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Brain Alpha Rhythm Component in fMRI and EEG

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Abstract: This paper presents a new approach to investigate spatial correlation between independent components of brain alpha activity in functional magnetic resonance imaging (fMRI) and electroencephalography (EEG). To avoid potential problems of simultaneous fMRI and EEG acquisitions in imaging pure alpha activity, data from each modality were acquired separately under a "three conditions" setup where one of the conditions involved closing eyes and relaxing, thus making it conducive to generation of alpha activity. The other two conditions -- eyes open in a lighted room or engaged in a mental arithmetic task, were designed to attenuate alpha activity. Using a Mixture Density Independent Component Analysis (MD-ICA) that incorporates flexible non-linearity functions into the conventional ICA framework, we could identify the spatiotemporal components of fMRI activations and EEG activities associated with the alpha rhythm. Then, the sources of the individual EEG alpha activity component were localized by a Maximum Entropy (ME) method that is specially designed to find the most probable dipole distribution minimizing the localization error in sense of LMSE. The resulting active dipoles were spatially transformed to 3D MRIs of the subject and compared to fMRI alpha activity maps. A good spatial correlation was found in the spatial distribution of alpha sources derived independently from fMRI and EEG, suggesting the proposed method can localize the cortical areas responsible for generating alpha activity successfully in either fMRI or EEG. Finally a functional connectivity analysis was applied to show that alpha activity sources of both modalities were also functionally connected to each other, implying that they are involved in performing a common function: "the generation of alpha rhythms".

Key words: Alpha activity, Mixture density ICA, Functional magnetic resonance imaging, Electroencephalography, Functional Connectivity

INTRODUCTION

The alpha activity of the brain is a rhythmic pattern of EEG with a characteristic frequency band of 8 to 12 Hz and occurs when the brain is relaxed. It is significantly attenuated with eyes open or mental tasks. Its activity is intermittent and involuntary. Several investigators [1-4] have used combined EEG-fMRI measurements to localize asynchronous alpha activity using conventional model-based approaches. These approaches have relied upon linear correlation analysis [5] or SPM [6] to detect the activated pixels. The temporal modulation of EEG alpha band power in concurrent EEG measurement is used to model the predictor (or reference function). It was found that 1) the fMRI signal, which represented a combination of blood oxygenation level dependent (BOLD) and in-flow effects, decreased in portions of the occipital and parietal lobes while alpha activity peaks (i.e., negative correlation). 2) a positive correlation between alpha power and the BOLD signal in occipital and mid-cingulate regions and a negative correlation in specific prefrontal and parietal regions in simultaneous EEG/fMRI data. Thus it appears that a negative correlation between alpha power and the BOLD signal is established within the parietal, temporal and certain prefrontal regions but at the present time it is unclear whether there is a positive or negative correlation in certain occipital and frontal regions.

To avoid potential problems of simultaneous fMRI and EEG acquisitions such as signal distortion due to the interference of both modalities and patient safety, the study reported here was conducted to use fMRI and EEG separately measured. A three-condition fMRI study was designed where one of the conditions involved closing eyes and relaxing and thus making it a condition likely to generate alpha activity. The other two conditions -- eyes open in a lighted room or engaged in a mental arithmetic task, were designed to attenuate alpha. Separate EEG measurements outside

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the MRI magnet were also conducted during the same three conditions.

To isolate alpha activity in both modalities, we adapted a Mixture Density Independent Component Analysis (MD-ICA) [7] that does not require any *a priori* information about unknown source density and provide more stable convergence rather than conventional ICA, especially for higher dimensional data such as fMRI and EEG. The performance of this ICA was tested successfully in separating hidden task-related activities of fMRI and EEG [7]. In the framework of MD-ICA, the sources of fMRI (or EEG) alpha activity were assumed as *spatial* (or *temporal*) components that are mutually independent of the other components. The MD-ICA directly decomposes multi-channel fMRI (or EEG) data into *spatially* (or *temporally*) independent maps. In the analysis of fMRI, the time course associated with each map is referred in order to select the alpha activity maps and the active pixels of the selected maps are considered as the possible alpha activity regions of the brain. Meanwhile, in the analysis of EEG, the alpha power magnitude of an EEG independent component is used as an index to select alpha dominant components among all candidate components. The sources of the selected components are localized using a Maximum Entropy (ME) method that finds the optimal dipole configuration (locations and net strengths) in the framework of a classical four-sphere head model. The ICA-localized fMRI and EEG source regions of alpha activity were registered into the high-spatial resolution anatomical MRI volumes in order to show the spatial correspondence between fMRI and EEG sources of alpha activity.

Finally a connectivity analysis [8] was applied to investigate if the alpha activity sources are functionally connected each other. One of the alpha activity regions commonly identified in both fMRI and EEG was used as a seed to investigate other functionally connected regions. The result showed that activated regions in both modalities were also functionally connected to each other and thus could be involved in performing a common function.

