33rd Annual International Conference of the IEEE EMBS
Boston, Massachusetts USA, August 30 - September 3, 2011

Cortical networks for rotational uncertainty effect in mental rotation task by partial directed coherence analysis of EEG

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Abstract— **Partial directed coherence (PDC) as a frequency-domain representation of Granger casuality (GC) could detect both strength and direction of cortical interactions by multivariate autoregressive (MVAR) model of electroencephalography (EEG). In the present study, we investigate the underlying neural networks mechanisms of "rotational uncertainty effect" during mental rotation (MR) task by PDC analysis of multichannel EEG signals before and after the visual stimuli presented, we found that (i) temporally the "rotational uncertainty effect" involved an activated network before the visual stimuli presented, which could also affect the cognitive process of MR later; (ii) the causality functional connectivity network indicated that the bi-directional frontal ⇌ parietal networks played critical roles in maintaining the readiness during the MR task. These findings suggest that functional networks of un-cued preparation before visual stimuli presented are worth to be paid more attention. And these networks provide crucial casuality information to understand the neural mechanism for "rotational uncertainty effect" in MR task.**

I. INTRODUCTION

In neuroscience studies, there has been increasing interest in investigating the functional connectivity networks that involve in different parts of human brain. These networks could provide an integrate framework of complex brain functions. Many mathematical models for EEG signals have been used to describe the cortical correlation, e.g, synchrony, coherence, correlation and etc. Among these, Granger casuality (GC) is a promising technique that provides both direction and strength of the interdependence between different cortical regions. Such causality information is important in analyzing the information flow in complex brain networks [1]. Partial directed coherence (PDC), as a representation of GC in frequency domain, has been successfully used in analyzing the cortical causal connectivity by multivariate autoregressive (MVAR) model of the multichannel EEG signals [2][3].

In this paper, we'll use PDC method to investigate the neural mechanisms for the "rotational uncertainty effect" in mental rotation (MR). MR is a cognitive process of imagining an object turning around and it is an important operation in general mental transformation and a critical ingredient in spatial intelligence. It is typically studied in the normal-mirror discrimination task with stimuli presented in different orientations, and subjects are required to decide whether an alphanumeric symbol is presented in its normal form or as a mirror image [4]. Many studies reported that response time (RT) was longer for larger angle since the stimulus image had to be mentally rotated to upright position before parity judgment and response execution [4][5]. Cognitive process of MR involves at least four sub-stages: (i) stimulus identification, (ii) mental rotation itself, (iii) parity judgement and (iv) response selection and execution [5].

Obviously, when the stimulus is upright, subjects only perform normal-mirror discrimination task without MR involved. The question arises as to whether subject's response to upright stimuli in the session that includes stimuli of different angle with normal or mirror version (i.e., SU session hereafter) is the same or not as that in the session only includes upright stimuli with normal or mirror version (i.e., AU session hereafter). Previous studies using alphanumeric characters as stimuli clearly revealed that subjects took substantially longer time to judge the upright stimulus in SU session than that in AU session, which was called "rotational uncertainty effect" [6]. Some researchers argued that subjects might take "short-cut" strategy because alphanumeric characters are massively over-learned [6][7]. Will such an uncertainty effect occur in those non-alphanumeric stimuli, e.g., Chinese characters? Furthermore, few studies so far have addressed the underlying spatiotemporal neural mechanisms for the "rotational uncertainty effect". Therefore, in this study, firstly we are going to test if there is a "rotational uncertainty effect" in the MR task for Chinese characters, and then we are going to investigate the cortical functional networks underlying such uncertainty effect by both behavior results and the PDC analysis of the multichannel EEG signals before and after the stimulus presented.

II. MATERIALS AND METHODS

A. Subjects and Stimuli

All subjects (n=15, age: 23.73 ± 2.5 yrs; male/female: 8/7) were right-handed with normal or corrected-to-normal vision and signed an informed consent before the experiments. All experimental protocols were complying with the Declaration of Helsinki. Four Chinese characters were selected as stimuli with careful consideration of the stroke amount and structures (i.e., All these Chinese characters have six strokes which is the least number of strokes for the most frequently used($all > 0.65\%$); and all these Chinese characters are in simple structure that can not be divided into components or radicals to avoid possible influence of different configurations) [8].

