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Electrophysiological Neuroimaging: Cortical Correlates of Alpha Rhythm Modulation

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Abstract—**Eyes-open and eyes-closed are two widely accepted resting conditions in neuroimaging study. When alternating between the two conditions, electroencephalogram (EEG) studies have reported the modulation of alpha band (8-12 Hz) oscillation. Functional magnetic resonance imaging (fMRI) studies have found modulation of blood-oxygen-level dependent (BOLD) response. The neuronal correlates of the two modulations are not well understood. In the present study, we conducted an eyes-open-eyes-closed human experiment with simultaneous EEG and fMRI recordings. We investigated the spatial and temporal correlations between the alpha modulation and BOLD response. Besides the neural network generating the eyes-open-eyes-closed-task-induced modulation, we further examined other neural networks involved in the task. Their spatial and temporal relationship with the alpha modulation was investigated.**

I. INTRODUCTION

EEG and fMRI studies have consistently found the existence of spontaneous neural activity in awake resting states. In neuroimaging studies, eyes-open and eyes-closed are two widely accepted resting states. When alternating between these two conditions, the neural spontaneous activities change accordingly. The most significant change appears in the modulation of alpha oscillation. Posterior alpha signal increases in eyes-closed resting state, and decreases in the eyes-open resting state. This modulation of the alpha signal recorded on the scalp has been found to be correlated with BOLD fMRI temporal dynamics in cortical and subcortical regions [1]. However, the spatial and temporal correlations between the EEG cortical source of the alpha modulation and fMRI source of the BOLD change is not well understood.

In the resting brain, several brain networks have been found representing basic neural functions. These brain networks modulate spontaneously in the resting states and will be elevated or suppressed in the presence of cognitive task or external stimulation. Studying the resting state fMRI, a default network has been reported recently, which is featured with task induced suppression [2, 3]. A posterior network has also been found, which has the highest correlation with the spontaneous alpha oscillation [3]. Although it is known that the resting state networks change accordingly to cognitive task or external stimulation, the hemodynamic and electrophysiological change in these networks between the two resting states has not been well studied.

In the present study, we conducted an eyes-open-eyes-closed experiment with simultaneous EEG and fMRI recordings. We analyzed the EEG and fMRI data separately in order to answer these two questions: when alternating between the eyes-closed and eyes-open resting conditions, (1) what is the spatial and temporal relationship between the alpha modulation and the BOLD response, (2) which brain network is involved in the change between the two resting states and what is the relation between the network and the alpha modulation.

II. METHODS AND MATERIAL

A. *Experiment and data collection*

Six healthy volunteers with normal or corrected to normal vision participated in the study under the approval of the Institutional Review Board (IRB) at the University of Minnesota. Prior to the experiment, all subjects gave their written informed consent.

During the experiment, each of the subjects was cued by an aural signal or self-paced to open or close their eyes alternatively in a 3-to-4-minute period. The timings of the onsets of eyes-open and eyes-closed conditions were recorded. fMRI data and 64-channel EEG data were simultaneously recorded for four of the subjects. fMRI were recorded for the other two subjects.

The high-resolution anatomical MRI and fMRI data were acquired in a 3T MRI scanner (Siemens, TrioTim, Germany). The first two volumes of each fMRI scan were skipped for spin saturation. The EEG data were collected by a MR compatible system (BrainAmp MR 64 plus, BrainProducts, Germany) in the MR scanner. Two additional channels EOG (electrooculogram) and ECG (electrocardiogram) were added to record eyes movement and cardiac signal. The EEG signals were sampled at 5000 Hz.

B. *fMRI data analysis*

BrainVoyager QX (Brain Innovation, Netherlands) was used to analyze the MRI and fMRI data. The structural MRI images of the six subjects were rotated to an AC-PC plane and scaled into a standard Talairach coordinate. The fMRI data

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were preprocessed using slice scan time correction, motion correction, spatial smoothing (FWHM = 4) and temporal filtering. The fMRI data of each subject were then aligned and transformed to the Talairach space.