METHODS

Localization of Brain Alpha Activity in fMRI and EEG

Figure 1 shows a block-diagram of the proposed method to investigate the spatial correspondence of alpha activity sources separately measured in fMRI and EEG. Under three conditional experimental set-ups [7] that are specially designed to modulate alpha activity inside the MRI scanner, a normal volunteer was scanned. EEG data were obtained outside the magnet after the fMRI experiment using an international standard 10-20 EEG system. To isolate spatially or temporally independent alpha activity components from the measured fMRI and EEG data, we used the MD-ICA that employs flexible non-linearity function to minimize the separation errors due to the mismatch of the non-linearity functions to unknown source density functions.

In the framework of the MD-ICA, each image in the time series of fMRI is assumed to be a linear mixture of unknown *temporally* fixed and *spatially* independent components that contain either several neuronal activation or artifacts such as head movement, breathing and machine noise. Under this assumption, the MD-ICA directly decomposes fMRI data into the temporally fixed and spatially independent components which have their own time courses (temporally fixed) and active pixels (spatially independent). These components are categorized into "alpha activity-related components" or "artifact-related components by examining their associated time courses. The spatially independent components whose time courses are correlated with the reference function of alpha activity [7] are considered as "alpha activity maps". In these maps, the active pixels whose values are higher than a given threshold are selected as the regions of alpha activity in fMRI and then rendered to high resolution MRIs via multi-modal registration algorithm [9]. Also some pixels of the active pixels were selected as the seed pixels for functional connectivity analysis and then used to find other pixels that are functional connected.

Meanwhile in the application of the MD-ICA to EEG, spatio-temporal EEG data are considered as a linear mixture of *spatially* fixed and *temporally* independent components such as alpha activity, 60Hz power noise, and physiological artifacts including eye blink noise and cardiac pulsation. Under this assumption, the MD-ICA decomposes the EEG data into the spatially fixed and temporally independent components which have their own spatial distributions (spatially fixed) and temporal profiles (temporally independent). These components also are categorized into "alpha activity-related components" and "artifact-related components" by observing their temporal profiles. To identify which components are related with the alpha activity, the alpha-band power of each component is used as an index. The components having higher powers are determined as "alpha activity dominant components".

To localize the sources of the alpha activity dominant components, we applied the ME method that formulates the forward problem: "estimate the scalp potentials at the fixed electrode-locations" in the classical four sphere head model and solves the inverse problem: "find the most probable dipole distributions to minimize the errors between the measures and estimates of the scalp potential" in the sense of maximum entropy. The optimal dipole distribution of each alpha activity dominant component is estimated separately. In each estimated distribution, the active dipoles whose net strengths are higher than a give threshold are determined as the sources of the alpha activity in EEG data. To investigate the spatial

correlation between the active pixels of fMRI maps and the active dipoles of EEG components, the active dipoles (defined in the head model) and active pixels (defined in the fMRI) are registered to the high resolution MRIs using multi-modal registration method [9] and landmark registration method [10].

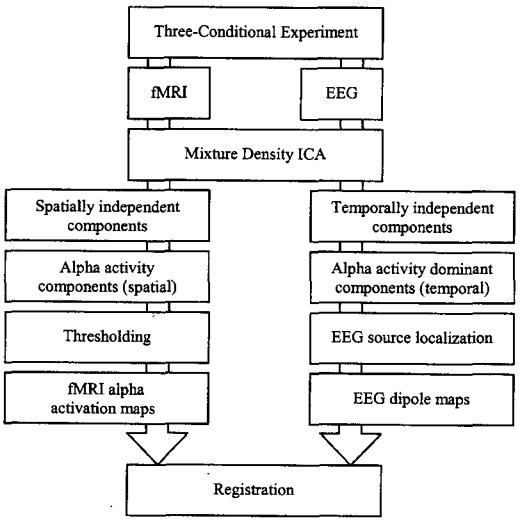

Fig. 1. Block-diagram of the proposed method to localize brain alpha activity in fMRI and EEG.

Source Localization of EEG Independent Component

To localize the EEG sources of the alpha activity dominant components, we combine the MD-ICA with the distributed source imaging approach in the frequency domain. As shown in Fig. 2, the *N*-temporally independent components, $\mathbf{u}_j$ j = 1, 2,..., N, were isolated from *N*-electrodes EEG data, $\mathbf{x}_i$ i =1, 2,..., N, using the MD-ICA. The alpha band power of each $\mathbf{u}_j$ is used to screen alpha dominant components, $\mathbf{u}_k$ k=1,2,..,K where K is total number of the alpha dominant components selected among all N-$\mathbf{u}_j$.

