's concluded that during approximation the higher complexity of alpha wave comes with the higher alpha wave activity. Also there results showed the non-verbal IQ has no relation with the estimation error and the brain dynamics.

Davis et al. (2009) in an fMRI study showed left hemisphere network is more related to arithmetic fact retrieval and exact calculation and the right parietal is more related to approximation task, compared with left parietal. Also Cappelletti, Lee, Freeman, & Price (2010) showed right parietal cortex activity implicates conceptual decisions more on numbers, while left parietal activity for numbers implicates more retrieval of learnt facts. In this view, as the DET is a simple approximation task that doesn't implicate to arithmetic fact retrieval, our results (no significant correlation between left parietal lobe and alpha wave dynamics) accords to the results of Cappelletti, Lee, Freeman, & Price (2010) and Davis et al. (2009).

As posterior alpha wave activity detected by EEG has an inverse relation with the fMRI posterior activity (Schultze-Kraft, Becker, Breakspear, & Ritter, 2011), the direct relation between alpha activity of right parietal and the DET approximate performance confirms results of de Smedt, Holloway, & Ansari (2011). De Smedt, Holloway, & Ansari (2011) showed children with lower arithmetical fluency showed higher activity in the right parietal (right intraparietal sulcus) during solving small-size arithmetic problems.

Furthermore analysis of individual alpha frequency instead of the fixed alpha range of 8-12 Hz, used in this study, may result in more significant correlation between alpha wave dynamics of the right parietal cortex and the DET performance. Also as the parietal alpha activity in the numerical processing is different between females and males (Glass, 1968), in future studies the relationships of the alpha wave dynamics of males and the DET performance would be investigated and compared with those of females. Also the obtained alpha dynamics (KFD and AP) may be useful for future studies on dyscalculia.

APPENDIX

Katz's Fractal Dimension (Katz, 1988)

Conceptually, irregularity in a time series in this algorithm is considered variation of distances of successive points. The distance is computed just between each two successive points, while in the HFD algorithm distances of successive points with delay *k* (which is called scale) are computed. Compared with HFD, KFD can be found simpler as follows:

Consider $\mathrm{x} = [x_1,...,x_N]$ as a time series with N sample times, where x_i indicates i^{th} sample times of x.

a) For $j=1,..,N$ find the maximum value of $|x_1 - x_j|$ and call it d.

b) Compute L as the total length of the time series x and a as the average distance between successive points of x:

$$L = \sum_{i=2}^{N} |x_i - x_{i-1}| \tag{1}$$

$$a = \frac{L}{N-1} \tag{2}$$

c) Compute KFD according to:

$$KFD = \frac{\ln(\frac{L}{a})}{\ln(\frac{d}{a})} \tag{3}$$

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Table 1: descriptive statistics of the age, nonverbal IQ, and handedness of the subjects.

	Mean	Std. Deviation
Age	13.25	1.05
Nonverbal IQ	109.78	7.98
Handedness	89.37	6.25

Table 2: descriptive statistics of estimation error and AP, KFD, and RP in right and left parietal lobes at alpha band of the subjects.

		Mean	Std. Deviation
	Estim. Error	-20.1536	4.2221
Right Parietal	Abs. Alpha P.	-1590.27	4872.052
	Alpha KFD	-0.002	0.01257
	Rel. Alpha P.	-0.0315	0.04738
Left Parietal	Abs. Alpha P.	-1531.41	3925.243
	Alpha KFD	-0.001	0.01422
	Rel. Alpha P.	-0.0257	0.02549

Table 3: The correlation matrix (including Pearson's coefficients and significance values) among the AP, KFD, and RP at alpha frequency in right parietal, estimation error, and nonverbal IQ.