This work was supported by National Natural Science Foundation of China (Grant No. 60901025, 81071192), and Med-X Research Fund of Shanghai Jiao Tong University (Grant No. YG2010MS86).

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978-1-4244-4122-8/11/$26.00 ©2011 IEEE

B. Experimental procedures

We investigated “rotational uncertainty effect” during MR experiment in two sessions, i.e., AU session and SU session. In SU session, there were 96 upright stimuli (0°) (48 normal and 48 mirror) plus 288 non-upright stimuli (60°,120°,180°,240°,and 300°) randomly presented . AU session only contains 96 upright stimuli (0°) (48 normal and 48 mirrored) (Fig.1). Since we only study “rotational uncertainty effect” in this paper, only 0° trials in both sessions were analyzed hereafter. All stimuli were randomly presented in the center of a 19 in. display (Model: FP737s, BenQ, Beijing, China) with a view angle of 6.69°. The duration of each Chinese character is 1500ms. The inter-stimulus interval (ISI) was a 1000-2000ms cross symbol ”+” of the same size as stimulus.

Subjects were asked to keep minimal head and eye movements during the experiments. They responded to stimulus by pressing the left button for the normal stimulus and the right button for the mirror stimulus as quickly as possible. EEG signals were continuously recorded with Ag-AgCl electrodes with impedance below 5 $k\Omega$. Since MR had been reported to be a cognitive process at parietal, central and frontal cortex, we only recorded the signals at frontal (Fp1, Fp2, Fz, F3 and F4), central (C3, Cz and C4) and parietal (P3, Pz and P4) loci in complying with the 10-20 international EEG systems with reference to the linked earlobes. The raw EEG signals were digitized at 1 kHz with an EEG amplifier with 16 bit A/D converter (Model: UB-12FS, Symtop, Beijing, China).

C. PDC Method

RT and error rate (ER) were automatically recorded by our customized software for the stimuli at each orientation. Only trials with correct responses were used for RT and PDC analysis. Our previous study of the ERPs (event-related potentials) showed that P200 (150-300ms post-stimuli) and P300 (300-700ms post-stimuli) were the two most significant components in MR tasks (Fig.2). Thus, to study the cortical networks related to MR, we will focus on three segments of EEG in each trial, i.e., segment including baseline (SB200 hereafter, 200 ms pre-stimuli), segment including P200 component (SP200 hereafter, 150-300ms post-stimuli) and segment including P300 component (SP300 hereafter, 300-700 ms post-stimuli). Before the PDC analysis, all EEG data were preprocessed as follows: (i) EEG signals were divided into three epochs, -200-0ms pre-stimuli (SB200), 150-300ms post-stimuli (SP200) and 300-700ms post-stimuli (SP300); (ii) an artifact criterion of $\pm 100\mu V$ was employed to reject the trials with excessive electrooculogram (EOG) or other artifact activities; (iii)all segments were detrended by subtracting the mean and then normalized with their standard deviations (SD) before MVAR modeling.

To have the MVAR model of the EEG signals, we defined the M-channel ($M = 11$ in this study) EEG vector at time t as

$$X(t) = [x_1(t), x_2(t), ..., x_M(t)]^T, \tag{1}$$

where $x_q(t)(q = 1, 2, ..., M)$ stands for the q^{th} channel of EEG signals and T represents the matrix transposition. The p^{th} order MVAR model can be represented as