For each subject, an fMRI regreesor was calculated by convolving the individual's eyes-open-eyes-closed paradigm with a canonical hemodynamic response function (HRF). General linear model analysis was conducted to derive an fMRI map.

In order to extract brain networks involved in the task, independent component analysis (ICA) was conducted using BrainVoyager QX (Brain Innovation, Netherlands) to decompose each fMRI dataset into 30 independent components (ICs). Each IC can be represented by a time series multiplied by a spatial map. An IC spatial map reflected the distribution of a neural network, while the time series was the temporal inference of the BOLD modulation within the network [3]

C. *EEG data analysis*

For the EEG data recorded inside the MRI scanner, the gradient artifact and cardiac ballistic artifact were removed by means of template subtraction using BrainVision Analyzer (BrainVision, Germany). The EEG data were down sampled to 250 Hz, and were filtered between 1Hz and 40 Hz.

For each subject, ICA [4] was applied to the decomposition of the EEG dataset into a time-by-space representation. Spectrograms were calculated for all the IC time series. We visually inspected the spectrograms and selected those ICs featured with alpha band modulation correlating with the eye-open-eye-close protocol. From the scalp potential maps of these selected ICs, EEG source distributions were estimated. We then multiplied these source distributions with the associated IC time courses, and sum across all the selected ICs. This step finally gives a spatiotemporal imaging of the alpha modulation [5].

III. RESULTS

The ICA analysis applied to EEG data revealed six ICs (Fig. 1A) showing alpha band modulation correlated with the experimental paradigm for one representative subject [5]. In order to extract and image the alpha rhythm modulated by the task, only these components showing strong correlation between the alpha band power and the experimental paradigm were selected for the source analysis. As indicated by the temporal dynamics of ICs' alpha spectral power, the modulation of the alpha activity was correlated with the eyes-open-eyes-closed paradigm. Alpha oscillation increased in eyes-closed condition and decreased in eyes-open condition. The ICs' scalp potential maps indicate the occipital focus of the alpha activity. These IC spatial and temporal patterns were commonly observed across the subjects, thus the data from other subjects were not presented here.

After deriving the spatiotemporal imaging of the alpha modulation from these selected ICs (See Method for detail), we averaged the spatial distributions over time. This averaged cortical distribution (Fig. 1B, left) implied that the alpha modulation was mainly originated from the occipital visual area and part of the parieto-occipital cortex. The fMRI GLM analysis (Fig. 1B, right) for this subject revealed significant BOLD increase in the occipital visual area and part of the parieto-occipital cortex (eyes-open condition in contrast to the eyes-closed condition). The neural origin of the alpha modulation and BOLD response were consistent in the spatial domain. Their temporal dynamics (Fig. 1C) from the activated regions were anti-correlated with each other.

ICA analysis of the fMRI data from a single subject revealed the existence of a posterior network (Fig. 2A, orange and blue color bar) which was spatially consistent with the cortical regions modulated by the eyes-open-eyes-closed task identified in our study. The temporal dynamics of the network (Fig. 2B Yellow) was anti-correlated with the alpha modulation (Fig. 1C Pink). It also revealed the presence of another brain network (Fig. 2A, purple and brown color bar) which was spatially consistent with default-mode network previous reported by other studies [2, 3]. These two networks were spatially non-overlapped and temporally uncorrelated (Fig. 2B). Other brain networks [3] have also been found from the ICA analysis (not shown). Similar to the default-mode network, their temporal dynamics were not correlated with the experimental paradigm.