		Abs. Alpha P.	Estim. Error	Alpha KFD	Rel. Alpha P.	Nonverbal IQ
Abs. Alpha P.	Pearson Corr.	1	0.708*	0.719*	0.193	-0.32
	Sig. (2-tailed)		0.005	0.004	0.509	0.265
Estim. Error	Pearson Corr.	0.708*	1	0.829**	0.194	-0.363
	Sig. (2-tailed)	0.005		0.000	0.507	0.202
Alpha KFD	Pearson Corr.	0.719*	0.829**	1	0.441	-0.246
	Sig. (2-tailed)	0.004	0.000		0.115	0.397
Rel. Alpha P.	Pearson Corr.	0.193	0.194	0.441	1	-0.436
	Sig. (2-tailed)	0.509	0.507	0.115		0.119
Nonverbal IQ	Pearson Corr.	-0.32	-0.363	-0.246	-0.436	1
	Sig. (2-tailed)	0.265	0.202	0.397	0.119	

** .Correlation is significant at the 0.001 level (2-tailed).

*. Correlation is significant at the 0.005 level (2-tailed).

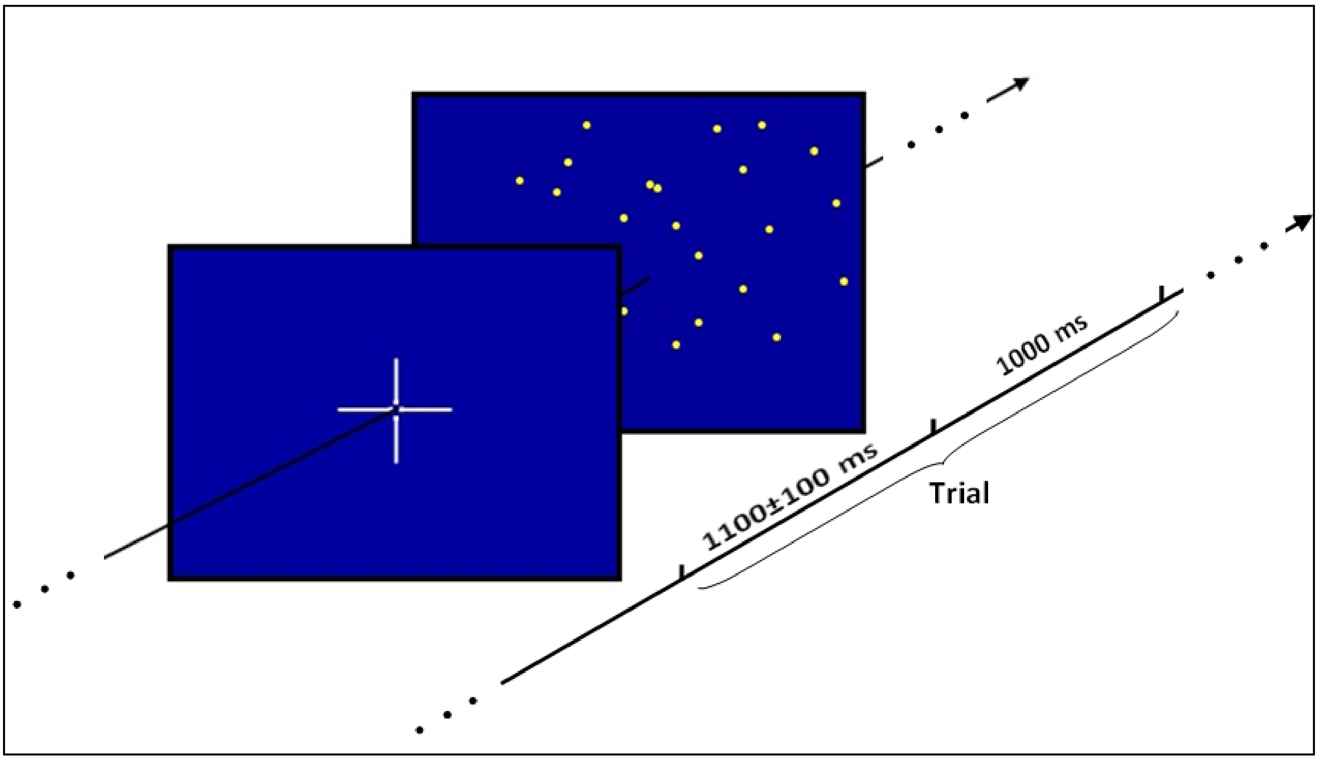

Figure 1: illustration of block 1 of DET task: dot stimulation without response.