Each $\mathbf{u}_k$ is projected back to the spatio-temporal domain in order to reconstruct the EEG data, $\tilde{\mathbf{x}}_i$, i =1, 2,..., N, containing only a specific alpha component $\mathbf{u}_k$. The DFT coefficient of each $\tilde{\mathbf{x}}_i$ at the alpha frequency f_a, $\hat{X}(f_a)$ consists of one point in the cosine-sine diagram of the FFT dipole approximation method. The least square fitting of all N-points is then applied to estimate the scalp potentials, $\mathbf{v}_i$ i =1, 2,..., N, where the center of all N-points is first determined and then the distance of each point from the center, $\mathbf{v}_i$ is modeled as the scalp potential at the i^{th} electrode due to a given $\mathbf{u}_k$. Finally the net dipole distribution, $[\bar{q}_1\ \bar{q}_2\ \ldots\ \bar{q}_L]$ where L represents total number of unit-dipole voxels in the brain sphere of the classical four-sphere head model, is numerically estimated from the framework of inverse problem. The active dipoles, $\bar{q}_l$ are identified by applying certain threshold to the value of each element in the L-net dipole strength vector of $[\bar{q}_1\ \bar{q}_2\ \ldots\ \bar{q}_L]$. The map of these dipoles is interpreted as the localization map of a given $\mathbf{u}_k$ in the brain.

Above localization procedure repeats for other alpha dominant components. The composition of individual alpha maps shows all possible regions of the alpha activity. The details of above EEG localization method were well described in our previous literatures [7], [10], [11].

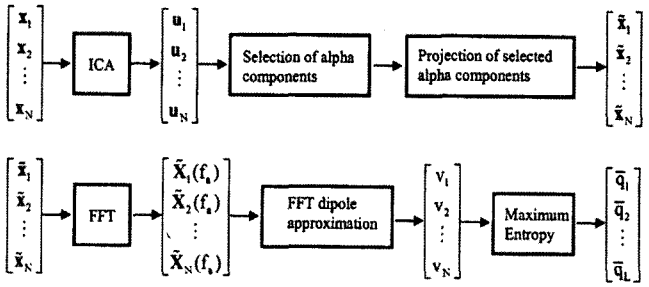

Fig. 2. Localization of an individual alpha dominant component using the ME method.

Functional Connectivity between fMRI Alpha Activity Sources

A rapid development of the functional modalities has made it possible to analyze functional connectivity in the distributed brain system. Generally functional connectivity is defined as "*temporal correlation of a neurophysiological index measured in spatially remote regions* ". This correlation of the measured signals underlies the communication between the local regions of brain involved in a specific brain response.

The first study of functional connectivity using fMRI [8] was presented by B. Biswal et al. They discovered that in the resting state, the ipsi or bilateral motor cortexes generate synchronized physiological fluctuations (coupling of blood oxygenation or flow) which characterize the low frequency fluctuations (< 0.1 Hz) in the time courses of EPI time-series images acquired at 1.5 Tesla. By applying the low-pass filter (cutoff frequency = 0.08 Hz) to the resting state time courses, they recovered the low frequency fluctuations, and found pixels whose filtered time courses were correlated with one of the reference pixel in the motor cortex. According to their resting fMRI studies at TR = 250msec, about 65 percent of pixels shared the correlated low frequency fluctuations in bilateral motor and approximately 85 percent of pixels in ipsi-lateral motor cortices. These pixels showed a good agreement with pixels which were identified as the motor areas in

a hand movement study. This agreement supports the usefulness of functional connectivity in the detection of the distributed regions involved in a specific function.

In this paper we first introduce the functional connectivity to confirm the spatial correspondence of two different alpha activity sources obtained from both fMRI and EEG (i.e., hemodynamic response in fMRI versus electric activity in EEG). The resting state fMRI data are acquired from the identical subject whom we had studied to localize alpha activity in three conditional experiment, and processed using the connectivity method proposed in [8]. The seed pixel for the connectivity analysis is selected from one of the activated regions obtained from three conditional experiment, and the FIR-filtered time course of the seed pixel in the resting state (i.e., cut-off frequency = 0.1 Hz) is used as the reference function to identify other pixels whose filtered time courses are correlated with the reference function. The identified pixels are considered as the connectivity map of the alpha activity in the resting state, and then compared with the results of three conditional fMRI and EEG localizations.

DATA ACQUSITION

fMRI Study

Within an IRB-approved protocol, five normal human volunteers were imaged on a 1.5T GE SIGNA scanner (Horizon) using an EPI sequence with TE = 45 msec, TR = 4 sec, angle = 90°, FOV = 24 cm x 24 cm, 4 oblique slices, 10 mm thickness, 64 x 64 matrix size, 125 images per slice.

To modulate alpha activity, we designed a blocked ON-OFF protocol with three conditions, namely (a) "Relaxation" (ON), (b) "Mathematical task" (OFF), and (c) "Eyes-open" (OFF).

During Relaxation, the subjects were asked to relax, which increases alpha activity. In the Mathematical task, the subjects performed silently a pre-assigned arithmetic task such as multiplication and division, which breaks the mental relaxation to decrease alpha activity. Also, during the Eyes-open portion, we turned on the room light and asked the subjects to open their eyes in order to suppress alpha activity, as well as to differentiate it from the visual activity in the occipital lobe. The duration of each block was set to 54 seconds. This cycle was repeated three times in a random order, Relation - Eyes-open - Mathematical task - Eyes-open - Mathematical task - Relaxation - Mathematical task - Relaxation - Eyes-open. The first five images were discarded due to the instability of images at the initial phase. The time misalignment due to the acquisition delay between neighbor slices was corrected using three point filter based on a Hanning window. Slice time-corrected volumes in the series were performed. For each time course, linear detrending and high-pass filtering using DCT decomposition were applied to remove the baseline drifting and physiological artifacts, and to retain the frequency components higher than the half of experimental periods.

