Neuroscience Letters 461 (2009) 185–189

Contents lists available at ScienceDirect

Neuroscience Letters

journal homepage: www.elsevier.com/locate/neulet

Cortical interactive network during mental rotation of Chinese character

Hong Zhang [a], Yu Sun [a], Jing Yan [a], Jingjie Wang [b], Yihong Qiu [a], Yisheng Zhu [a], Shanbao Tong [c,*]

[a] Department of Biomedical Engineering, Shanghai Jiao Tong University, Shanghai 200240, PR China
[b] Department of Psychology, East China Normal University, Shanghai 200062, PR China
[c] Med-X Research Institute, Shanghai Jiao Tong University, Shanghai 200030, PR China

ARTICLE INFO

Article history:
Received 11 March 2009
Received in revised form 29 May 2009
Accepted 2 June 2009

Keywords:
Cortical interactive network
Mental rotation
Chinese character
EEG
Partial directed coherence

ABSTRACT

Mental rotation (MR) of Chinese characters has been proposed to employ distinct strategies depending on task difficulty. Cognitive process in MR is associated with multi-component neural networks, and elucidation of specific cortical interactions taking place during MR will assist understanding of the cognitive processes involved. In this study, we investigated cortical interactive networks involved in Chinese character MR tasks of different difficulties. Scalp electroencephalogram (EEG) signals were recorded from nine subjects (male/female = 6/3) during MR of a Chinese character presented at different orientations (0°, ±60°, ±120° and 180°). Partial directed coherence (PDC) analysis based on multivariate Granger causality (GC) was used to assess cortical interactions. At ±60° and ±120°, lateral interactions from right to left counterparts were found in both the parietal and motor-related areas, and they were enhanced with the increase of rotation angle. The main interactions between parietal and motor-related areas showed feedforward at rotations of ±60° and ±120°, while feedback interactions appeared at rotations of ±120°. However, at 180° of rotation, neither lateral interactions within motor-related areas nor feedback interactions from motor-related to parietal areas were found. These findings show that during MR of Chinese character (1) cortical interactive networks change according to task difficulty, and (2) the right hemisphere plays an initiating role in bilateral cortical activation.

Mental rotation (MR) is a well-known cognitive task requiring the generation and manipulation of two- or three-dimensional spatial imagery [6,31]. In two-dimensional MR tasks, subjects were asked to discriminate whether a character was presented as the normal or the mirror-image version [6]; and it was found that subjects needed more time to respond as the image of the character was increasingly rotated away from the standard depiction [6]. Investigations over several decades have attempted to interpret the psychophysical mechanisms underlying MR. The most significant work in this field has addressed the relationship between MR and cortical network [10], and researchers increasingly agree that distributed neural systems [10,22] are involved in MR; neuroimaging has indicated that the networks principally comprise the parietal and motor-related areas [5,11,15,20,21,25,34,35], which was also confirmed by studies with event-related potentials (ERP) [16,17]. However, few studies have addressed cortical interactive network during MR, though some reports [10,22] have proposed plausible cortical connections according to the sequential order of neural activation. Recent work has also suggested that the cortical connections involved in MR differ according to task difficulty [5,10]. Moreover, some researchers have speculated that MR of Chinese characters might employ different cognitive strategies [36] although this contention requires validation through neurophysiologic experimentation. We surmise that the analysis of cortical interactions during MR is likely to provide new insights into cognitive processing taking place during Chinese characters MR. Specifically, we sought to address whether the cortical interactive networks involved in MR are dependent on the orientation of the character presented.

Neural engineers have proposed a variety of quantitative electroencephalogram (qEEG) analysis methods to describe interactions across the cerebral cortices [12,23,26,30]. In contrast to conventional methods including cross-correlation, mutual information and coherence analysis, partial directed coherence (PDC) analysis [2] based on Granger causality (GC) [13] has been more successful in describing both the directionality and the strength of cortical interactions. In this letter, we reported on the use of a multivariate autoregressive model (MVAR) of EEG signals with PDC analysis to address the cortical interactive networks involved in Chinese character MR tasks of different difficulties.

Nine graduate volunteers from Shanghai Jiao Tong University (all right-handed; age = 23.81 ± 0.52 years; male/female = 6/3) were paid to participate in the study. They had no history of neurological diseases and reported normal or corrected-to-normal vision.