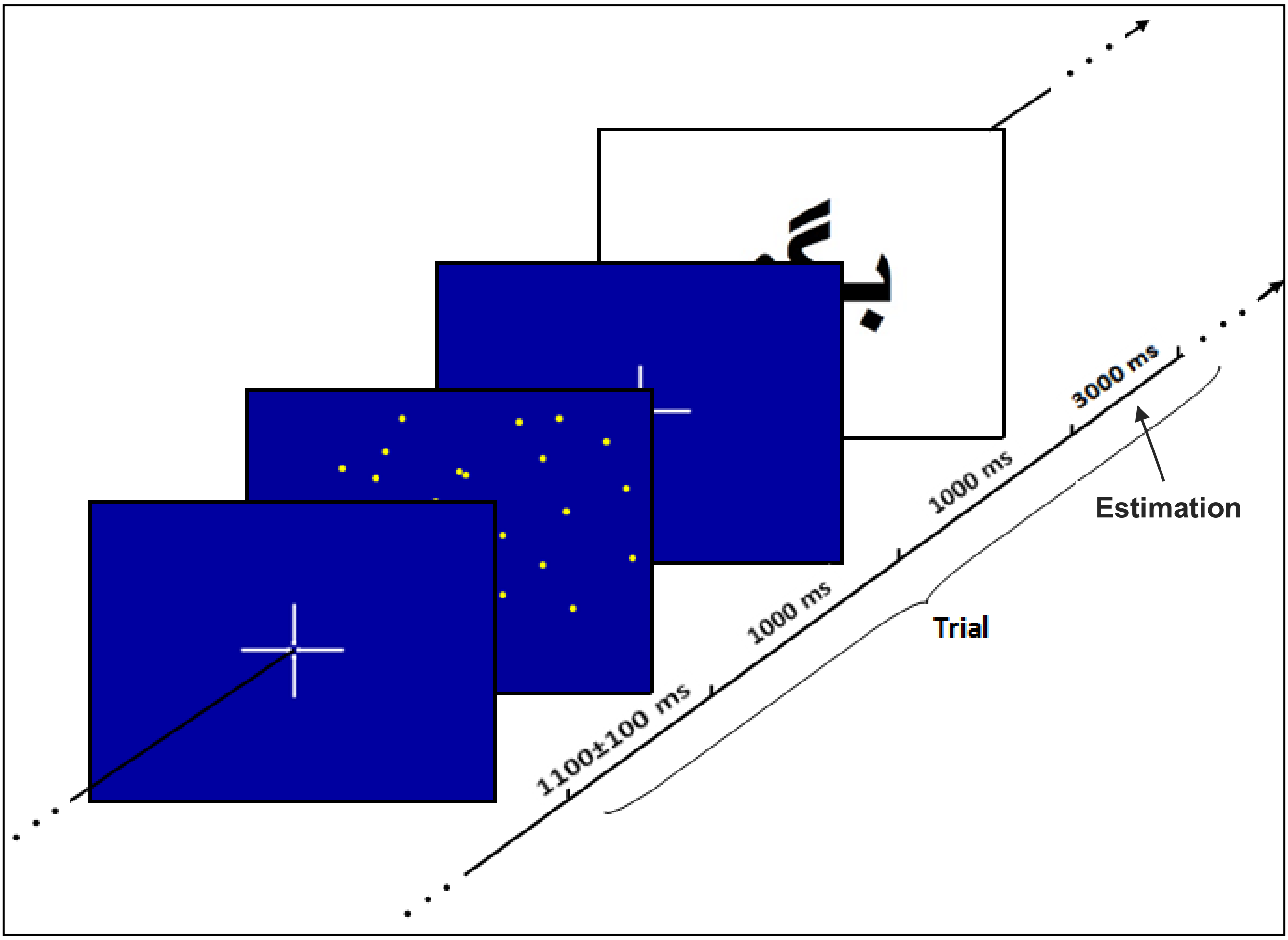

Figure 2: illustration of block 2 of DET task: dot stimulation with response.