$$X(n) = \sum_{r=1}^{p} A_r X(n-r) + E(n), \tag{2}$$

in which $A_r(r = 1, 2, ..., p)$ denotes the $M \times M$ coefficient matrix and $E(n)$ is a white Gaussian noise vector. The coefficient $a_{qj}(r)$ in matrix A_r represents the contribution of the past j^{th} channel $x_j(n-r)$ to the current q^{th} channel $x_q(n)$. If all $a_{qj}(r)(0 < r \leq p)$ are equal or close to zero, signal x_j does not have a direct causal influence to signal x_q. The order of the MVAR model was determined by minimizing the Akaike information criterion (AIC) value. Let $\overline{A}(f)$ denote the Fourier transfer function

$$\overline{A}(f) = I - A(f) = [\overline{a}_1(f), \overline{a}_2(f), ..., \overline{a}_M(f)], \tag{3}$$

where

$$A(f) = \sum_{r=1}^{p} A(r) e^{-i2\pi f r}. \tag{4}$$

The PDC value from the j^{th} channel to the q^{th} channel at frequency f is then defined as

$$PDC_{j \to q}(f) = \left|\overline{A}_{qj}(f)\right| / \sqrt{\overline{a}_j(f)^T a_j(f)}, \tag{5}$$

where $\overline{A}_{qj}(f)$ are elements of the matrix $\overline{A}(f)$. We averaged the PDC values over the frequency band Δf of 0.05-30 Hz,

$$\overline{PDC}_{j \to q} = \sum_{f} PDC_{j \to q}(f)/\Delta f, \tag{6}$$

as the average directed interaction from the electrode j to the electrode q. We investigated the cortical interactive networks by above PDC analysis using a bootstrap re-sampling method to determine the statistical significance [3]. In each session, $N1$ trials of EEG randomly re-sampled from 80 preprocessed trials of one subject were modeled with MVAR to compute $\overline{PDC}$ for 20 times. The re-sampling size $N1$ is the minimal number to have a stable mean and SD for $\overline{PDC}$, e.g., $N1 = 45$ for our data.

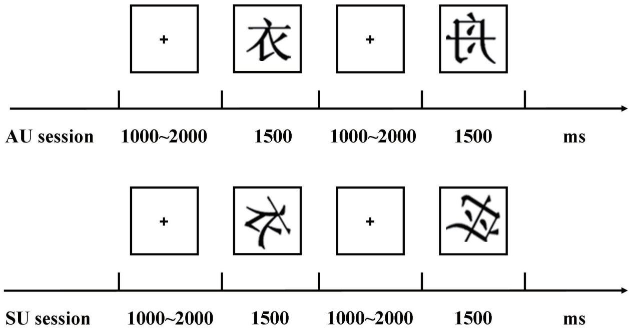

Fig. 1. Schematic diagram of experimental procedures. The first Chinese character means “clothes” and the second one means “boat”. The ISI duration was randomly selected from 1000 to 2000 ms. The visual stimulus were presented for 1500 ms. The upper one is AU session and the bottom one is SU session.

D. Statistical analysis

Analysis of variance (ANOVA) was used for statistical analysis of behavior results. For RT and ER analysis, "session (i.e., SU vs. AU)" was between-subject factor. Since "parity (normal vs. mirror)" had no effect on behavior results, data were averaged across this factor (all $Fs < 1; p > 0.05$); which is consistent with previous studies [5]. We compared $\overline{PDC}$ values (all $\overline{PDC} > 0.1$, only those $\overline{PDC}$ value larger than 0.1 were considered as causality interaction [3]) in three segments under AU session and SU session respectively by Student's t-test for all paired electrodes. All data presented as mean ± SD. Statistical significance was accepted for values of $p < 0.05$.

III. RESULTS

In ANOVA of RT, main effect of "session" ($F(1, 28) = 4.623$, $p = 0.04$) was observed (Fig.3). Under $0°$, subjects took longer time to respond to Chinese character stimuli in SU session than that in AU session, and the "rotational uncertainty effect" is about 66ms (i.e., $RT_{SU} - RT_{AU} = 66ms$), indicating that "rotational uncertainty effect" was also observed during MR with Chinese character as stimuli. ER is very low in both sessions (SU vs. AU: 10.7 ± 0.01 % vs. 6.6 ± 0.01 %) and main effect of "session" ($F(1, 28) = 0.92$, $p = 0.345$) was not observed. In order to investigate whether interactions between two different cortical regions in SU session are strengthened or suppressed compared with that in AU session, $\overline{PDC}$ ratio index (RI) between AU and SU session was calculated, i.e.,

$$RI = \overline{PDC}^{SU}_{j\to q}/\overline{PDC}^{AU}_{j\to q}, \qquad (7)$$

for all electrode pairs with $\overline{PDC} > 0.1$.

