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Constrained Independent Component Analysis Based Extraction and Mapping of the Brain Alpha Activity in EEG

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Abstract

In order to extract only the alpha activity related signals from EEG recordings, we have applied Constrained Independent Component Analysis (cICA), a new extension of ICA in which some *a priori* knowledge of the alpha activity is utilized to extract only desired components. Its extraction (or filtering) performance has been compared to that of the conventional band-pass filtering via the scalp alpha power maps and cortical source maps of the alpha activity. Our results demonstrate that the alpha power maps and cortical source maps from the cICA-extracted alpha signals reveal more focalized alpha generating regions of the brain than those from the band-pass filtered alpha EEG signals. Furthermore they match more closely the activated regions of the brain mapped using fMRI, validating our results. We believe that the cICA-based filtering approach of EEG signals is a more effective means of extracting a specific brain activity reflected in EEG signals that will result in more accurate source localization or imaging maps.

Key words: EEG, Alpha Activity, Band-pass Filtering, Constrained Independent Component Analysis, fMRI

I. INTRODUCTION

Ever since researchers measured the electrical activity of the brain using Electroencephalogram (EEG), numerous attempts have been made to elucidate the generators of the brain activities. Among the brain activities, the alpha activity (or alpha rhythm) of the brain is defined as the oscillations of electric potentials within an 8 to 12 Hz range: normally recorded as sinusoidal waves with larger amplitudes over posterior regions and present in roughly 95% of healthy adults especially during their eyes closed. There have been numerous studies to find the generators of this alpha activity of the brain using EEG, functional magnetic resonance imaging (fMRI), and simultaneous EEG-fMRI techniques [1-6].

In the conventional approaches of examining the generators or sources of the alpha activity, linear bandpass filtering is typically employed in extraction mainly due to the frequency content of the alpha rhythms (i.e., 8~12Hz), followed by source localization via solving the inverse problems of EEG to get the source maps [7, 8]. However, since the validation of the localized sources in EEG is a generally difficult task, fMRI is usually performed in companion to EEG experiments. Recently, due to the availability of EEG systems that can be operated inside MRI, simultaneous EEG and fMRI experiments have been carried out [3, 5].

Apart from these common approaches, a novel method had been also developed where statistically independent sources for the alpha activities are sought by an algorithm called mixture density independent component analysis (ICA) [2]. Since the brain waves is a mixture of various electrical activities of the brain processes, if we assume the alpha wave is one of sources contributing to the mixture linearly, ICA can separate the alpha wave from the rest of the brain waves. We could also expect improved EEG source localization or imaging since we only deals with the alpha wave only. In fact, our previous study reported better match of the localized alpha sources to the activated regions of fMRI by preprocessing EEG data with ICA [2]. This result indicates that proper preprocessing of EEG data helps source localization or

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imaging greatly. One of disadvantages of ICA is the manual selection of ICs, which represent alpha activities, by examining the entire ICs.

Recently, an extension of this approach has been made where some constraints are used to extract only the desired sources of the signals. This method, known as constrained ICA (cICA), can be effective in a sense that only the desired components can be extracted up on the availability of some prior information of the desired signals [9]. An example of this approach can be found in [10], where only ballistocardiogram artifacts are extracted from EEG signals recorded inside MRI and removed.

In this study as an extension of our previous work in [2], we have attempted to extract only the alpha activity-related signals from EEG recordings using cICA. The performance of cICA extraction of the alpha rhythms from EEG data has been compared to that of the conventional band-pass filtering. Then the alpha power maps are reconstructed to compare the identified focal regions of the brain responsible for alpha activity. To analyze the results further, the cortical source maps are reconstructed via distributed source imaging and compared to the results from the band-pass filtered alpha signals. To validate the cortical source maps, we have also performed fMRI independently with the same alpha modulation protocols to find the activated regions of the brain. Our results clearly show that the localized sources from the cICA extracted alpha signals better match the alpha activated regions of fMRI, thus indicating that cICA can extract the alpha rhythms from EEG recordings more effectively than the conventional band-pass filter approaches. We believe that the cICA-based signal extraction is a more effective approach as a pre-processing tool toward more accurate EEG source localization or mapping.