For the study of functional connectivity the subjects were imaged on a 1.5T GE scanner using an EPI sequence with TR = 1.2 sec, TE = 45 msec, flip angle = 90° and FOV = 24 cm x 24 cm, 64 x 128 matrix size. During the acquisition the subject was in the resting state and instructed to refrain from any cognitive, language, imaging visual and motor task as much as possible. Pre-processing such as the registration and slice timing correction is applied to correct the movement artifacts and temporal mis-alignment between neighbor slices in the EPI series.

EEG Study

The 10-20 EEG system with 19 electrode cap was used to measure the scalp potentials of the subject under the condition in which a subject closed eyes and stayed relaxed in the dark room. Also we measured the potential when the subject opened her eyes and performed mathematical tasks in order to validate the modulation of alpha power in the system. The 60 epochs were acquired in both conditions respectively. The electrode impedances were kept below 25 KΩ. Sampling frequency was set at 256 Hz. The signals were amplified by a gain of 64 K and low-pass filtered at 30 Hz.

RESULTS AND DISCUSSION

Localization of Alpha Activity using fMRI and Functional Connectivity

Figure 3 shows two spatially independent alpha maps superimposed on anatomical MRIs and their associated time courses. The elements of each map were scaled and thresholded at $p = 0.01$. As we can see in Fig. 3 (a), most activated pixels were localized in the precuneus gyrus, right and left angular gyrus in occipital and parietal lobe and they match the suggested areas responsible for alpha activity in previous EEG studies [1], [11]. Also the frontal activation around cingulate gyrus shown in Fig. 3 (c) is in accordance with the results of increased frontal alpha activity measured in EEG during relaxation [11]. Interestingly, major activations of two different ICA component maps showed different time courses plotted in Fig. 3 (b) and (d), respectively. This observation suggests that the occipito-frontal activations may be involved in generating different phased alpha activities. In both areas, we observed a positive correlation of BOLD signals with the increase of alpha activity during relation (i.e., compare the solid and dashed lines in Fig. 3 (b) or (d), which indicate the BOLD times courses of

the activations and the relaxation period in the experimental protocol, respectively).

Furthermore these two areas were also functionally connected each other as shown in Fig. 3 (e). For instance, the right angular gyrus (seed region) in the third slice is connected with the precuneus gyrus, the left angular gyrus and middle frontal gyrus in the first and second slices, which were consistent with two alpha maps of Fig. 3 (a) and (c).

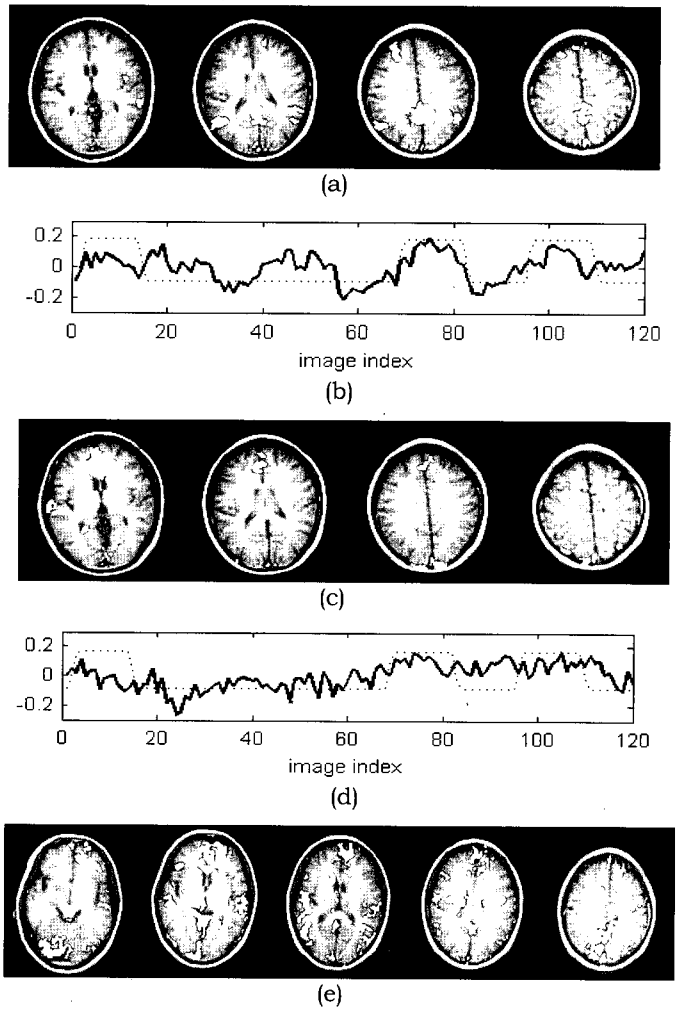

Fig. 3. Two spatially independent maps with associated time courses highly correlated with experimental paradigm showing increased alpha activity (the first subject). (a) 9th map thresholded at $p = 0.01$. (b) Time course associated with (a) and experimental protocol of relaxation, cc = 0.48. (c) 4th map thresholded at $p = 0.01$. (d) Time course associated with (c) and experimental protocol of relaxation, cc = 0.42. (e) Functional connectivity map at $p = 0.001$.

