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Spectrum power and brain functional connectivity of different EEG frequency bands in attention network tests

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Abstract— **There have been many previous studies on brain electrical activity and attention function, but the research on observing the cognitive function of attention from frequency brain electrical indicators remains insufficient. This study proposed an attentional network test (ANT) of Chinese version and used frequency analysis methods to observe the power spectrum activity and functional connectivity of delta (δ), theta (θ), alpha (α) bands of EEG signals to further understand their relationship with attention networks. The attentional network test was composed of alerting network, orienting network and execute conflict network, and these networks were compared with the resting state in different frequency bands. The results showed that α band activity was significantly suppressed in all three attentional states, and the power of θ band activity dramatically increased for the execute conflict network. The negative connection of α band in the long distance (frontal lobe to parietal lobe or occipital lobe) might be a sign of resting state network, and the positive connections between δ and θ band in similar areas could be an indicator of execute conflict network. This pilot study suggests that the frequency domain analysis of EEG signals could be a great tool to visualize the brain activities in response to different attentional networks.**

Clinical Relevance— **This pilot study proved that the frequency bands activity might be suitable objective neuro-markers to distinguish different attention states.**

I. Introduction

Cognition is the process by which the human brain receives external information, processed it, and transformed it into internal mental activities, thereby acquiring knowledge or applying knowledge [1]. It includes memory, language, visual space, execution, calculation, comprehension and judgment, etc., and attention function is the basis of all complex cognitive activities and learning. The study of the neural activity of attention in normal healthy people is an exploration of the correlations between brain wave activity. Comparing the cognitive process related to attention with the resting state can help to understand the neural mechanism of the corresponding state. It can also provide more information for the neuro markers of cognitive function of attention and prepare for attention deficit assessment research.

Based on the research of cognitive psychology and neuroimaging, Posner divided attention into three functionally independent sub-networks of alerting, orientation, and executive control [2]. Alertness is related to wakefulness and sustained attention. The alertness network focuses on the brainstem arousal system and thalamic neuromodulation system in the right cerebral cortex. Orientation refers to the ability to select specific information and prioritize sensory input. Executive control generally refers to the ability to detect and resolve conflicts. The executive control network is mainly completed by the dorsolateral prefrontal cortex, frontal medial cortex, thalamus and anterior cingulate gyrus [3]. The attention network test (ANT) designed by Fan et al. can evaluate the efficiency of three sub-networks through different types of visual cues [4]. So an improved version of ANT experiment will be applied in this research and three sub-network components will be independently analyzed.

Due to characteristics such as real-time, non-invasiveness, ease of use and low cost, EEG technology seems to be a reliable way to analyze three attentional networks. Attention can be measured indirectly through EEG technology and the main research focus is to conduct P300 induction experiments in the time domain [5]. The activities of different frequencies of EEG signals constitute the neural oscillation of the neuron cluster, and this oscillation mode is rhythmic. A large number of studies have explored the cognitive regulation of selective attention through the modulation of neural oscillations and energy analysis [6]. In addition to analyzing the time-domain and frequency domain features of EEG, researches were also conducted to analyze attention by functional brain network based on coherence coefficients and phase locking values. The attentional level could be classified and measured by brain functional network [7]. However, current studies usually used resting state experiments to construct brain networks, and there is a lack of network connection research based on ANT experiments.

In this study, the spectrum power method and functional connectivity method were used to investigate different frequency bands activity. The resting state and three attentional networks will be explored in detail.

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II. METHODS

A. Subjects

Four healthy volunteers (mean age =23±2 years) were employed in this study. All participants were right-handed, had normal vision and were free of cognitive deficit. The protocol of this study was approved by the Institutional Review Board of the Shenzhen Institutes of Advanced Technology, China. All subjects gave written informed consent and provided permission for publication of photographs for scientific and educational purposes.

B. Experimental Procedure

In this experiment, a version of the attentional network test (ANT) was translated into Chinese for the EEG research. This task contains four cue conditions (no cue, center cue, binary cue, spatial cue) and three target stimuli (neutral, congruent and incongruent). These stimuli were selected from a large number of previous studies on attentional function [4, 8]. In addition, this experiment was written using Eprime 3.0, and the button feedback device was Chronos.