II. METHODS

A. Experimental Protocols for Alpha Activity Modulation

A well-established protocol for alpha activity modulation for humans is closing (thus inducing the alpha activity) and opening (thus suppressing the alpha activity) of the eyes [6]. By adopting this in the first experimental protocol, after several minutes of dark adaptation, we asked each subject (5 male, 26±3 years old) to open his eyes for 30 sec and then close for 30 sec. This cycle was repeated three times for EEG and fMRI experiments which were conducted separately.

In the second experimental protocol for EEG only, in order to monitor the alpha activity in natural settings, the same subject was asked to close his eyes throughout the entire experimental period of 3 min during data acquisition. Fig. 1 shows these two experimental protocols.

B. Acquisition of EEG Data

A 32-channel EEG recording system (BrainAmp, Brain Products GmbH, Germany) was used to acquire EEG data using the first and second experimental protocols. Continuous EEG recordings were performed with the sampling rate of 1kHz and low-pass filtered at 40Hz. All EEG recordings were performed with the standard 10-20 uni-polar system referenced to FCz. The ground electrode was positioned between Cz and Fz. Electrode-skin impedance was kept below $1K\Omega$. To minimize motion artifacts in EEG on the scalp electrodes of the subjects, we tightly fixed the EEG cap on the scalp using the adhesive tapes.

C. Acquisition of fMRI Data

fMRI data were acquired on a 3.0T MR scanner (Magnum 3.0, Medinus, Korea) using a T2-weighted EPI sequence (TR = 2850ms, TE = 36ms, flip angle =70°, 64 × 64 matrix, FOV = 240 × 240 mm, slice thickness = 4mm, voxel size = 3.75 × 3.75 × 4mm^3) with 29 transaxial slices covering the whole brain regions. To minimize motion artifact, we tightly fixed the head using sponge in the head coil. During the data acquisition, we used only the first experimental protocol (i.e., opening and closing of the eyes). The purpose of fMRI experiment was to validate the localized sources of the alpha activity identified in the alpha power maps and cortical source maps of EEG.

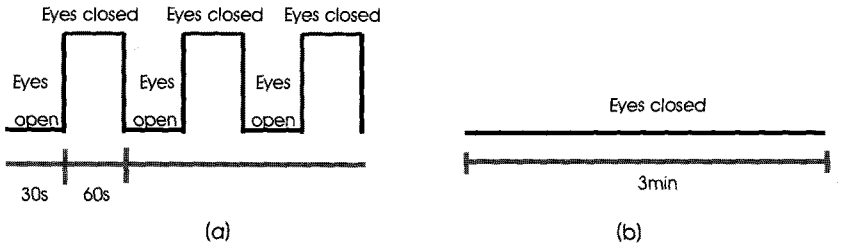

Fig. 1. (a) Experimental protocol Ifor EEG and fMRI, and (b) protocol II for EEG only.

D. Constrained Independent Component Analysis with References

ICA is a blind source separation technique for multi-channel signals which are assumed to be a linear mixture of independent signal sources. The technique has been successfully applied in many biomedical fields such as [2] and [10]. In an extension of the technique, recently cICA techniques have been developed where one or multiple reference signals are used as *a priori* information of the sources or constraints to extract only the desired ICs [9]. This is a clear advantage over the conventional ICA in which entire ICs must examined manually to select a subset of ICs responsible for a specific brain process, such as the alpha. In our previous study, we used this approach to extract the ballistocardiogram artifacts from EEG signals acquired inside MRI and remove them [10]. In this study, we have applied cICA to extract only the alpha-related signals from EEG data.