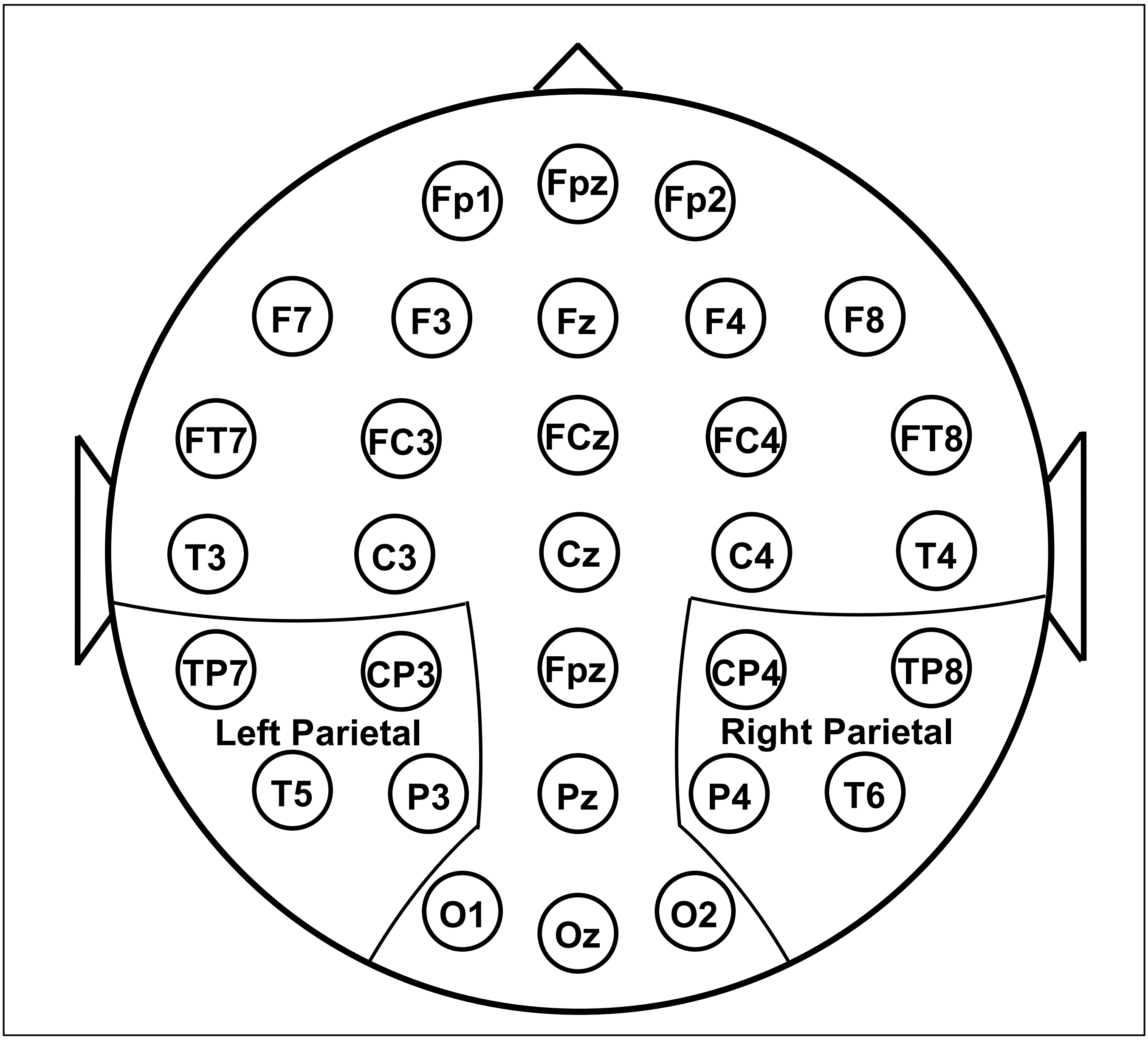

Figure 3: illustration of the 10-20 32 channels EEG recording and the right (P4, CP4, TP8, and T6) and left (P3, CP3, TP7, and T5) parietal channels used in this study.

