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Analysis of Propagation of Multi-channel EEG in the Test of Sustained Attention

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***Abstract*—the psychological construct 'sustained attention' describes a basic component of attention characterized by the subject's readiness to detect rarely and unpredictably occurring signals over prolonged periods of time. In this study, six healthy volunteers underwent a sustained attention to response task (SART), while their electroencephalographic (EEG) were recorded contemporarily. Directed Transfer Function (DTF) was used as estimator for direction of propagation of EEG function coupling. The results of DTF showed that the information flux within EEG functional coupling changed when attention condition changed from inattention state to sustained attention state, principally at alpha and beta rhythms. The DTF could be used to evaluate sustained attention condition and they might be used for research on damage of attention mechanisms of ADHD and TBI diseases in future.**

***Keywords*: sustained attention, electroencephalographic, Directed Transfer Function**

I. Introduction

The psychological construct 'sustained attention' describes a basic component of attention characterized by the subject's readiness to detect rarely and unpredictably occurring signals over prolonged periods of time [1-3]. Sustained attention is an important cognitive function in human behavior, having influence on other attentional aspects (selective attention, divided attention). In the past few years, the cognitive researchers have devoted themselves to understanding the sustained attention process within the human brain so as to understand the neuronal mechanisms underlying this cognitive function and to be sensitive to discrete information processing impairments that were often associated with clinical disorders, such as Attention Deficit Hyperactivity Disorder (ADHD) and Traumatic Brain Injury (TBI) [4-6]. The brain imaging studies have demonstrated that the activation of frontal and parietal cortical areas, especially in the right hemisphere, is associated with the sustained attention performance [7]. In recent contexts, the sustained attentional activity was achieved by the recurrent circuit mechanism. Three foundation systems (anterior attention system, posterior attention system and thalamic neurons system) constitute the network to mediate the sustained attention performance in the recurrent circuit mechanism [1, 2, and 8].

Techniques of brain imaging such as Positron Emission Tomography (PET) and Functional Magnetic Resonance (fMRI) have become popular in the cognitive research. However, electroencephalogram (EEG) was still the cheapest and most widespread technique in neuronal mechanisms research. EEG signals can give the direct information about the brain electrical activity and have the highest temporal resolution. Moreover, the rhythmicity which often occurs in EEG signal is reflecting the synchronization of neuronal activity. EEG signals are also applied to researching the activation of cortical areas related to sustained attention [5, 9, and 10]. However, in recent contexts, EEG signals were analyzed in each channel and can not estimate the strength and directionality of information flow between any pair of active brain areas during sustained attention. Directed Transfer Function (DTF), proposed by Kaminski *et al* [11], can be used as estimator for direction of propagation. DTF is based on multichannel autoregressive model (MVAR), and can estimate the intensity of activity flow between structures, depending on frequency of the signal. The value of DTF indicates the information flow (including direction) between two given structures. So we can detect the influence from one structure to another. In this study, DTF method was used for estimating the information flows among anterior frontal cortical areas, frontal cortical area and parietal cortical areas during sustained attention process.

Sustained Attention to Response Task (SART) [12] was used in this study. This task is sensitive to absentmindedness and attention. In this study, we utilize multi-channel EEG signals, collected from healthy people during SART and Inattention Task, to estimate the information flows between these areas by using DTF.

II. Material and Methods

A. Subjects

Six healthy volunteers participated in the experiment. All subjects were right-handed, with a mean age of 24.5 years (SD 2.4 years, range 22–28 years). All volunteers were students and were not paid to participate, and all of volunteers were male. None of them had the anamnesis of psychiatric disorders and their cognitive level and attentive capability were normal. We ascertained that the participants had no neuropsychological illness. Written informed consent was obtained from all volunteers before the examination. The participants were required to have a good rest before the examination. Whenever they felt tired during the examination, the task was paused.out any text that may try to fill in next to the graphic.

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B. *SART task*

The random SART task [12] was used in our examination. In this procedure, digits were presented randomly from '1' through '9'. Each digit was presented for 150 msec, followed by an interstimulus interval (ISI) that varied randomly between 1000 and 1200 msec. 225 digits were presented randomly (25 of each of the nine digits) and the period of one block was about 4 min. A variable ISI was used to prevent subjects succumbing to a speed–accuracy trade-off that could occur when ISIs were regularly paced [13]. Subjects were required to respond by button press to every number except the number "3". In our examination, the digit 3 was the target and others digit were go-trials. Then we defined the false presses on target as commission errors.

In keeping with Robertson [12], five randomly allocated digit sizes were presented to increase the demands for processing the numerical value and to minimize the possibility that subjects would set a search template for some perceptual feature of the target trial ('3'). Digit sizes were 100, 120, 140, 160 and 180 in arial text. Five allocated digit sizes subtended vertical angles of 1.39°, 1.66°, 1.92°, 2.18° and 2.45° respectively. Digits were presented 0.25° above a central across. The digits and masks were presented centrally in yellow against a black background on a computer monitor. The screen (320×240 mm; Dell PC) was positioned approximately 40cm from the participant. Task specifications were programmed using STIM2 which was published by NeuroScan Inc. Figure 1 shows the procedure of random SART task. sent to the corresponding author only.