If we denote the time varying observed signal by $X= \{x_1(t), \cdots, x_n(t)\}^T$ and the source signal consisting of independent components by $S= \{s_1(t), \cdots, s_n(t)\}^T$. The linear ICA assumes that the signal X is a linear mixture of ICs:

$$X= AS \tag{1}$$

where X is the observed multi-channel signal. The matrix **A** of size n x n represents a linear memory-less mixing channel. The algorithm must find a separating or de-mixing matrix **W** such that

$$S= WX \tag{2}$$

In cICA, *a priori* information about the desired IC as a reference signal, $r(t)$ is used to obtain a source which is statistically independent from other sources. The reference signal must carry some information about the desired IC close enough to point the algorithm in the direction of a particular IC. The closeness constraint can be written as

$$g(w)= \varepsilon(y, r)- \xi \leq 0 \tag{3}$$

where ε is a closeness measure, ξ a closeness threshold parameter which we set to be a small number, but not too small for better convergence (e.g., 0.15 in our case). w the weight vectors to be learned, $y= \hat{s}$ a source output or an estimated source, and $g(w)$ the closeness constraint. The measure of closeness can take any form such as mean squared-error (MSE), correlation, any other suitable closeness or similarity measures. In our implementation of the algorithm, we used MSE as a measure of closeness and to adjust the value of the threshold parameter as mentioned in [9].

In turn, the cICA algorithm can be expressed as the constrained optimization problem where the negentropy approximated by Eq. (4) is maximized to yield the ICs or sources closer to the given reference r in a mean squared-error sense. Thus,

$$\begin{aligned} &\text{Maximize:} \quad \sum_{i=1}^{t} J(s_i) \\ &\text{Subject to} \quad g(w) \leq 0, h(w)= E\{y^2\}-1= 0 \end{aligned} \tag{4}$$

where $J(s) \approx \rho[E\{G(s)\}- E\{G(\nu)\}]^2$ denotes the one-unit ICA contrast function approximating the negentropy [12,13]. ρ is a positive constant, ν a Gaussian variable having zero mean and unit variance, and $G(\cdot)$ a non-quadratic function. $h(w)$ ensures the contrast function and the weight vector are bounded.

More technical details regarding the cICA algorithm can be found in [9] and [10].

E. Extraction and Localization of Alpha Activity in EEG

From the acquired raw EEG data according to the first and second experimental protocols, we used cICA to extract only the alpha activity-related signals. For the reference signal for the alpha activity in cICA, we used a band-pass filtered signal of an EEG channel (i.e., O1) at 8-12Hz, such that the cICA algorithm is directed to search for an IC that is most similar to the given reference: but statistical independence is ensured via cICA. Some difference references could be used as long as they contain some partial information of the alpha.

The alpha power maps and the cortical source maps were generated using the BESA software [14] (MEGIS Software, GmbH) from the regular band-pass filtered EEG signals at 8-12Hz and cICA-extracted EEG signals during the periods of eyes-closed. The alpha power is computed according to the following equation:

$$p_{alpha}(\widetilde{x_i})= \sum_{f=8Hz}^{12Hz} |DFT(\widetilde{x_i})|^2 \tag{5}$$

where $\widetilde{x_i}$ is the signal of original EEG, band-pass filtered EEG, or cICA-extracted EEG at the i-th channel position. Then using the alpha power values of entire channels, 3D topographies were obtained as the alpha power maps from BESA.

The cortical source maps were reconstructed from the peaks of alpha wave in the periods of eyes-closed, as done in [8] using the minimum-norm current image method provided by