As shown in Fig.4, some interactions were clearly strengthened in SU session compared with AU session during SP200 and SP300. Student's t-test in SP200 showed that the causal interactions Fp2 → Fz, Pz → F4, Pz → P3, and P3 → F4 were strengthened significantly (all $RI > 1$, $p < 0.05$) in SU session (Fig4.b). While in SP300, it was showed that only one interaction between central and parietal cortex (C3 → P4) and two interactions within parietal cortex were strengthened significantly (Pz → P3, Pz → P4) (all $RI > 1$, $p < 0.05$) in SU session (Fig4.c). It should be noted that we didn't find a suppressed cortical connection in the SU session with uncertainty effect.

However, during the period before the stimuli, i.e., SB200, we observed more complex cortical connectivity change from AU to SU session. There were five connections significantly strengthened in SU session compared with AU session (all $RI > 1$, $p < 0.05$), including two parietal → frontal interactions (P4 → Fp2, Pz → Fz), two frontal → parietal interactions (Fp1 → Pz, F3 → P3) and one central → frontal interaction (C4 → Fz). All strengthened interactions were showed with solid lines in Fig4.a. Different from SP200 and SP300, four significant suppressed interactions were observed in SU session compared with AU session (all $RI < 1$, $p < 0.05$) before the stimulus presented, i.e., two parietal → frontal interaction (P3 → Fp2, Pz → F3), one frontal → central interaction (F3 → C3) and one parietal → central (P4 → C4). All suppressed interactions in SU sessions were showed with dash lines in Fig4.b. If we look into the casual connections within each hemisphere during SB200, we can notice that in the right hemisphere the parietal → frontal forward connections were strengthened significantly (P4 → Fp2, Pz → Fz), while such forward connections in the left counterpart (P3 → Fp2, Pz → F3) were significantly suppressed. In addition, the frontal → parietal backward connections (Fp1 → Pz, F3 → P3) were significantly strengthened during SB200. These showed a significant "hemisphere effect" during this period.

IV. DISCUSSION

In this study, we investigated the functional connectivity of "rotational uncertainty effect" during MR task using Chinese characters as stimuli by comparing responses to upright stimuli in SU session and AU session. Our results implied that the "rotational uncertainty effect" involved an activated cortical network before the stimulus presented, and in particular, the interactions between frontal and parietal cortex played special roles in such an uncertainty effect. Both sessions used the same duration and number of stimuli. And subjects were asked to follow the same instructions to respond i.e., left button for normal-version stimuli and right button for mirror-version stimuli. Our previous results showed that the RT in SU session increased with angle, indicating that subjects indeed mentally rotated the stimuli when they were non-upright (results had been published in previous paper [10]). The behavior results in this study indicated that "rotational uncertainty effect" was a common cognitive process during MR task regardless of stimulus type. Cortical interactive network analysis showed that only a few interactions between central and parietal cortex significantly changed during both SP200 and SP300. Cortical interactive networks before the visual stimulus presented showed a complex activated connections for the upright stimuli in SU session. Compared with SP200 and SP300, cortical interactions with frontal cortex were significant during SB200.