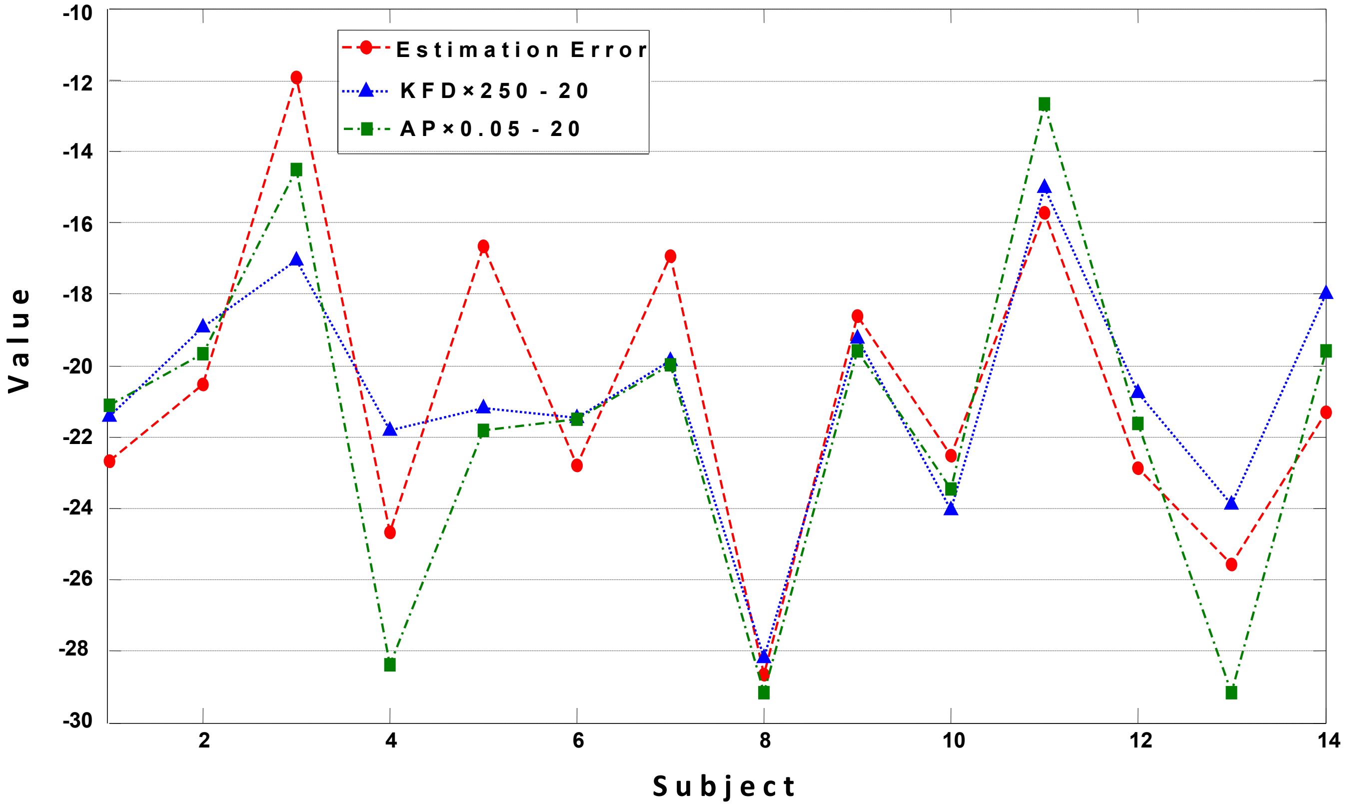

Figure 4: Illustration of the diagrams of 0.05×AP-20 (squares), 250×KFD-20 (triangles), and the estimation error (circles) overall the subjects.