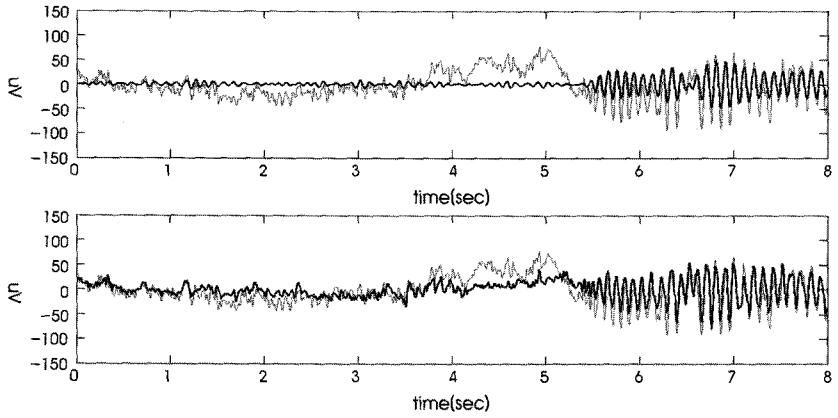

Fig. 2. (Top) Filtered alpha signal in black superimposed on the raw EEG signal in gray from the O_1 channel with the experimental protocol I. (Bottom) cICA-extracted alpha signal in black superimposed on the same original EEG signal in gray.

the software BESA which uses the Dale & Sereno 1993 [11] and spatio-temporal weighting options without the depth weighting.

F. Analysis of fMRI Data

The SPM99 software [15] was used for an individual analysis of fMRI data. The standard procedures for realignment, normalization, and spatial smoothing (10mm FWHM) were performed. The reference function was designed according to the protocol I as a box-car function. It is believed that the alpha activity reflected in the blood oxygenation level- dependent (BOLD) effect is negatively correlated with the alpha modulation protocols, as this observation is supported by many recent studies [1,2,6]. In accordance with these previous studies, we have also analyzed fMRI data in the same way: the negative correlation maps were obtained at $p < 0.001$, uncorrected.

III. RESULTS

A. Alpha Signal Extraction from EEG Signals

Figs. 2 and 3 show a set of exemplary results of filtering respectively. Fig. 2 (a) shows the extracted alpha waves (indicated with a solid black line) from the O1 channel signal (a gray line) using bandpass filtering at 8-12Hz, whereas Fig. 2 (b) shows the cICA extracted alpha (a black line) superimposed on the same original signal. In both Fig. 2 (a) and (b), the onset of alpha activity due to eye-closing (due to the protocol I) is clearly discernable. Fig. 3 (a) and (b) show the similar results with the protocol II.

In both cases, the cICA extracted alpha signals show more high and low frequency components in comparison to the alpha waves extracted by the bandpass filtering. Fig. 4 shows the frequency components of Fig. 2: the magnitude of frequency components of the original EEG signal of O1 is shown in gray

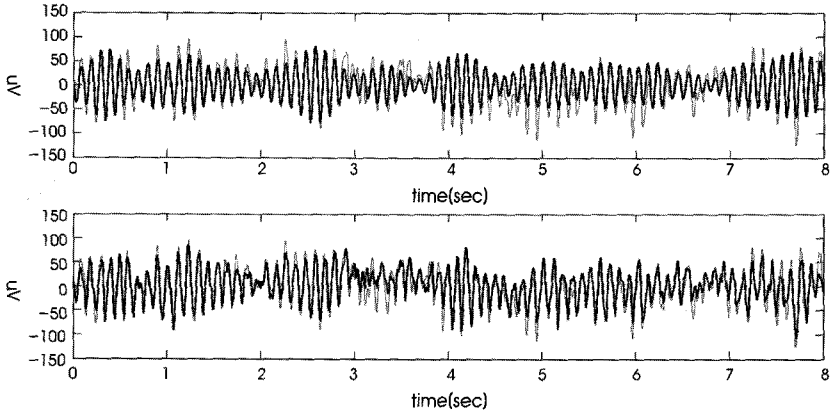

Fig. 3. (Top) Filtered alpha signal in black superimposed on the raw EEG signal in gray from the O_1 channel with the experimental protocol II. (Bottom) cICA-extracted alpha signal in black superimposedon the same original EEG signal in gray.