The details of this simplified version of the ANT are illustrated in Figure 1. All participants were told that this was a task about feeding small fish and were instructed to learn the rules before the practice part. They need to choose the direction the fish is facing and press the corresponding button. First, the subject needs to focus on the screen and wait for the cue stimulus (a star symbol). The center cue and binary cue will show that the small fish is about to appear, but it does not indicate where the fish is. While the spatial cue will clearly indicate that the small fish appears in the same position as the cue stimulus. If the subject completes the operation within 2s, the feedback picture and the sound stimulation will appear on the screen immediately. Each subject will complete 120 trials and the whole experiment process is about half an hour.

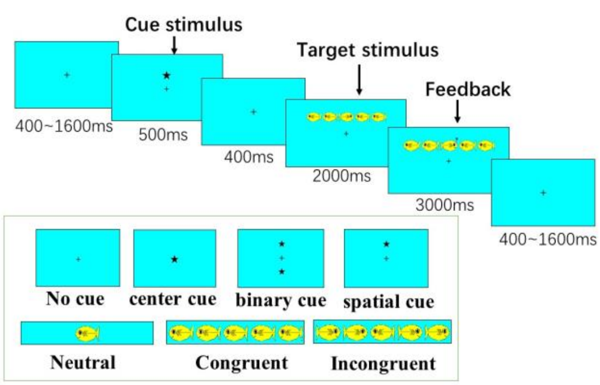

Figure 1. Procedure of each trial in ANT. A fixation cross appears in the center of the screen all the time. Different cue stimulus (no cue, center cue, binary cue or spatial cue) appears for 500 ms. The target fish stimulus are presented until the participants responds. After that, corresponding feedbacks appear for 3s.

Througth the ANT, the efficiency of three attetional networks could be explored. In this task, alerting network would be analysed by brain activity resulting from center cue and binary cue stimulus. Orienting network would be analysed according to spatial cue signal. Executive network is related to incongruent target stimulus.

C. EEG recording

The EEG was recorded using a 64-channel Neuroscan QuikCap system. Scalp electrodes were fixed according to the International 10-20 brain electrode positioning method and referenced to two mastoids for data analysis. Impedances were kept below 10 kΩ. Data were recorded in DC mode using a SynAmps II amplifier with Scan 4.5 software, using a sampling rate of 1000 Hz.

D. Signal processing and data analysis

The preprocess of the EEG data was performed using EEGLAB [9]. A Hamming windowed sinc FIR filter (0.5 to 60 Hz) was applied to all channels for each subject. Then 50 Hz notch filter was applied to remove power noise. Independent Component Analysis (ICA) was used to remove EEG components related to eye-blinks and muscle movement. In order to explore different attention networks activity, each epoch was extracted from -200ms to 800ms. To ensure that the data is clean enough, visual reject was used before further analysis.

This study used the FieldTrip toolbox for frequency decomposition and functional connectivity analysis of corresponding frequency bands [10]. Because two mastoid electrodes were referenced, only 62 channel's data were used. And the EEG data was decomposed into 5 frequency band (δ 2-4 Hz, θ 4-7 Hz, α 7-13Hz, β 13-30Hz, γ 30-60 Hz) by fast Fourier method. Then the connectivity of different bands was calculated by the WPLI (weighted phase lag index) method. Phase-synchronization is a manifestation of interaction between neuronal groups measurable from EEG signals, however, volume conduction can cause the coherence and the phase locking value to spuriously increase. Compared to phase locking value or the imaginary part of the coherency, WPLI has the advantage of being less influenced by phase delays and uncorrelated noise source [11]. Next, the WPLI matrix between the 62 channels of each frequency band could be used as the edge of the brain network. Finally, the resting-state network and attentional networks were processed using BrainNet toolbox [12]. One-way analysis of variance (ANOVA) was also used to statistically analyze the average power change and phase synchronization of brain waves in different attentional activity.

III. RESULTS

A. Spectrum power activity of δ, θ and α bands

In this study, the spectrum power activities related to alerting network, orienting network and executive network will be mainly observed. The resting state (eyes open) activity will be compared, too.