Comparing the sustained attention process, we also designed an inattention task. In inattention task, the screen also presented the random SART digits, but the volunteers were asked to keep sight on the screen but ignore the digits running.

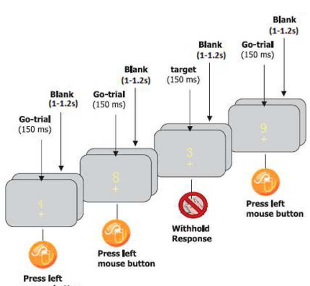

Fig. 1. A schematic diagram of the random sequence SART.

C. *EEG recordings*

There were 64 electrodes located on the scalp according to the standard "10-20 system" placement, 16 of which were selected at positions FP1, FP2, F3, F4, FC3, FC4, CP3, CP4, P3, P4, P7, P8, Fz, FCz, CPz, Pz. A1 and A2 were used as reference. Two additional bipolar pairs of electrodes were used to record horizontal and vertical EOG: one pair was placed at the outer canthi and the other one was below and above the right eye. All EEG recordings were performed by means of a 64-channel AC/DC-amplifier (Neuroscan) and its data acquisition software (Scan, version 4.3). EEG was sampled with 32 bits of accuracy and the A/D sampling rate was 1000 Hz. The band pass analog filters were set at 0.1-70Hz and notches filtered at 50 Hz. The impedances of all electrodes were below 5kOhm. All volunteers were required to complete three SART blocks and inattention blocks in clam room, and the volunteers were asked not to move their bodies during the experiments.

D. *EEG processing*

1) Pre-processing

Firstly, EEG data were cleaned up from EMG, ECG, EOG and head movement artifact manually by using scan software. Secondly, EEG signals were down sampled at 256 Hz. Wavelet packet analysis was performed to every EEG data segment. Daubechies 6 was adopted as the mother wavelet. After eight-octave wavelet packet decomposition, the EEG components of the following four frequency bands were obtained: θ (4–7 Hz), α (8– 12 Hz), β (13–30 Hz) and total (4-30Hz).

2) *Directed Transfer Function (DTF)*

The DTF method is based on a multivariate autoregressive model (MVAR) fitted to the EEG signal. K-channels EEG signals recorded in time can be described as X vector:

X (t) =(X1(t), X2(t),.., Xk (t)). Then the MVAR model can be expressed as:

$$X(t)=\sum_{i=1}^{p}A(i)X(t-i)+E(t) \tag{1}$$

Where X(t) is the EEG data vector in t time , E(t) is the vector of white noise values, A(i) are the k×k matrices of model coefficients (A0 = I) and p is the model order. The model order can be found by means of criteria derived from information theory. The sensitivity of MVAR performance depending on the model order was tested and it was demonstrated that small changes of model order do not influence results in previous research [14]. AIC criterion was used to find the most Satisfying order in our study. To estimate the spectral properties of the investigated process, the signal has to be transformed by z-transformation of the above equation. We get:

$$X(f)=H(f)E(f)=A^{-1}(f)E(f) \tag{2}$$

$$H(f)=(\sum_{j}^{p}A_{j}e^{-2\pi ijf\Delta t}) \tag{3}$$

Where H (f) is a transfer function of the system and f is the frequency. Δt is the temporal interval between two samples.

From the transfer function we can get the spectral matrix S:

$$S(f)=H(f)VH^{*}(f) \tag{4}$$

Since the transfer function H (f) is not a symmetrical matrix, the information transmission from the jth to ith channel is different from that of the ith to jth channel. The DTF can be defined as:

$$\gamma_{ij}^{2}(f)=\frac{\left|H_{ij}(f)\right|^{2}}{\sum_{i}^{m}\left|H_{ir}(f)\right|^{2}} \tag{5}$$

There $\sum_{i}^{m}\left|H_{ir}(f)\right|$ means the sum of the contributions from all the input electrode n = 1, …, k to the i-th electrode i. So normalized $\gamma_{ij}^{2}(f)$ may suggest an information flow from electrode j to electrode i. Its value close to 1 indicates that most of the signal in electrode j consists of signal from electrode i, values of DTF close to 0 indicate that there is no flow from electrode j to electrode i at this frequency.

To analyze the difference of information flows in the regions of our interest between sustained attention state and inattention state, normalized process was adopted before calculating DTF. According to previous research, the DTF values for shorter periods were considered to be less reliable [15, 16]. And so the 20s EEG data (5120 points) were chosen as a segment for the DTF value calculation. All the recorded data were calculated in this way. The MVAR order was set to 10 according to AIC criterion. To eliminate the influences of parameter fluctuation, the mean value within one minute was calculated for statistical analysis.

III. Results

According to the previous research, the sustained attention was mainly related to right fronto-parietal and thalamic networks, so our research focused on electrode arrays: FP2-F4, F4-FC4, CP4-F4, P4-CP4, F4-P4 and P4-P8.