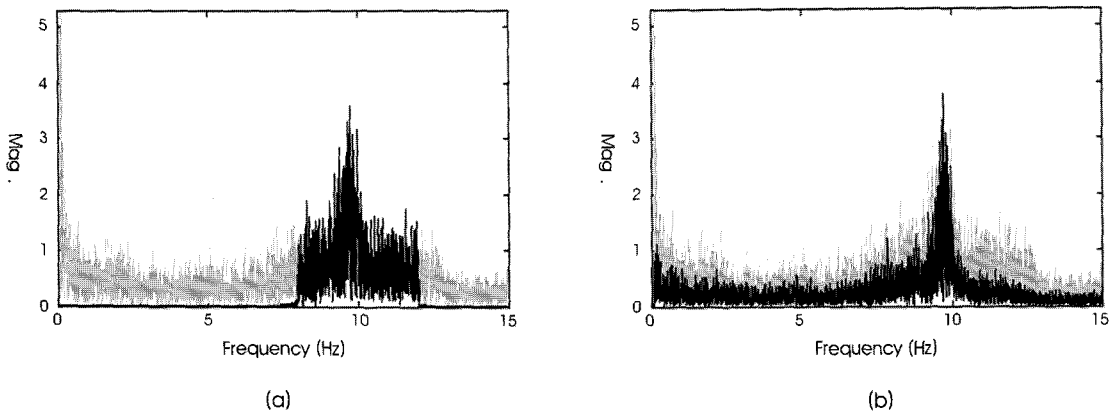

Fig. 4. (a) Frequency components of the original EEG signal of O_1 in gray and the bandpass filtered in black. (b) Frequency components of the same original in gray superimposed by the cICA extracted in black. Note the difference in the magnitude of frequency components in the alpha band from 8 to 12Hz.

whereas that of the bandpass filtered in black in (a) and that of the cICA extracted in black in (b). Note the difference in the magnitude of frequency components in the alpha band from 8 to 12Hz, clearly indicating the performance difference between the bandpass and cICA filtering.

B. EEG Alpha Power Maps

The comparisons of alpha power value at all electrodes from the raw data, the band-pass filtered, and the cICA-extracted are given in Fig. 5, showing different power levels of alpha activity across all EEG channels, explaining the differences in the power maps.

Fig. 6 shows a set of results of alpha power maps from one subject. Fig. 6 (a) shows the alpha power maps from the band-pass filtered EEG data at 8-12Hz of a single subject with the protocol I. Fig. 6 (b) shows the alpha power maps from the cICA-extracted alpha EEG signals of the same subject. More focalized alpha power sources are clearly noticeable in Fig. 6 (b).

Fig. 6 (c) shows the alpha power maps from the band-pass filtered EEG data with the protocol II. Fig. 6(d) shows the alpha power maps from the cICA-extracted alpha EEG signals. From the independent EEG experiments using the protocols I and II, similar and consistent power maps were obtained using cICA as shown in Figs. 6 (b) and (d).

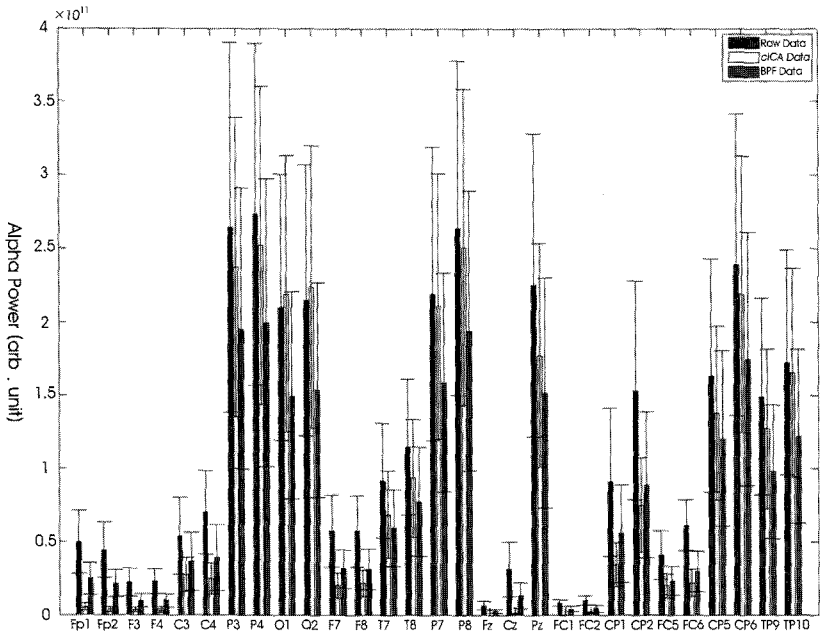

Fig. 5. Comparison of the alpha power values at each electrode (left: raw data, middle: band-pass filtered, and right: cICA-extracted).