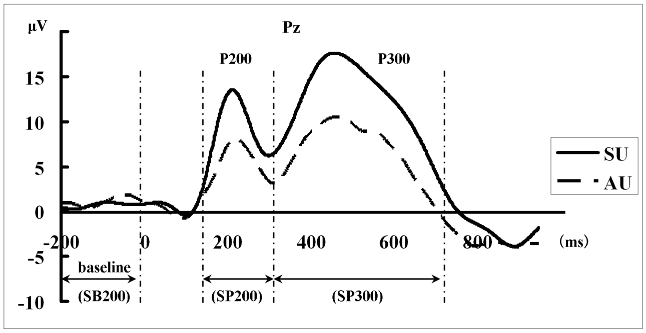

Fig. 2. ERP results of Chinese characters at parietal cortex. ERP curve in SU session were indicated by solid line and the dash line was for AU session. The two important components (P200 and P300) and baseline were marked. The three segments SB200, SP200 and SP300 are also designated for cortical connectivity analysis.

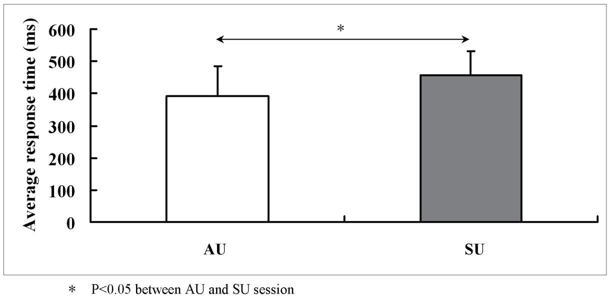

Fig. 3. Average response time for upright stimuli in AU and SU sessions. The gray column is for SU session and the white one is for AU session. Significance were indicated by "*" ($p < 0.05$).

Especially, frontal $\rightleftharpoons$ parietal interactions were significantly different for trials with uncertainty effect. Our results implied that "rotational uncertainty effect" could be tracked back to 200ms before the stimuli onset, and the frontal cortex played a critical role in such an uncertainty effect. In addition, frontal activations showed significant "hemisphere effect" during SB200.

Previous studies of MR usually used a cue before the visual stimulus so that there was a cue-induced "response preparation" before the judgment sub-stage of MR [11]. The "rotational uncertainty effect" might be associated with such a "response preparation" during which the subjects were making preparation for the MR. Therefore, the results in this study might imply that the "response preparation" also existed in an un-cued experimental paradigm. Furthermore, most papers so far have only focused on the cognitive process after the visual stimuli [12]. Our results suggested that the pre-stimuli period could also be an important cognitive stage related to the rotational uncertainty or response preparation.

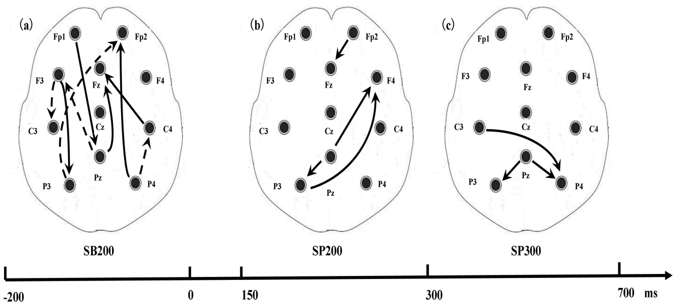

Fig. 4. Cortical neural networks corresponding to SB200, SP200 and SP300 with arrows indicating significant causality differences between AU and SU session (all $p < 0.05$). Arrows with dash line represent suppressed interactions and those with solid line represent strengthened interactions in SU session compared with AU session.

Further analysis of the cortical connectivity before the visual stimuli indicated the significant involvement of the prefrontal cortex in MR, which is consistent with the role of prefrontal cortex in cognitive preparation [13].

V. CONCLUSION

In summary, cortical network analysis with PDC method indicated that "rotational uncertainty effect" occurred most likely before stimuli presented and frontal $\rightleftharpoons$ parietal functional connectivity were critical in maintaining readiness before and during MR. It should be noted that only eleven channels of EEG signals were used to construct the cortical causal networks, further studies with higher density of EEG recordings and source analysis are needed to know more details of the roles of other cortical regions and the localized sources in the brain for cognitive process of MR. And, studies which avoid MVAR modeling and with other connectivity estimation techniques should be used in the future work to confirm the functional connectivity of MR.

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