Actually, we acquired EEG in 5 kinds of frequency band, but the β and γ activity were always suppressed, and their power is relatively small. The spectrum power topographic map of δ, θ and α is shown in Figure 2. Among them, the alerting data was obtained from center cue stimulus and binary cue stimulus, the orienting data was obtained from spatial cue stimulus and the execute conflict data was obtained from incongruent target stimulus. In the resting state, δ was active in the frontal lobe area, θ was inactive in all area and α was active in parietal lobe area, especially on the right lateral. In the alerting state and the orienting state, only δ is active in frontal region and central region. While in the execute conflict state, δ power increased in all area and θ power also increased in frontal area.

Through ANOVA calculations, we could find out whether three frequency bands affected four cognitive states. If the p value is smaller than 0.05/groups, it would be considered correlated. The δ power activity had a strong relation with different attentional states ($F_{3,244} = 24.93$, $p = 4.17e-14$). The θ power activity also had a relation with four states ($F_{3,244} = 12.79$, $p = 8.67e-8$). But there was no correlations between resting state, alerting state and orienting state in θ power activity ($F_{2,183} = 1.3$, $p = 0.2763$). The α power activity is similar to the θ power activity ($F_{3,244} = 236.96$, $p = 5.51e-72$).

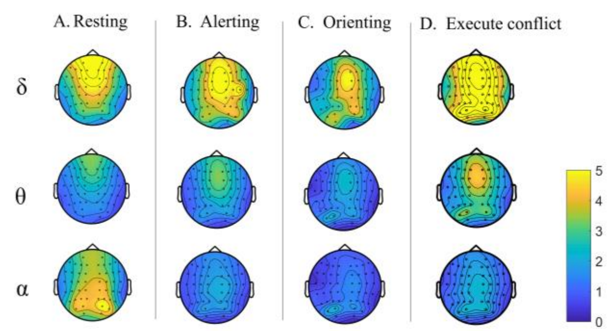

Figure 2. The spectrum power topographic map of δ, θ and α bands. Spectrum power activity in resting state (A), alerting state (B), orienting state (C) and execute conflict state (D).

In the figure 2, each attentional state was represented by a single stimulus while the efficiency of attention network was usually examined by changes in reaction time from two stimulus. In order to further analyze attention network components from the perspective of spectrum power changes, the result of calculating the center cue/binary cue stimulus minus the no cue stimulus is related to the efficiency of the alerting network. Similarily, the spatial cue stimulus minus the center cue/binary cue stimulus is related to the efficiency of the orienting network and the incongruent stimulus minus the congruent stimulus corresponds to execute conflict network.

As is shown in figure 3, the alerting network efficiency can be reflected in the increased power in θ band, the decreased power of δ in occipital area and increased power of δ in lateral parietal area. The orienting network efficiency can clearly be reflected in the increased power in δ band. There is few change of θ power in parietal area. For execute conflict network, it's obvious that the δ power in frontal area decreased while the θ power in center area increased. In addition, there is almost no change in α power for three networks.

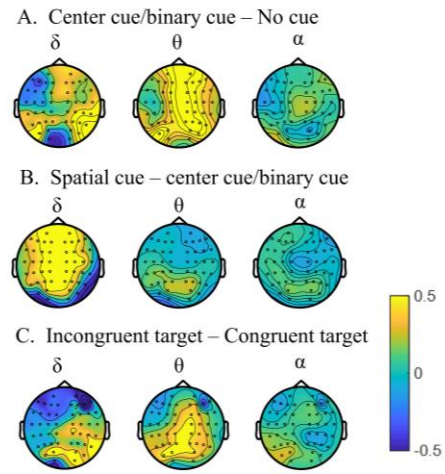

Figure 3. The spectrum power topographic map of δ, θ and α bands in three different states. The power changes in center cue/binary cue minus no cue (A), spatial cue minus center cue/binary cue (B) and incongruent target minus congruent target (C).

B. Brain functional connectivity of δ, θ and α bands

In this part, the functional connectivity of three attentional state and resting state will be compared. The brain network consists of 62 nodes and an appropriate number of edges. The nodes are 62 channel electrodes, and edges are selected from the 62x62 connection matrix calculated by WPLI. Therefore, the results of brain network shown next means the strength of functional connectivity or phase synchronization in different brain area.