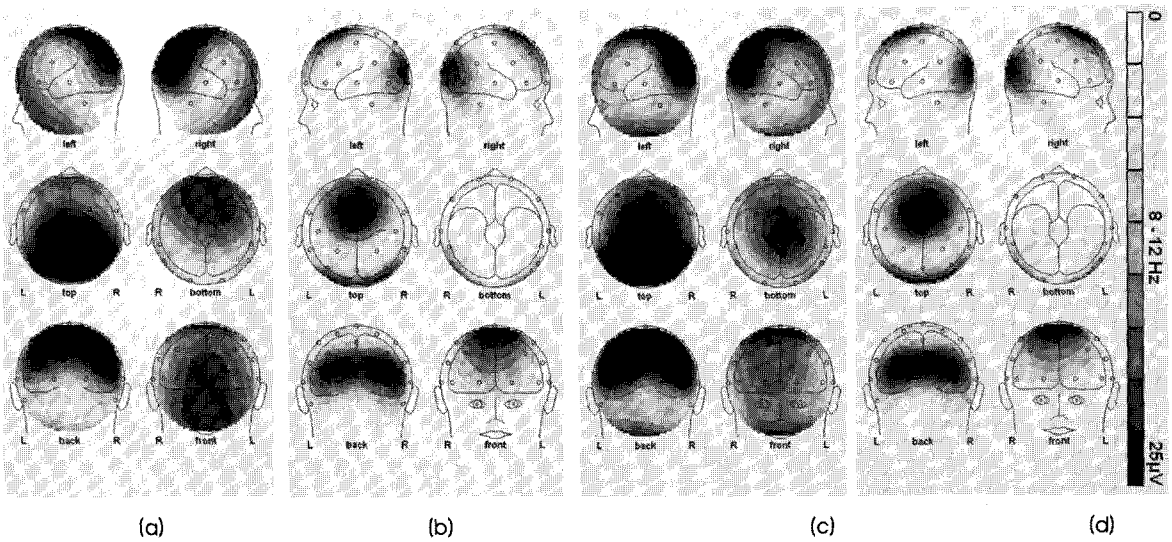

Fig. 6. Alpha power maps obtained via BESA. (a) From the band-pass filtered data with the protocol I, (b) From the cICA-extracted data with the protocol I, (c) From the band-pass filtered data with the protocol II, and (d) From the cICA-extracted data with the protocol II.

C. EEG Cortical Source Maps

Fig. 7 shows a set of cortical source maps from the same subject in Fig. 6. Figs. 7 (a) and (b) were obtained from the data with the protocol I. Fig. 7 (a) shows a cortical source map from the band-pass filtered EEG data during the eyes-closed period. Fig. 7 (b) shows the cortical source map from the cICA-extracted alpha EEG signals at the same period.

Fig. 7 (c) shows the cortical source maps from the band-pass filtered EEG data with the protocol II. Fig. 7 (d) shows the cortical source maps from the cICA-extracted alpha EEG signals. We confirm that the alpha sources in Figs. 7 (b) and (d) are more focal than those in Figs. 7 (a) and (c). The cortical maps of EEG data using cICA show alpha activated regions involving the frontal and occipital lobes that spatially match the alpha power maps as shown in Figs. 6 (b) and (d). The alpha power maps represent the alpha power distribution on the surfaces of the head (i.e., the scalp), whereas the cortical source maps indicate the actual current sources related to the alpha activated regions.