* Corresponding author. Tel.: +86 21 34205138; fax: +86 21 34204717.
E-mail address: stong@sjtu.edu.cn (S. Tong).

0304-3940/$ – see front matter © 2009 Elsevier Ireland Ltd. All rights reserved.
doi:10.1016/j.neulet.2009.06.026

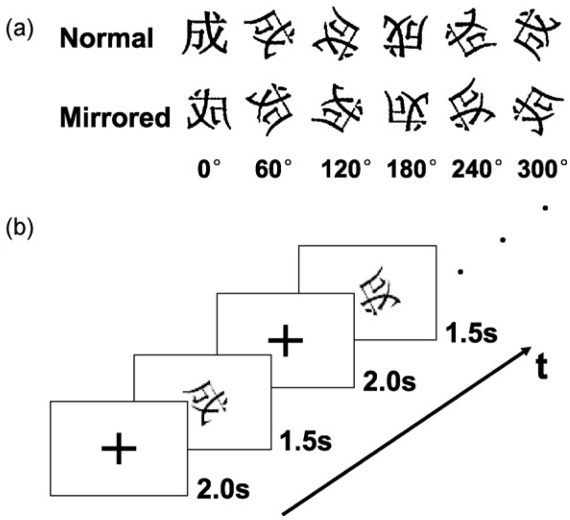

Fig. 1. The stimuli used in the study. (a) Both the Chinese character and its mirror-image copy were randomly presented at 0°, 60°, 120°, 180°, 240° and 300°. (b) Samples of stimulus sequences. The stimulus sequences in one block included 48 trials which were presented randomly. In all trials the stimulus was presented for 1.5 s followed by a cross '+' lasting for 2 s.

Written informed consent was provided by all subjects before the experiments and the protocols were approved by the local ethics committee.

The Chinese character, 成 ('complete'), was selected for the MR experiment due to its relatively simple structure and high frequency of use. Stimuli were generated by its two enantiomorphs (normal and mirror-image) at six different orientations (0°, 60°, 120°, 180°, 240°, 300°) (Fig. 1a). Each experiment included three blocks, with each normal or mirror-image stimulus being presented four times. A total of 48 stimuli in each block were randomly presented at the center of the display (Model: FP737s, BenQ, Beijing, China) in a size of 7.9 cm width by 6.2 cm height; each stimulus lasted for 1500 ms. In all trials, subjects were asked to keep their eyes fixed on a cross "+" on the display that lasted for 2000 ms prior to each stimulus (Fig. 1b). Subjects were requested to discriminate the enantiomorph type of each stimulus and respond by clicking the left (for normal) or right (for mirrored) button of the computer mouse as quickly and accurately as possible using their right hands. Ag-AgCl scalp electrodes were placed in compliance with the international 10–20 system with reference to the linked earlobes. The raw EEG recordings were digitized at 1 kHz with a 16-bit A/D converter (Model: UB-12FS, Symtop, Beijing, China).

The interval between the stimulus onset and the subject's response was termed the response time (RT). In order to ensure that the data covered the complete MR process, the EEG within the time window of the longest RT, hereafter termed the time of interest (TOI), was selected for further MAVR modeling. The majority of earlier studies have reported the involvement of parietal [5,15,20,21,25,34] and motor-related cortices [5,11,20,25,35] in MR processing, while it is notable that little involvement of the visual cortex has been reported [9,28]. We therefore focused on the cortical interactions involving the parietal (P3, P4, Pz) and motor-related (C3, C4, Cz) areas during multi-channel EEG analysis. Preprocessing of the EEG [8] included:

(1) A band-pass filter (0.5–30 Hz) was used to remove the linear noise artifacts, preserving approximately 98% of the power of the EEG [33].
(2) EEG signals were divided into epochs from 500 ms pre-stimulus to 1500 ms post-stimulus; an artifact criterion of ±100 μV was employed to reject the trials with excessive electrooculogram (EOG) activity.
(3) The EEG within each TOI was selected for MVAR modeling and further analysis.
(4) For selected epochs, EEGs within TOIs were detrended by subtracting the mean and then normalized with their standard deviations [8] before MVAR modeling and the following analysis as described below.