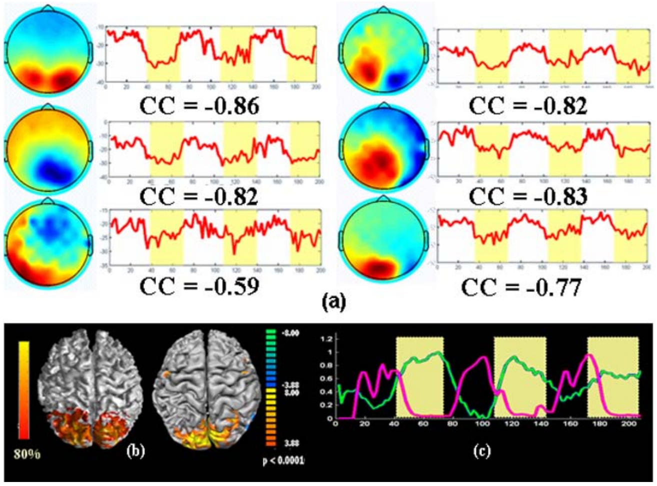

Fig 1. (a) Six ICs extracted from one subject. The left panels are the scalp potential maps and the right panels are the temporal dynamics of the alpha band spectral power. CC indicates the cross correlation between the alpha power and experimental paradigm [5] (b) Cortical distribution of the alpha modulation averaged overtime (left) in contrast to the fMRI map (right). (c) Time course of the alpha band activity convolved with a hemodyanmic response function (Pink) extracted from the regions of interest (ROIs: activated regions defined in Fig. 1B left) compared with time course of the BOLD response extracted from the ROIs (activated regions defined in Fig. 1B right).

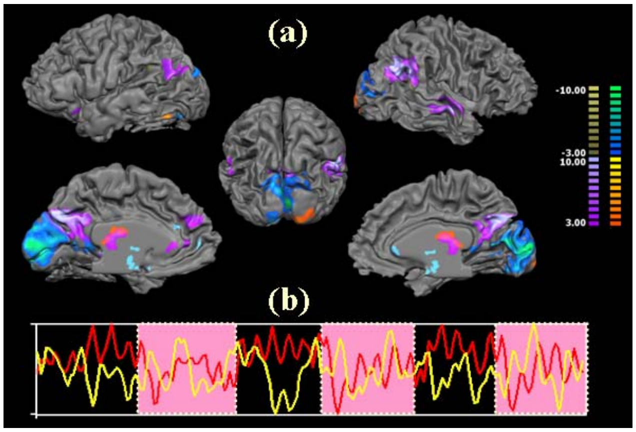

Fig 2. (a) Spatial maps of two independent components extracted from the fMRI data from a subject. (b) Time courses of the components spatially consistent with the default-mode network (yellow) in contrast to the component spatially consistent with the posterior network (red). Pink labels the eyes-open conditions.

IV. CONCLUSION AND DISCUSSION

Eyes-open and eyes-closed are two widely used baseline conditions in neuroimaging studies. In the present study, we demonstrated that the spontaneous brain activity changes across the two resting states in both electrophysiology and hemodynamics. This result implied the significance to carefully design a baseline condition in a neuroimaging study.

During the alternation between the two resting states, the cortical origins of the alpha band modulation and BOLD response are spatially consistent. Their temporal features are negatively correlated with each other. This result suggests the existence a posterior neural network which drives the modulation of spontaneous activity across different resting states. The alpha modulation and the change of BOLD response represent the different level of spontaneous activity between the two resting states.

It is important to notice that in the current study, we only imaged the spatiotemporal features of the alpha modulation correlated with the experimental paradigm. This part of the alpha activity is induced by the change between the eyes-closed and eyes-open resting states. Other background alpha signals were excluded from the analysis. This is significantly different with most other alpha source imaging studies, which image the source activity of the entire alpha band.

This posterior network drives the change of spontaneous oscillatory activity and BOLD response between two resting conditions. It is consistent spatially with one resting brain network reported by other fMRI studies [3]. Besides this posterior network, our fMRI-ICA analysis reveals that, some other brain networks also exist but modulate independently with the task. Their temporal dynamics are not correlated with the alpha modulation. This result answers the second question of the study. Only the posterior brain network is involved in the change between the eyes-closed and eyes-open resting states. This change is accompanied with the modulations of alpha oscillation and BOLD response level. Spontaneous activity of other functional neural networks is not influenced by the difference between the two resting states. Among these networks, a default-mode system has been well-known for its task-induced suppression [2]. Correlation between the hemodynamic response of this network and alpha signal has also been reported [6]. However, our results suggested that the default mode network may not respond to the change induced by the eyes-closed or eyes-open actions. And this default mode network may not necessarily correlate with all the alpha band activity.

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