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Cortical functional connectivity under different auditory attentional efforts

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Abstract— **Auditory attentional effort (AAE) could be tuned to different levels in a top-down manner, while its neural correlates are still poorly understood. In this paper, we investigate the cortical connectivity under different levels of AAE. Multichannel EEG signals were recorded from nine subjects (male/female=$6/3$) in an auditory discrimination task under low or high AAE. Behavioral results showed that subjects paid more attention under high AAE and detected the probe stimuli better than low AAE. Partial directed coherence (PDC) was used to study the cortical functional connectivity within the first 300 ms post-stimulus period which includes the N100 and P200 components in the event-related potential (ERP). Majority of the cortical connections were strengthened with the increase of AAE. The right hemispheric dominance of connectivity in maintaining auditory attention was found under low AAE, which disappeared when the AAE was increased, indicating that the right hemispheric dominance previously reported might be due to a relatively lower AAE. Besides, most cortical connections under high AAE were found to be from the parietal cortex to the prefrontal cortex, which suggested the initiative role of parietal cortex in maintaining a high AAE.**

I. INTRODUCTION

Attention is not an all-or-none phenomenon, and it can be tuned to different levels in a top-down manner, which is termed as "attentional effort" [1][2][3]. Endogenous modulation of attentional effort is a robust everyday experience, such that we have to pay "more" attention to achieve a good cognitive performance in a challenging environment. Imagine you're seated in the back of a large classroom and listen to a speaker with quite a low volume, you must make more attentional effort to follow the speaker. Some reports have demonstrated that attentional effort could be modulated by task difficulty in visual modality for both humans and primates [2][3]. For example, when monkey was challenged by a more difficult visual discrimination task, its discriminative ability improved and the neural activities in V4 area responding to the stimuli became more active and selective [2]. In contrast with visual modality, attentional effort in auditory modality has received much less research interest so far, and its fundamental cognitive mechanisms and neural correlates are still poorly understood. It would be an interesting topic to study how the brain maintains the auditory attentional effort (AAE) at different levels. Or alternatively, we would ask "what is the difference of cortical functional connectivity for maintaining different levels of AAE?"

Multichannel event-related potential (ERP) studies have identified the auditory ERP components, i.e., N100 and P200, which are modulated by auditory attention [4][5]. Besides, some recent reports have suggested that top-down auditory attention involves a distinctive neural network with distributed brain areas [6][7]. Neuroengineers and neuroscientists have developed lots of methods to study the functional connectivity based on multichannel EEG signals [8]. As a successful example, partial directed coherence (PDC), a linear description of Granger causality (GC) in frequency domain [9][10], has been used widely to analyze the cortical causal interactions in the past years [11][12]. PDC provides not only the direction but also the strength of interdependence between two regions on the scalp, which is superior to other symmetric measures, e.g., correlation, coherence and phase synchronization [10][11]. In this paper, we will analyze PDC connections of EEG signals in the time window of 0-300 ms post-stimulus onset which fully includes N100 and P200 components to investigate the cortical connectivity under different levels of AAE.

II. MATERIALS AND METHODS

A. Subjects

Nine healthy subjects from Shanghai Jiao Tong University(left/right-handed=$1/8$; age=23.7 ± 3.4 years; male/female=$6/3$)were paid to participate in this study. All subjects reported normal hearing and had no history of neurological or psychiatric disorder. Each subject had given a written informed consent before the experiment. Experiment protocols were complying with Helsinki declaration.

B. Stimuli and Procedure

In order to investigate the neural correlates of maintaining different AAEs, we need to design an experiment to keep subjects at a low or high level of AAE. Most studies so far have generally thought that attentional effort was task difficulty-related such that subjects make more attentional efforts with the increase of task difficulty [1]. Nevertheless, most experimental paradigms so far could not guarantee more attentional efforts in more difficult tasks. In this paper, we designed an auditory duration (310 ms or 190 ms duration) discrimination task consisting of two sessions at different sound intensities. In the hard session, the

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intensities of most stimuli were quite low (20 dB sound press level (SPL), 80%), so that the stimuli duration was difficult to discriminate. While in the easy session, the intensities of most stimuli were quite high (60 dB SPL, 80%) and the discrimination was easy. We hypothesized that subjects would maintain a high AAE in the tasks of low SPL, but a less AAE is needed under the stimuli of high SPL. To test this hypothesis, the same probe stimuli (70 dB SPL, 20%) were randomly presented in both sessions, and the performance for the probe stimuli would be used to "measure" the AAE. We expect that subjects can discriminate the probes better in the hard session, which indicates a higher AAE in the hard session.