GC affords a robust indication of causal influences underlying neurophysiologic signals [3,4]. The most commonly used representation of GC is based on the estimation of the MVAR model for EEG signals [18], for example PDC analysis was proposed by Baccala and Sameshima in 2001 [2]. Briefly, we defined the M-channel (M = 6 in this study) EEG vector at time t as $X(t) = [X(1,t), X(2,t), \ldots, X(M,t)]^{\mathrm{T}}$, where $X(m,t)$ ($m = 1, 2, \ldots, M$) stands for the mth channel of EEG signal and T represents the matrix transposition. The pth-order MVAR model can be represented as $\sum_{r=0}^{p} A(r)X(t-r) = E(t)$, in which $A(r)$ (r = 0, 1, 2, ..., p) denotes the $M \times (p+1)$ coefficient matrix and $E(t)$ is a zero-mean un-correlate noise vector. MVAR model can be estimated from multiple realizations using the Levinson–Wiggins–Robinson (LWR) algorithm [8]. The order (p) of the MVAR model was determined by minimizing the Akaike information criterion (AIC) value [24]. Let $\bar{A}(f)$ denote the transfer function $\bar{A}(f) = I - A(f) = [\bar{a}_1(f),\ \bar{a}_2(f),\ \ldots,\ \bar{a}_M(f)]$, where $A(f) = \sum_{r=1}^{p} A(r)e^{-i2\pi fr}$. The PDC value from the jth channel to the ith at the frequency f is then defined as $PDC_{j\to i}(f) = |\bar{A}_{ij}(f)| / \sqrt{\bar{a}_j^{\mathrm{T}}(f)\bar{a}_j(f)}$, where $\bar{A}_{ij}(f)$ are elements of the matrix $\bar{A}(f)$. We averaged the PDC values over the frequency band Δf of 0.5–30 Hz [32], $\overline{PDC}_{j\to i} = \sum_f PDC_{j\to i}(f)/\Delta f$ as the average directed interaction from the electrode j to the electrode i.

We recorded EEG traces during the Chinese character MR tasks of different difficulties. It was previously reported that both clockwise and counterclockwise rotations had the same angle effect on MR [31,36]. We therefore merged the data for +60° and −60° (+300°) of rotation as well as that for +120° and −120° (+240°). Wrong-response trials were discarded and trials with a RT greater than 900 ms or less than 250 ms were regarded as outliers [36] and excluded from further analysis. The average RT was found to be prolonged as the rotation angle increased (Fig. 2); the mean RTs (mean ± SD) for 0 (the upright), ±60°, ±120° and ±180° were 378.00 ± 24.69, 418.67 ± 19.61, 528.96 ± 41.01 and 711.82 ± 92.45 ms, respectively. The error rates for 0°, ±60°, ±120° and 180° were 4.02 ± 0.59%, 4.15 ± 0.66%, 7.56 ± 1.34%, and 15.88 ± 3.45%, respectively.

Analysis of variance (ANOVA) was used to address the significance level of the change in RT; and it was indicated that the increase in RT with rotation angle was statistically significant (F = 325.561, p < 0.001). TOIs for 0°, ±60°, ±120° and 180° were 450, 500, 610 and 900 ms, respectively.

We investigated the cortical interactive networks by above PDC analysis using a bootstrap re-sampling method to determine the statistical significance [8,27]. Under each condition, N1 EEG trials randomly re-sampled from 50 preprocessed epochs across subjects were modeled with MVAR to compute $\overline{PDC}$ for 50 times. The re-sample size N1 is the minimal number to show a stable mean and SD for $\overline{PDC}$ [8], e.g. N1 = 35 for our data. We compared $\overline{PDC}$ s under MR (±60°, ±120° and 180°) with those of baseline (0°) by Student's t-test for all paired electrodes (Table 1).

Interactions with $\overline{PDC}$ significantly above the baseline (p < 0.05) were considered to represent cortical interactive networks relating to Chinese character MR. Fig. 3 illustrates the topographies of these networks, and shows the most significant (p < 0.001) interactions for MR at ±60° (Fig. 3a), ±120° (Fig. 3b) or 180° (Fig. 3c), respectively,