Two spatially independent maps of the second subject were shown in Fig. 4. The identical threshold setting was applied to process the fMRI data of this subject. We found the activations in the frontal, parietal, and occipital lobes that are consistent with the findings from the first subject. Also the time course associated with each components shows a good correlation with the reference function (i.e., cc = 0.47 for the first map and cc = 0.43 for the second map). As shown in Fig. 4 (e), main activations near frontal and occipito-parietal lobes were functionally connected to generate the alpha activity. In all five subjects, we observed coherent fMRI activations in the frontal and occipito-parietal lobes during three conditional experiment as well as their connectivity in the resting state, indicating that these activations are responsible for the generation of alpha activity during the relaxation.

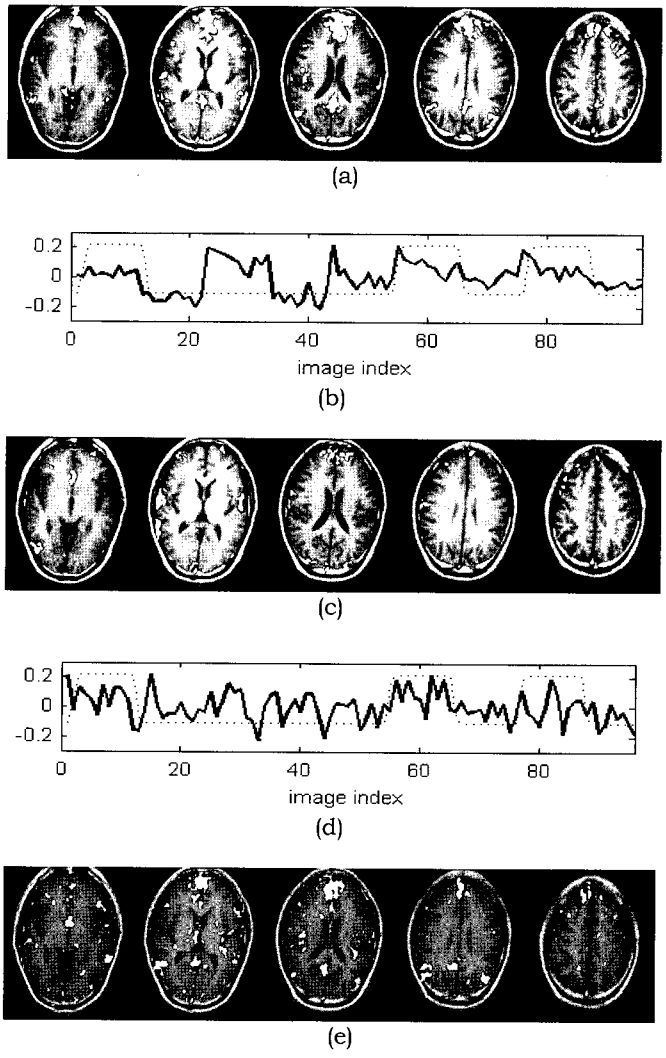

Fig. 4. Two spatially independent maps with associated time courses highly correlated with experimental paradigm showing increased alpha activity (the second subject). (a) 16th map thresholded at $p = 0.01$ (b) Time course associated with (a) and experimental protocol of relaxation, cc = 0.47. (c) 60th map thresholded at $p = 0.01$. (d) Time course associated with (c) and experimental protocol of relaxation, cc = 0.43. (e) Functional connectivity map at $p = 0.001$.

Localization of Alpha Activity using EEG

Figure 5 (a) shows four seconds EEG segment, $\mathbf{x}_i(t)$ i =1, 2,..., 19 of the first subject. Obviously, intermittent alpha bursts were measured in the EEG acquired at the parieto-occipital lobe such as P3 ($\mathbf{x}_3(t)$), P4($\mathbf{x}_{15}(t)$), O1($\mathbf{x}_{14}(t)$), and O2($\mathbf{x}_{16}(t)$). The 19 independent components by the MD-ICA, $\mathbf{u}_j(t)$ j = 1, 2,..., 19, were shown in each row of Fig. 5 (b). As we can see, the cardiac pulsation and 60 Hz background noise are obviously isolated in $\mathbf{u}_{16}(t)$ and $\mathbf{u}_{13}(t)$ respectively. Four different components, $\mathbf{u}_3(t)$, $\mathbf{u}_7(t)$, $\mathbf{u}_{12}(t)$, and $\mathbf{u}_{19}(t)$ were identified as alpha dominant components since they showed the highest alpha band powers.