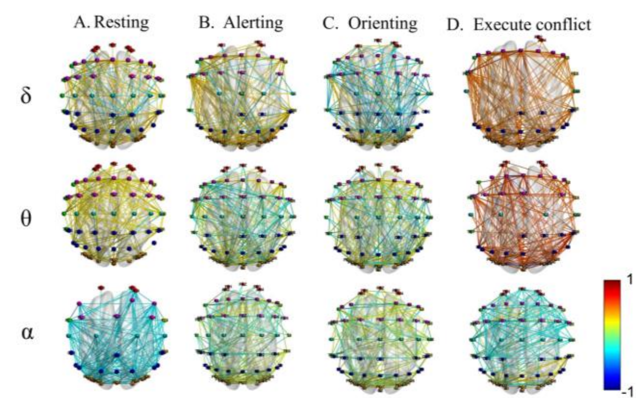

Figure 4. The brain functional connectivity map of δ, θ and α bands (visuallized by BrainNet toolbox). Axial view of brain networks in resting state (A), alerting state (B), orienting state (C)and execute conflict state (D).

In order to show the small-world network characteristics of the brain network, the connection threshold (denote by T below) was dynamically set to a 10% sparsity of network edges. So, the brain network has enough effective connections and different attentional network has similar clustering coefficient and structure. In the figure 4, the α band connectivity is negative in resting state (T = 0.247), while the δ band and θ band have a small number of positive connections (δ-T = 0.285, θ-T = 0.256). As we can see, the alerting network and the orienting network are only slightly different in δ band (alerting network has more positive connections), and their connections is weak in the θ band and α band ($T < 0.2$). For execute conflict network, both δ band and θ band have positive connections and the connection of θ band is the strongest (δ-T = 0.465, θ-T = 0.527). Interestingly, the connections of δ band in the execute conflict network are mostly the connections between the frontal lobe and the parietal or occipital lobe regions.

IV. Discussions

In this study, the three attentional networks were investigated by spectrum analysis and functional connectivity analysis. In frequency analysis, we mainly focus on the δ, θ and α bands activity while the high frequency band is not within the scope of discussion. The brain functional connectivity networks have the same frequency bands.

First, we compared the spectrum power changes in the resting state and three attentional states which are obtained from corresponding stimulus. The θ band activity was suppressed and α band activity was enhanced in the resting state. When participants are stimulated by the experiment, whether it was alert stimulus, directed stimulus or conflict stimulus, their α band activity was all suppressed. In the previous study, α band activity was related to an attentional suppression mechanism when objects needed to be specifically ignored or selected against [13]. Therefore, the reduced power of α band activities may mean that participants are paying attention to the screen which is related to the process of choosing cognitive functions. When participants were executing conflict stimulus, their θ band power in frontal area was increased. It seems that θ band activity is related to control the conflict task. And one study thought that θ band activities over the midfrontal cortex appear to reflect a common computation used for realizing the need for cognitive control [14].

Since the single stimulus did not clearly show the efficiency of three attentional components, we further observed the spectrum power changes in two cue stimulus or target stimulus. Then we could preliminarily think that the θ band activity is related to alerting cognitive process, which represents a mechanism about down-top control. As previous study of spatial attention shown, orienting network involved top-down control and selective attention [15], and one study shown that δ band inhibitory oscillations would modulate the activity of those networks that should be inactive to accomplish the task [16]. Our research results can illustrate that δ band activity might play a role in this cognitive process.

In the end we compared the functional connectivity of the resting state and three attentional networks, the negative connection of α band in the long distance might be a sign of resting state network. And positive connections of δ band in frontal area to parietal area or occipital area could be a sign of execute conflict network. One study indicated that enhanced θ band connectivity is a core electrophysiological mechanism that underlies internally directed attention [17]. In this study, the strong connections of θ band are also related to execute conflict network. But the other strong connections in brain regions need to be further investigated.

V. Conclusion

The study showed that α band activity was all suppressed in three attentional states, increased power of θ band activity reflected execute conflict network. And the negative connection of α band, positive connections of δ band and θ band in the long distance (frontal lobe to parietal lobe or occipital lobe) might be a sign of distinguish different cognitive states. Frequency-domain analysis of EEG signals could be an important tool for visualizing and distinguishing different attention networks. This will help further research on EEG rhythm activities and attentional cognitive function.

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