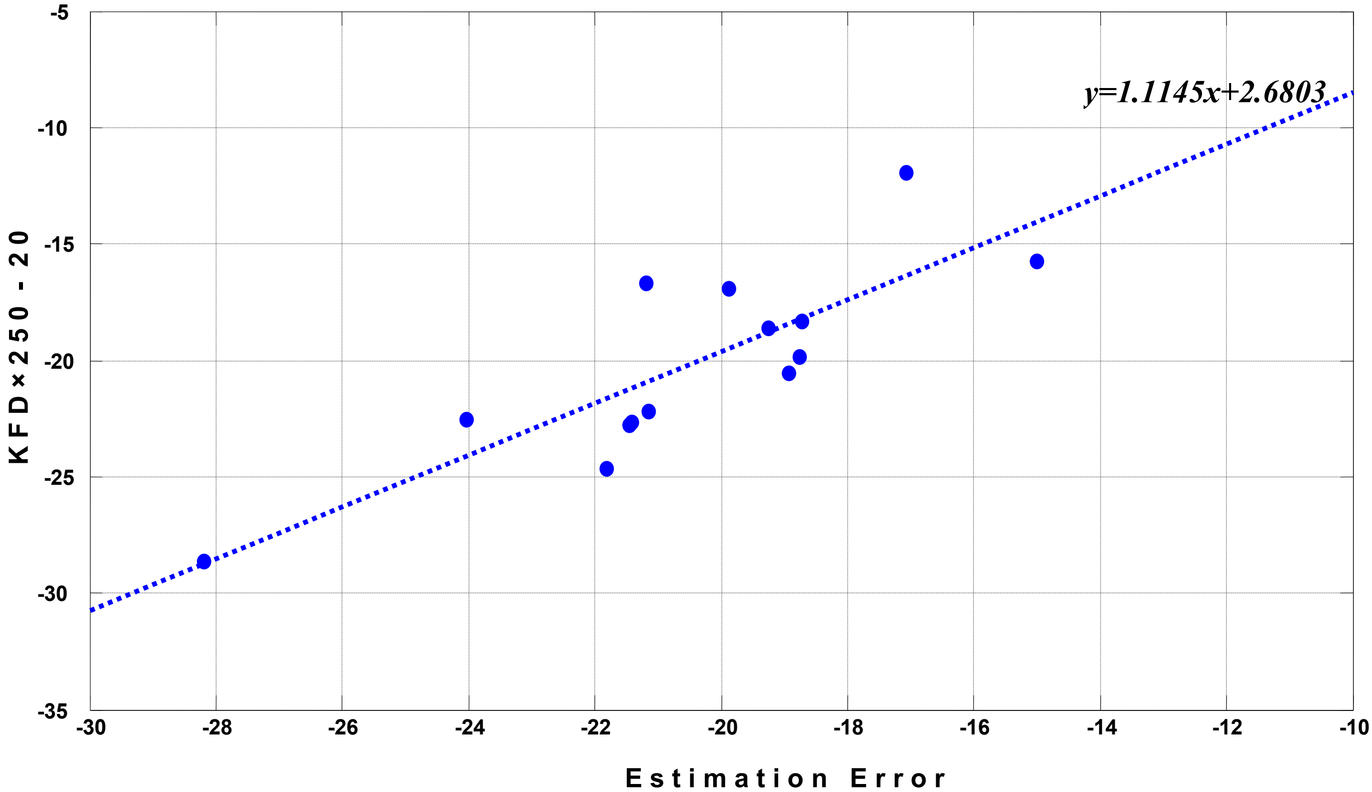

Figure 5: Illustration of the relationship between estimation error and KFD at alpha band in the right parietal lobe. It shows the fitted line of $y=1.1145x+2.6803$, where y is 250×KFD-20 and x is the estimation error.