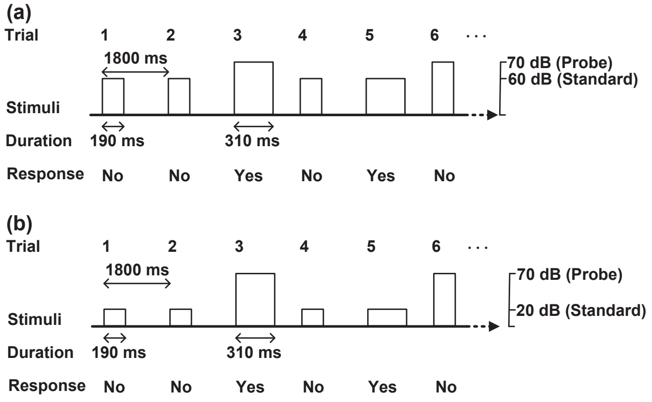

Fig. 1. Schematic diagram of the experimental procedures in (a) the easy session and (b) the hard one.

Subject was seated in a sound attenuated room ($3\times3.5m^2$, Union Brother, Beijing, China) and performed an auditory discrimination task. Each experiment has an easy session followed by a hard one. Both sessions had three blocks with 200 stimuli in each. All stimuli were 1000 Hz in frequency with 5 ms rise & fall time and the subjects were only required to respond to the targets (duration=310 ms) by pressing the left button of the mouse with the right index finger as quickly as possible while neglect the non-target ones (duration=190 ms). The stimuli onset asynchrony (SOA) was fixed at 1800 ms. Subjects were asked to keep fixation at a crosshair centered in a LCD display (Model: KLV-32J400A, Sony, Japan) throughout the experiments. In each easy block, 80% were standard stimuli with 60 dB SPL (80 targets and 80 non-targets). The rest 20% were probe stimuli with 70 dB SPL (30 targets and 10 non-targets). In each hard block, the number of probe stimuli and the ratio of the target/non-target standard stimuli were exactly the same as the easy block except that the standard stimuli were changed to 20 dB SPL instead. Fig.1 illustrates the details of experimental procedures in the easy session (Fig. 1a) and the hard one (Fig. 1b), and the details of all stimuli used in this study were listed in Table I. Each block was preceded with 20 training trails so that the subjects could get familiar with the experiment procedure and tune their attentional efforts to the relative low or high level. All kinds of stimuli (standard or probe, target or non-target) in every block were randomly presented via a loudspeaker (Model: R1600T08, Edifier, Beijing, China). There was a 3 min break between every two blocks. Each experiment lasted about 90 min, including 60 min of behavioral and EEG recording plus 30 min of preparation.

TABLE I

STIMULI IN EASY AND HARD SESSIONS.

Session	Stimuli	Intensity (dB)	Duration (ms)	Response	Percentage
Easy	Standard	60	190	No	40%
	Standard	60	310	Yes	40%
	Probe	70	190	No	5%
	Probe	70	310	Yes	15%
Hard	Standard	20	190	No	40%
	Standard	20	310	Yes	40%
	Probe	70	190	No	5%
	Probe	70	310	Yes	15%

C. EEG recording

Ag-AgCl electrodes were placed at scalp according to the international 10-20 system with reference to the linked earlobes. EEG signals were recorded throughout the course of experiment from 10 scalp channels (Fp1, Fp2, F3, F4, C3, C4, P3, P4, T3, T4). Raw EEG data was band-filtered into 0.1-60 Hz and digitized at 1000 Hz by an EEG amplifier with 16 bit A/D converter (Model: UB-12FS, Symtop, Beijing, China). Eye movements and blinks were rejected off-line by an artifact criterion of $\pm60\mu V$.

D. Data analysis

Accuracy (ACC) and reaction time (RT) to target stimuli in both easy and hard sessions were analyzed as the behavioral performances. The typical responses to the targets are within 300-1000 ms. Trials with RTs less than 300 ms or longer than 1000 ms were considered as the outliers to be excluded in the further behavioral (i.e., ACC and RT) and PDC analysis.