For confirming the "direction" of information flow, we defined the substantial difference (DTF-diff) between DTF $(f)_{ij}$ and DTF $(f)_{ji}$ as "direction" descriptors. When DTF $(f)_{ij}$ was greater in magnitude than DTF$(f)_{ji}$, the "direction" of the information flow was from electrode j to electrode i, displayed as j→i. On the other hand, the "direction" of the information flow was from electrode i to electrode j when DTF (f)ji was greater in magnitude than DTF(f)ij . No "direction" or opposite "direction" of similar magnitude result in a lack of differences between values of DTF $(f)_{ji}$ and DTF$(f)_{ij}$. Figure 2 shows the comparison of the grand average of the DTF-diff (DTF difference in sustained attention and inattention conditions). In order to further study the change of value of DTF-diff in difference frequency between sustained attention and inattention conditions, statistical analysis of the DTF-diff values was performed by using Kolmogorov-Smirnov test for all segments of EEG data. The results of statistical analysis were illustrated in figure 3. In comparison with inattention state, the values of DTF-diff in alpha and beta band were stronger increases (P<0.005) in F4→FP2, FC4→F4 under sustained attention performance. In right fronto-parietal area, the values of DTF-diff had a convert change between inattention state and sustained attention state. This result suggested that the sustained attention caused the direction change of information flow between the right frontal area and right parietal area. The convert change in theta, beta band also appeared in parietal areas. Moreover, there was stronger decrease (P<0.05) in CP4→P4, which means the information flow from P4 to CP4 was increase.

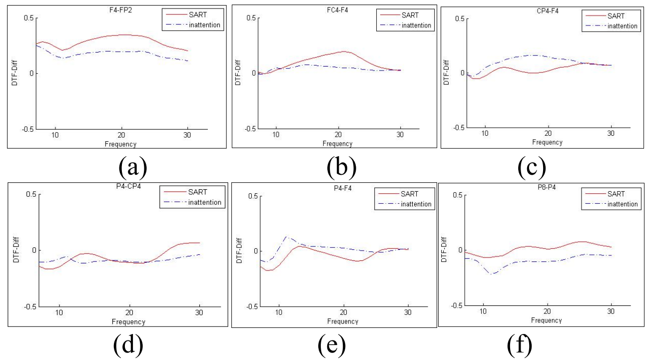

Fig.2. Grand average (N= 6) of the DTF values for the six electrode pairs. These values refer to the DTF difference between DTF $(f)_{ij}$ and DTF $(f)_{ji}$ (i.e. DTF-diff).The DTF-diff values are illustrated for the frequency bands of interest.

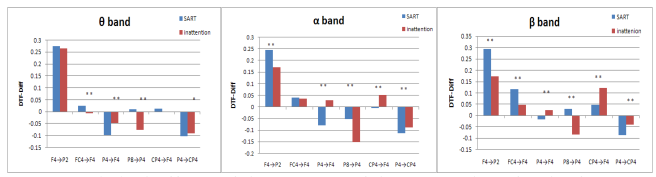

Fig.3. Statistical effects of the *K-S* test of the DTF values for the frequency bands of interest. $* P < .05$, $** P < .005$, statistical significance of difference between two states.

IV. Discussion

Theta rhythms could be characterized as an index of hippocampal–cortical interactions for mental arousal, focus attention and working memory [17]. Alpha and beta bands could be related to the neuronal mechanisms of attention and reflected the engagement of forebrain cholinergic pathways, thalamo-cortical, and cortico-cortical connectivity [18-20]. The previous DTF research showed that parietal-to-frontal functional connectivity could be an intrinsic characterization of the connection in brain function [21]. So the right frontal-to-parietal direction flow in theta, alpha and beta functional coupling could reflect the integration function of cognition expressed in fronto-parietal and hippocampal networks, which could be considered to be involved in attentive processes. The direction of information flow from parietal to frontal might reflect a bottom-up flux of sensory signals from parietal to frontal areas. Contrast to the direction of information flow from frontal to parietal might reflect a top-down flux of "control" signal. So the increase of that top-down flux could be related to enhance cognitive demands. In present study, the values of direction of information flow in right fronto-parietal area had a convert change when the condition state changed from inattention state to sustained attention state. The direction with dominant information flow in inattention condition was from right parietal areas to frontal areas, but the direction changed from frontal areas to parietal areas in sustained attention condition. This result implied that the cognitive demands in sustained attention might increase for keeping vigilance condition and working memory.

V. CONCLUSIONS

This study tried to investigate the change of global functional brain state and function coupling using surface EEG signal under sustained attention and inattention condition in a healthy population. DTF results show that the information flux within EEG functional coupling converted from "right parietal to frontal" to "frontal to right parietal" in sustained attention condition, principally at alpha and beta rhythms. These results suggest that the top-down flux of "control" signal was preponderant in comparison with the bottom-up flux of sensory signals in sustained attention and directional information flux within EEG frontal-to-parietal coupling is quite sensitive to the stage of sustained attention. So the applications of these methods make evaluation of sustained attention condition more objective and these methods are used for the research on damage of attention mechanisms of ADHD and TBI diseases.

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