To investigate the spatial distribution of the alpha band powers due to an individual $\mathbf{u}_k(t)$, each $\mathbf{u}_k(t)$ was projected to reconstruct $\tilde{\mathbf{x}}_i$ i = 1, 2,..., 19. The power sum of $\tilde{\mathbf{x}}_i$ from 8 MHz to 12 MHz was calculated and then displayed in 2D topographies where black dots indicate the locations of the electrodes and bright color represents high alpha band power. The alpha power sum due to $\mathbf{u}_3(t)$, $\mathbf{u}_7(t)$, $\mathbf{u}_{12}(t)$, and $\mathbf{u}_{19}(t)$ were shown in the left to right subplots of Fig. 6 (a), respectively.

It is clear that the alpha power of each $\mathbf{u}_k(t)$ is highly concentrated in the electrodes of parietal, occipital, and frontal lobe that correspond to the fMRI activations shown in Fig. 3.

Also we could observe identical localizations of high alpha band powers in the second subject as shown in Fig. 6 (b).

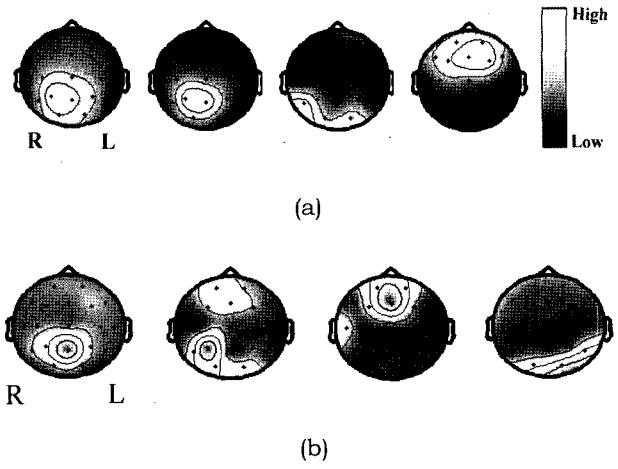

Fig. 6. ICA based topographies from four alpha dominant components. (a) The first subject. (b) The second subject

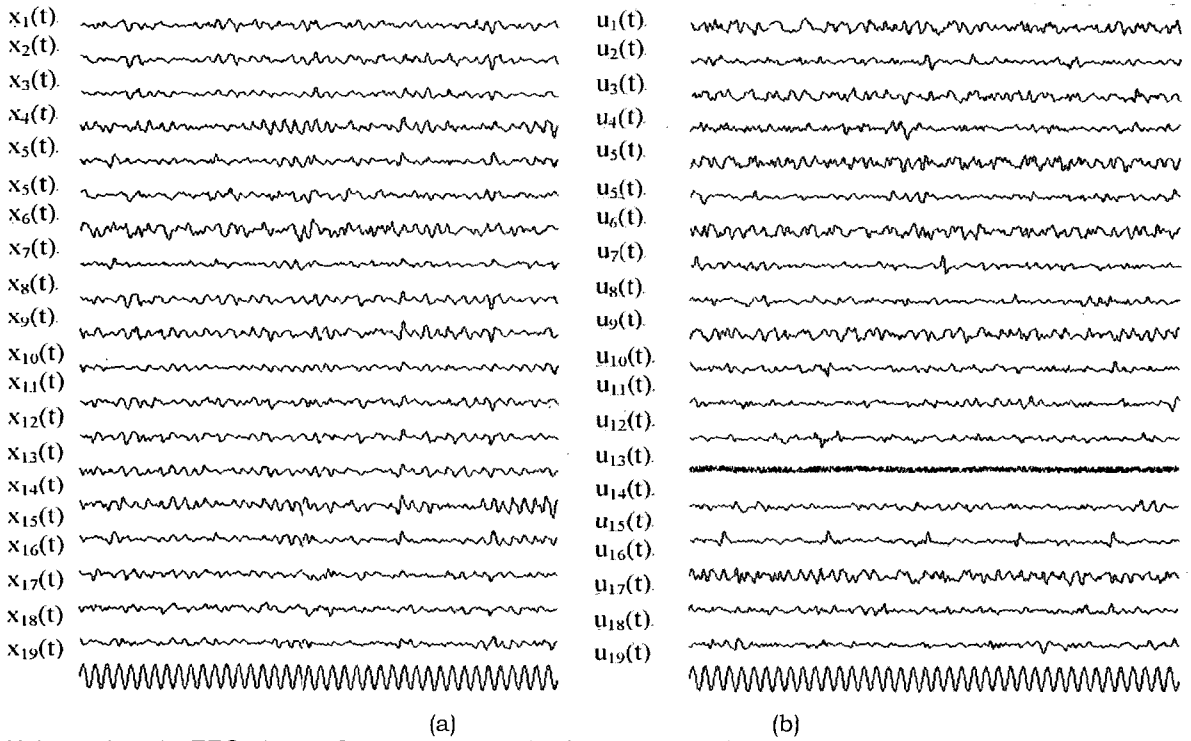

Fig. 5. Alpha activity in EEG. (a) EEG segment with the highest alpha band power. Each row shows four seconds EEG measurement at each electrode. The bottom plot represents 10Hz sinusoids mimicking alpha rhythms. (b) Temporally independent components separated from (a). Each row represents the temporally independent components estimated by the MD-ICA.