In PDC analysis, the EEG epochs of 0-300 ms from the target probe stimuli onset were selected to study the cortical functional connectivity. Each EEG epoch was pre-processed by subtracting the mean and then normalized with their standard deviations before multivariate autoregressive (MVAR) modeling [13]. The PDC analysis of the EEG time series can be described as follows. Given M-channel pre-processed EEG epochs at time n by a vector:

$$Y(n) = [y_1(n), \ldots, y_M(n)]^T, \qquad (1)$$

($M = 10$ in this study). Then $\{Y(n) : n = 1, \ldots, N\}$ ($N = 300$ in this study) can be suitably represented by the p^{th} order MVAR model:

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

where $\{A_r : r = 1, 2, \ldots, p\}$ are the $M \times M$ coefficient matrices to be estimated. Each element $A_r(i,j)$ reflects the linear predictability of the past value in the j^{th} channel

$y_j(n-r)$ to the present value in i^{th} channel $y_i(n)$, and $E(n)$ is a k-channel uncorrelated Gaussian white noise. The order p of the model can be estimated using the Akaike Information Criterion (AIC), and the typical value of p was 4 or 5 in this study. The coefficient matrix A_r can be estimated via Levison-Wiggins-Robinson (LWR) algorithm [14][15]. As a measure for GC in spectral domain, PDC can be derived from the Fourier transform of the coefficient matrix:

$$A(f) = I - \sum_{r=1}^{p} A_r e^{-\mathbf{i}2\pi f r}, \tag{3}$$

where I is a M-dimensional identity matrix. Specifically, PDC at frequency f from channel j to channel i is defined as [10][11]:

$$PDC_{j\rightarrow i}(f) = |A_{ij}(f)| / \sqrt{\sum_{k} |A_{kj}(f)|^2}, \tag{4}$$

In this letter, the PDC values were averaged over frequency range of 0.1-60Hz as the overall strength of the cortical connection from channel j to channel i:

$$\overline{PDC}_{j\rightarrow i} = \sum_{f} PDC_{j\rightarrow i}(f)/\Delta f, \tag{5}$$

There are several criterions for significance assessment of the calculated PDC values [10][16]. In this paper, spectral causality criterion(SCC) was used [10][12], where the electrodes pairs with mean PDC (mPDC) values greater than 0.1 were regarded as active cortical connections.

E. Statistical analysis

Paired student's t-test was used to check the statistical significance of behavioral performances and PDC values between the two sessions under different AAEs. All statistical analysis was operated with SPSS 16.0 and statistical significance was accepted for values of $p < 0.05$.

III. RESULTS

A. Behavioral performances

Subjects performed better responding to all targets of standard and probe stimuli in the easy session than in the hard one (95.7% vs. 91.9%, $p = 0.035$), which infers the task in the hard session was more difficult than that in the easy one. However, subjects were less accurate at discriminating the duration of probe stimuli in the easy session than in the hard one (90.6% vs. 94.7%, $p = 0.005$). Meanwhile, subjects spent more time responding to the probe stimuli in the easy session than in the hard one (655 ms vs. 632 ms, $p = 0.017$). This suggests that subjects should make more AAEs and detect the probe stimuli better in the hard session than that in the easy one.

B. PDC analysis

Fig. 3 illustrates the significant cortical functional connectivity (connections with mPDC values greater than 0.2 were shown) under low (Fig. 3a) and high (Fig. 3b) AAE respectively. Under low AAE in the easy session, some primary connections were found (P4→C4, P4→T4, T4→C4, P4→Fp2, F4→Fp2, Fp2→Fp1), mostly in the right hemisphere. The left hemisphere was much less activated and the inter-hemispheric communications were not prominent under low AAE. While under high AAE in the hard session, we found more cortical connections than that in low AAE, and it didn't show a hemispheric dominance of cortical connectivity. The inter-hemispheric connections under high AAE (C3→Fp2, F3→Fp2, F4→Fp1) were also enhanced compared with low AAE (Fp2→Fp1). Moreover, almost all interactions were feedforward, with several connections from parietal to frontal cortex under high AAE.

In order to illustrate the change of functional connectivity under different AAEs, Fig. 3 shows those significantly ($p < 0.05$) enhanced (Fig. 3c) or suppressed (Fig. 3d) connections with the mPDC values greater than 0.2 in either easy or hard session. Under high AAE, connections at electrode pairs (F4→Fp1, P3→Fp1, T3→Fp1, F3→Fp2, C3→ Fp2, P4→Fp2, P4→F4, P4→C4) were significantly enhanced, while only two connections (Fp2→Fp1, F4→Fp2) were significantly suppressed compared with that under low AAE.