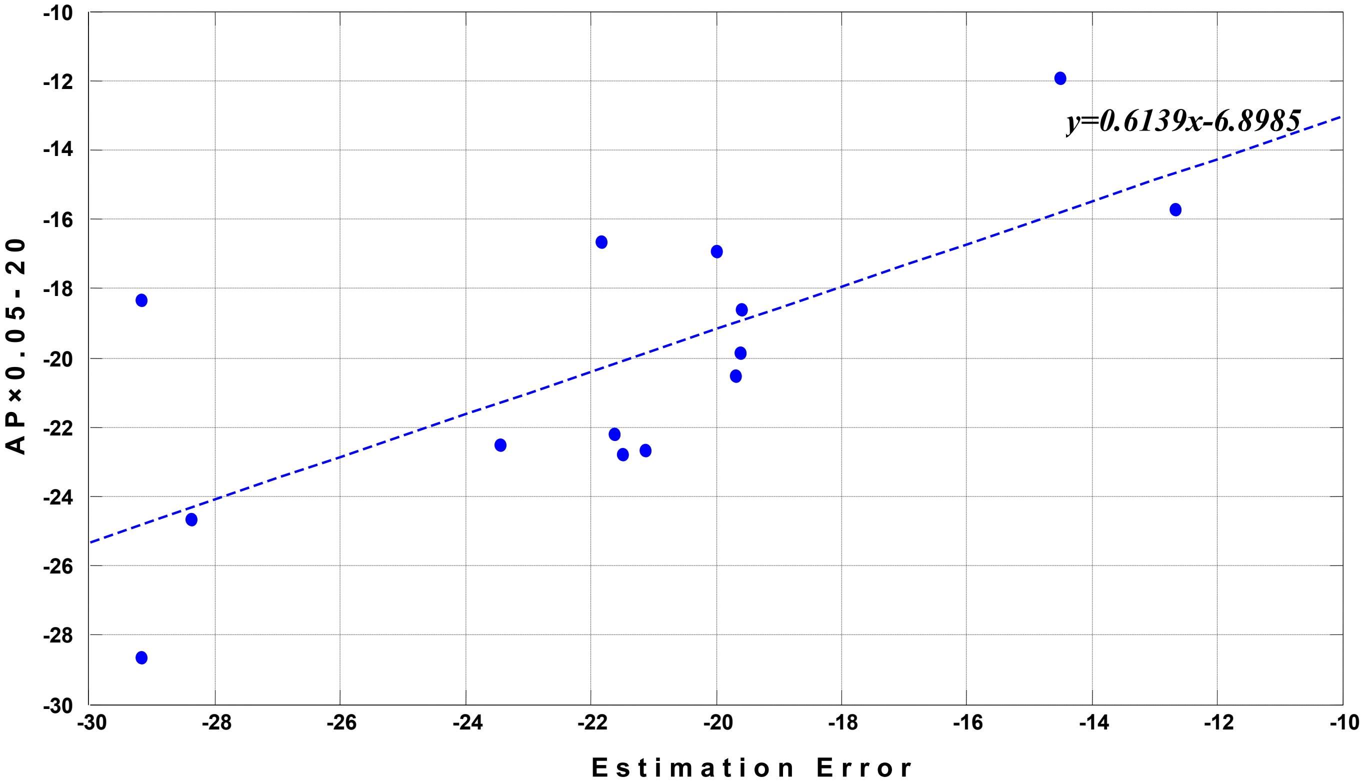

Figure 6: Illustration of the relationship between estimation error and AP at alpha band in the right parietal lobe. It shows the fitted line of $y=0.6139x-6.8985$, where y is 0.05×AP-20 and x is the estimation error.