Figure 7 shows an example to show the source localization of a single alpha dominant component using the ME method. An alpha activity dominant component with the highest alpha power and its spatial power distribution were shown in Fig. 7 (a) and (b), respectively. The dipole locations of Fig. 7 (a) using the ME method are shown in Fig. 7 (c) where we sampled the brain sphere at $1cm^3$ voxels (i.e., L = 2080). Most active dipoles were found in the occipital-parietal lobes and frontal lobe, showing good agreement with the EEG topographies shown in Fig. 7 (b). Also, these localizations are in good agreement with the previous EEG study [11] showing that at least four alpha activity components near central posterior alpha, left frontocentral alpha, lateral posterior alpha, and right central alpha) contribute to the alpha rhythms.

Other three independent components were selected as the alpha dominant components from an identical subject and then localized by the same ME method where the threshold of the net dipole strength was applied at p = 0.001 for all four components.

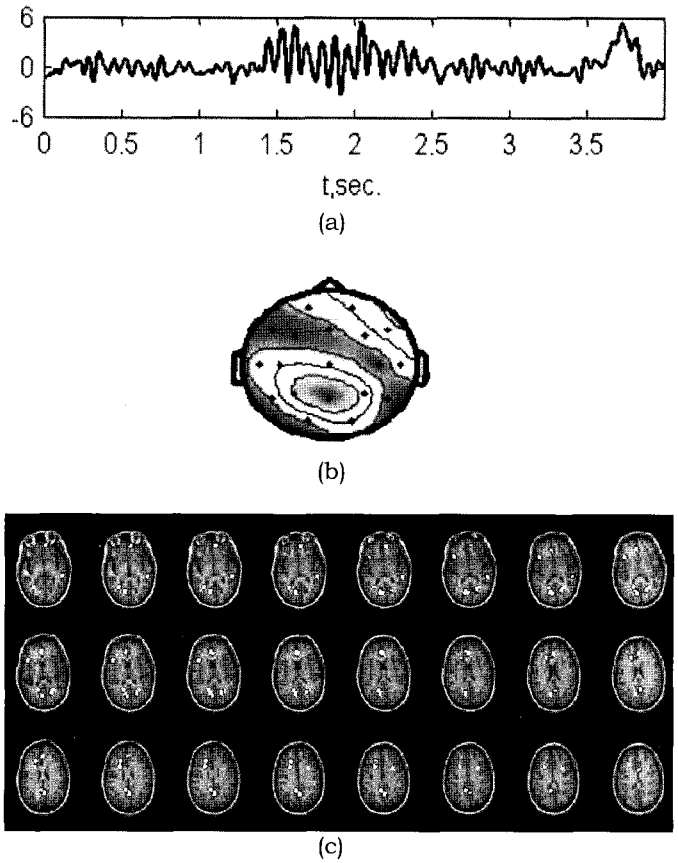

Fig. 7. Source localization of a single alpha activity dominant component (the first subject). (a) Identified alpha activity dominant component. (b) Spatial distribution of alpha power of (a). (c) Reconstructed dipole sources of (a) using the ME localization, p = 0.001.

Figure 8 (a) shows the net dipole distributions reconstructed from total four alpha dominant components. Active dipoles of Fig. 8 (a) were shown in Fig. 8 (b) where the x axis defines the posterior (-) to anterior (+) and the y axis defines the left (-) and right (+) hemisphere of the brain sphere in classical four-sphere head model. Most dipoles in the posterior and frontal region were identified. The locations of these active dipoles were rendered in the subject's MRI via the registration. It is clear that active dipoles from each alpha dominant component were sparsely distributed in different regions of the brain like the precuneus gyrus of the middle occipito-parietal lobe, the cingulated gyrus, and middle frontal gyrus of the frontal lobe which have been known as the possible regions of the alpha activity [1-3].