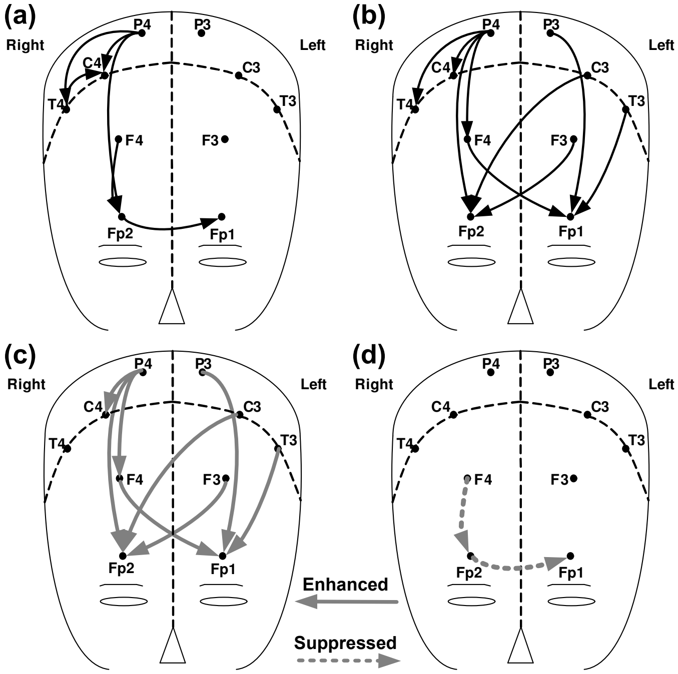

Fig. 2. Cortical functional connectivity in the aspect of PDC under different AAEs. Causal interactions with significant causality (connections with $mPDC > 0.20$ were shown) are presented under (a) low and (b) high AAE respectively. (c) and (d) illustrate the significantly ($p < 0.05$) (c) enhanced and (d) suppressed connections under high AAE compared with those under low AAE.

IV. DISCUSSION

In this study, we designed an auditory discrimination task under low and high sound intensities respectively. Behavioral results show that when the intensities of most stimuli were much smaller in the hard session, the duration discrimination task was more difficult than that in the easy session. Importantly, the probe stimuli were used as an "attention scale" to "measure" the AAEs in the two sessions, and the results show that subjects discriminated the probe stimuli better in the hard session than that in the easy one. In daily life, people mostly stay at a relative low AAE, unless facing a challenging condition in which we have to "pay more attention" to achieve good performance. In this study, we used a rather low auditory intensity (20 dB), which was just above the normal hearing threshold, to increase subjects' AAEs as much as possible. Such behavioral results suggest that the manipulation of AAEs was successful in this paper.

PDC analysis of the first 300 ms post-stimuli period showed that a distributed cortical network, including frontal, parietal and temporal regions, was involved in the auditory discrimination task, which was consistent with previous reports [6][7]. We further found that in the easy session with low AAE, the cortical connectivity was sparse and mainly located in the right hemisphere. Such a functional asymmetry infers the right hemispheric dominance under low AAE, which was consistent with many neuroimaging studies that the right hemisphere of human brain was more specialized for auditory attentional network than its left counterpart [7][17]. However, when subjects had to make more AAEs in the hard session, the cortical connectivity became more symmetrical with the increase of the connectivity in the left hemisphere. Furthermore, most existing cortical connections were significantly strengthened when more AAEs were demanded. Our results imply that the right hemispheric dominance in previous studies could be due to the relative low AAE in the tasks. In addition, the inter-hemispheric connections under high AAE are also clearly enhanced compared with that under low AAE, which suggests that the communications between two cerebral hemispheres are crucial for performing the discrimination tasks under high AAE.

In particular, we found that majority of the connections were related to the frontal and parietal cortex in both sessions, which is consistent with the previous work on the role of frontoparietal brain network in top-down attentional control of both auditory and visual modalities [1][6][18]. Furthermore, several studies have investigated the causality between frontal and parietal areas in top-down control of visual space-based attention, but the relation between these two regions still remains controversial [19][20]. In this study, we found that almost all connections were feedforward in both sessions. Specifically, under high AAE, several connections were derived from the parietal regions (i.e. P3 and P4), and targeted the frontal area (i.e., Fp1, Fp2, F3 and F4). Our results support the initiative role of parietal cortex in maintaining high AAE, rather than frontal cortex.

V. CONCLUSIONS

In conclusion, we used auditory stimuli of different SPL to keep the subjects in low or high AAE. PDC analysis of EEG shows that a large-scale cortical network, including frontal, parietal and temporal regions, is involved in maintaining the level of AAE. Our results suggest that the right hemispheric dominance in previous studies could be resulted from the low AAE, and parietal cortex plays the initiative role in maintaining high AAE.