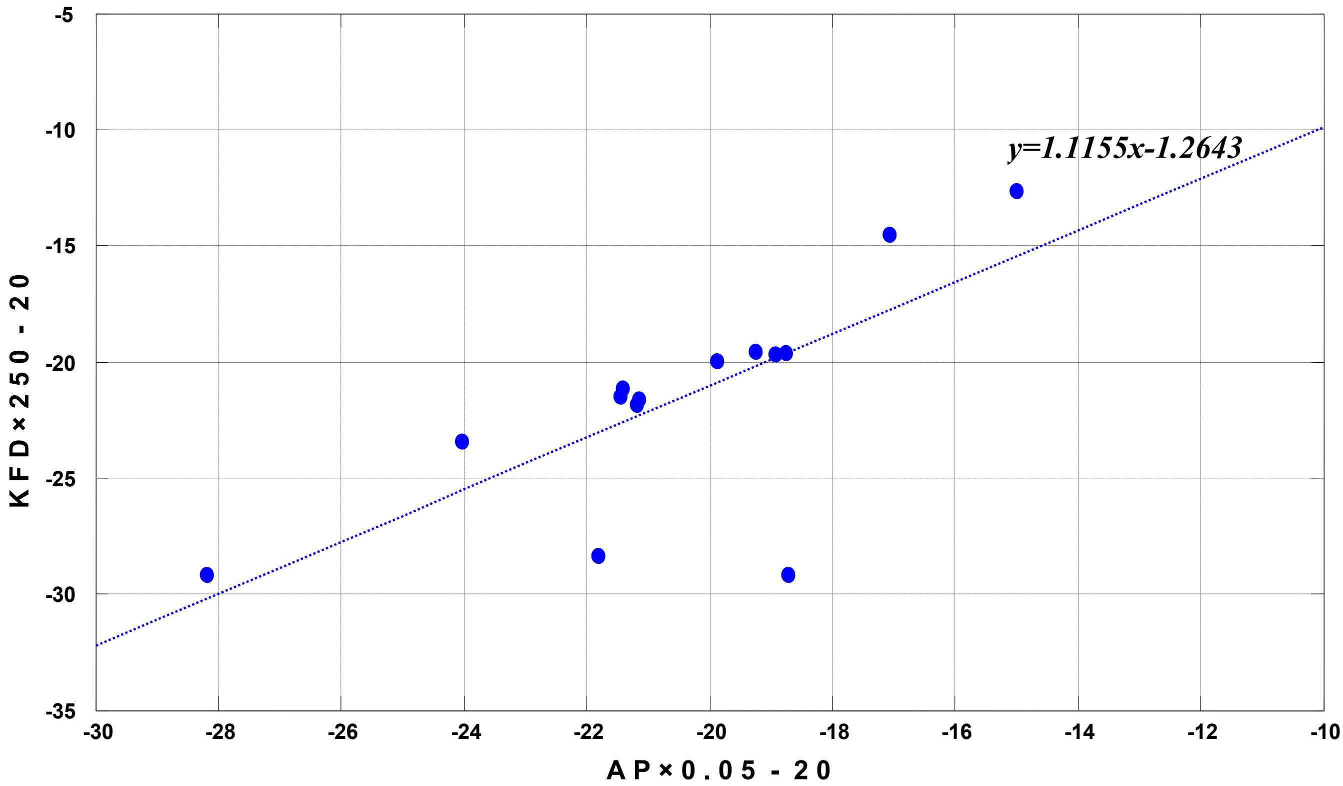

Figure 7: Illustration of the relationship between KFD and AP at alpha band in the right parietal lobe. It shows the fitted line of *y=1.1155x-1.2643*, where *y* is 250×KFD-20 and *x* is 0.05×AP-20.