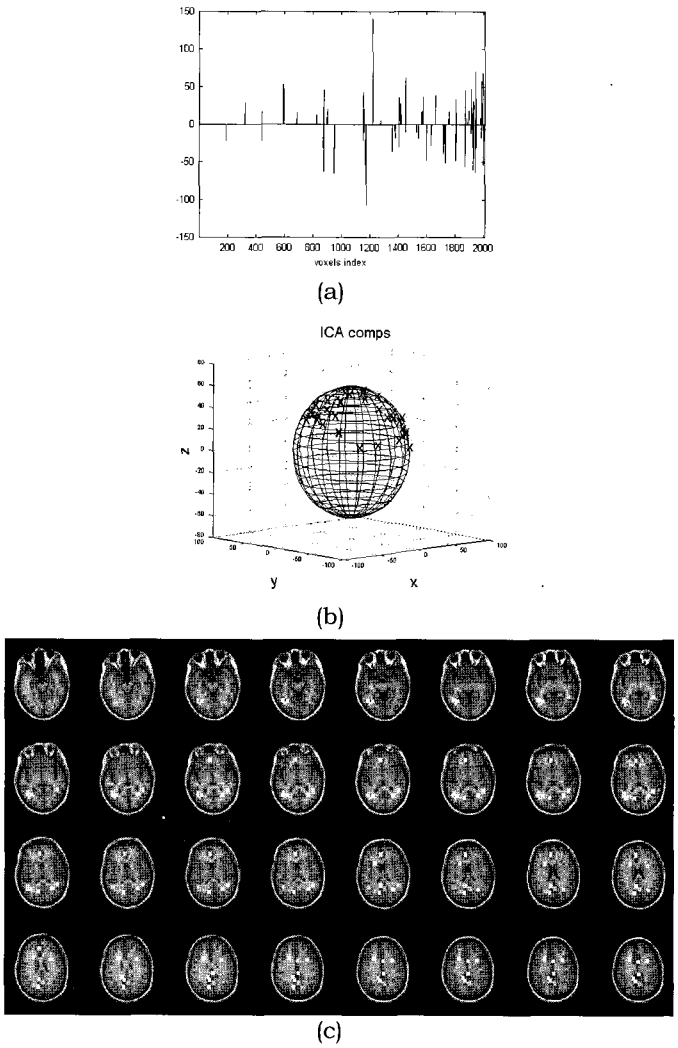

Fig. 8. Results of the EEG source localization using the ME method (the first subject) (a) Net dipole strengths of all four alpha dominant components. (b) The locations of active dipoles in the brain sphere, p = 0.001. (c) The locations of active dipoles in the subject's MRI.

Figure 9 shows the comparison of the active dipoles with the fMRI activations. Active dipoles were identified from three different EEG segments. Active EEG dipoles were denoted as white box and the activations in fMRI colored as black. We observed that active dipoles were sparsely distributed in different regions such as near the angular gyrus of the parietal lobe, the precuneus gyrus of the middle occipital lobe, the cingulated gyrus, and middle frontal gyrus of the frontal lobe. Active dipoles around angular gyrus were distant 1-3 cm from the activations which fMRI identified as the alpha activity. This localization error may be caused by both poor sampling of scalp potentials (due to small numbers of electrodes) and unrealistic head model used for the forward problem (sphere head model). However, active dipoles in the precuneus gyrus, cingulated gyrus, and middle frontal gyrus were exactly overlapped with the fMRI activations. Especially using the MD-ICA as the pre-processing step for the ME method, we could find active dipoles in the cingulated gyrus and middle frontal gyrus which have a good agreement with the fMRI activation. It supports the usefulness of the MD-ICA in the EEG localization problem.

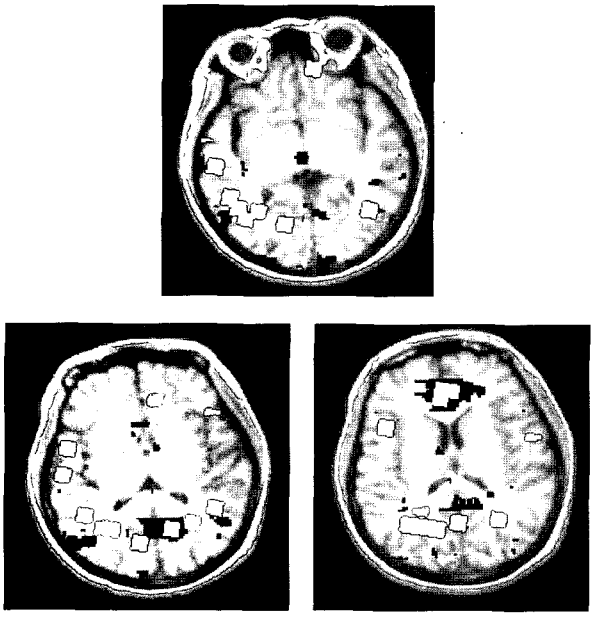

Fig. 9. Reconstructed dipole sources of the first subject in overall EEG segments(white) and activation in fMRI (black). EEG localization was performed on overall segments with the alpha power higher than averaged power during the closed eye and relaxed state. Maximum entropy with ICA was used to construct the histogram of reconstructed dipole distributions.

CONCLUSION

We used the MD-ICA to isolate alpha activity related components from the separately measured fMRI and EEG data. It was found that the MD-ICA could separate the sources of alpha activity modulated by the experimental paradigms successfully. Through co-registration, we observed that the ICA-detected alpha activity maps of fMRI are spatially correlated with the ICA-detected alpha activity dipole maps of EEG and also functionally connected each other, suggesting the usefulness of the proposed localization approach in analyzing spatio-temporal data like fMRI and EEG.

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