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REFERENCES

[1] M. Sarter, W. J. Gehring, and R. Kozak, "More attention must be paid: the neurobiology of attentional effort," *Brain Res. Rev.*, vol. 51, pp. 145–160, Aug 2006.

[2] H. Spitzer, R. Desimone, and J. Moran, "Increased attention enhances both behavioral and neuronal performance," *Science*, vol. 240, pp. 338–340, Apr 1988.

[3] D. Urbach and H. Spitzer, "Attentional effort modulated by task difficulty," *Vision Res.*, vol. 35, no. 15, pp. 2169–2177, 1995.

[4] C. S. Herrmann and R. T. Knight, "Mechanisms of human attention: event-related potentials and oscillations," *Neurosci. Biobehav. Rev.*, vol. 25, pp. 465–476, Aug 2001.

[5] S. A. Hillyard, R. F. Hink, V. L. Schwent, and T. W. Picton, "Electrical signs of selective attention in the human brain," *Science*, vol. 182, pp. 177–180, Oct 1973.

[6] J. B. Fritz, M. Elhilali, S. V. David, and S. A. Shamma, "Auditory attention–focusing the searchlight on sound," *Curr. Opin. Neurobiol.*, vol. 17, pp. 437–455, Aug 2007.

[7] M. C. Stevens, V. D. Calhoun, and K. A. Kiehl, "Hemispheric differences in hemodynamics elicited by auditory oddball stimuli," *Neuroimage*, vol. 26, pp. 782–792, Jul 2005.

[8] R. E. Greenblatt, M. E. Pflieger, and A. E. Ossadtchi, "Connectivity measures applied to human brain electrophysiological data.," *J. Neurosci. Methods*, vol. 207, pp. 1–16, May 2012.

[9] C. Granger, "Investigating causal relations by econometric models and cross-spectral methods," *Econometrica*, vol. 37, no. 3, pp. 424–438, 1969.

[10] K. Sameshima and L. A. Baccalá, "Using partial directed coherence to describe neuronal ensemble interactions," *J. Neurosci. Methods*, vol. 94, pp. 93–103, Dec 1999.

[11] L. A. Baccalá and K. Sameshima, "Partial directed coherence: a new concept in neural structure determination," *Biol. Cybern.*, vol. 84, pp. 463–474, Jun 2001.

[12] Y. Sun, Y. Li, Y. Zhu, X. Chen, and S. Tong, "Electroencephalographic differences between depressed and control subjects: an aspect of interdependence analysis.," *Brain Res. Bull.*, vol. 76, pp. 559–564, Aug 2008.

[13] M. Ding, S. L. Bressler, W. Yang, and H. Liang, "Short-window spectral analysis of cortical event-related potentials by adaptive multivariate autoregressive modeling: data preprocessing, model validation, and variability assessment," *Biol. Cybern.*, vol. 83, pp. 35–45, Jul 2000.

[14] M. J. Kamiński and K. J. Blinowska, "A new method of the description of the information flow in the brain structures," *Biol. Cybern.*, vol. 65, no. 3, pp. 203–210, 1991.

[15] M. Morf, A. Vieira, D. Lee, and T. Kailath, "Recursive multichannel maximum entropy spectral estimation," *IEEE Trans. Geosci. Electron.*, vol. 16, no. 2, pp. 85–94, 1978.

[16] B. Schelter, M. Winterhalder, M. Eichler, M. Peifer, B. Hellwig, B. Guschlbauer, C. H. Lcking, R. Dahlhaus, and J. Timmer, "Testing for directed influences among neural signals using partial directed coherence.," *J. Neurosci. Methods*, vol. 152, pp. 210–219, Apr 2006.

[17] C. S. Gilmore, B. A. Clementz, and P. Berg, "Hemispheric differences in auditory oddball responses during monaural versus binaural stimulation," *Int. J. Psychophysiol.*, vol. 73, pp. 326–333, Sep 2009.

[18] M. Corbetta and G. L. Shulman, "Control of goal-directed and stimulus-driven attention in the brain," *Nat. Rev. Neurosci.*, vol. 3, pp. 201–215, Mar 2002.

[19] J. J. Green and J. J. McDonald, "Electrical neuroimaging reveals timing of attentional control activity in human brain," *PLoS Biol.*, vol. 6, no. 4, p. e81, 2008.

[20] T. Grent-'t-Jong and M. G. Woldorff, "Timing and sequence of brain activity in top-down control of visual-spatial attention," *PLoS Biol.*, vol. 5, p. e12, Jan 2007.