D. fMRI Activation Maps

Fig. 8 shows the activated regions of the brain with the

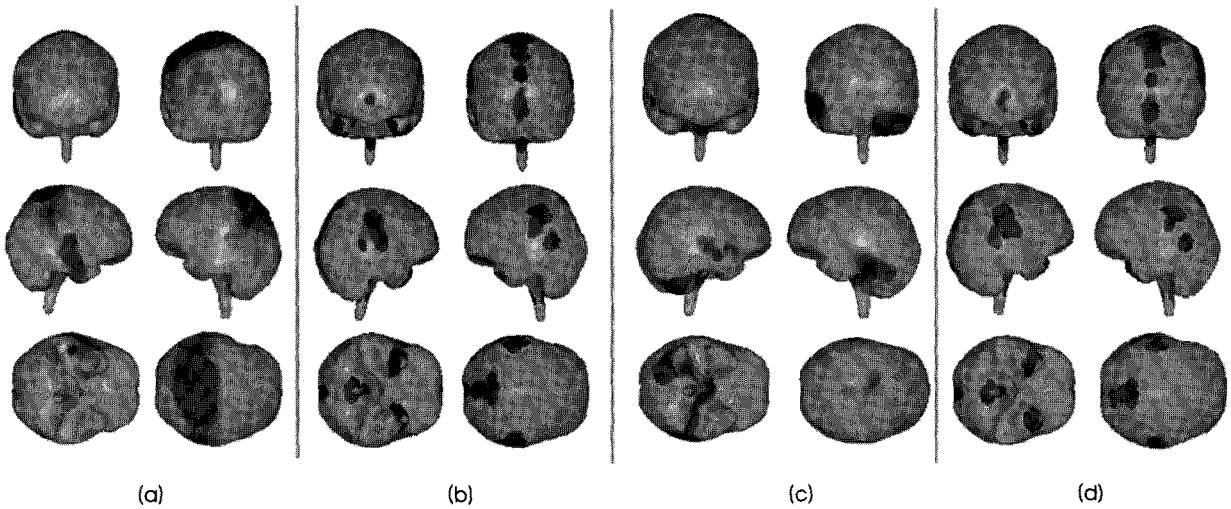

Fig. 7. Cortical source maps via BESA. (a) From the band-pass filtered data with the protocol I, (b) From the cICA-extracted data with the protocol I, (c) From the band-pass filtered data with the protocol II, and (d) From the cICA-extracted data with the protocol II.

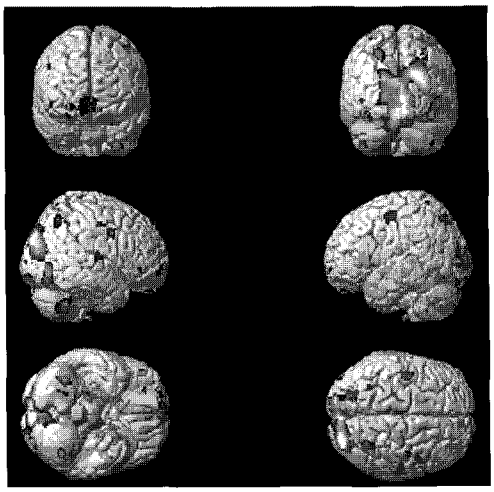

Fig. 8. fMRI activation maps. The activated areas with negative correlation to the experimental protocol I are shown ($p < 0.001$, uncorrected).

protocol I of the alpha modulation. The independent fMRI experiments were performed to validate the alpha maps obtained from cICA.

The functional maps of fMRI in Fig. 8indicate that the associated alpha activated regions include the frontal and occipital lobes which are consistent with the localized areas in the alpha power maps and cortical source maps of EEG using cICA as shown in Figs. 5 and 6. Note that the activated visual cortex in Fig. 8 is not due to the visual stimulation, but due to the alpha activity: as mentioned earlier, the activated regions are negatively correlated with the protocol.

The comparison results from the rest of four subjects are shown in Fig. 9. To investigate the spatial correspondence of the alpha sources, we compared the cortical source maps to the fMRI activation maps. Fig. 9 (a) shows the cortical source maps from the band-pass filtered EEG data in the anterior, posterior, and superior views. Fig. 9(b) shows the cortical source maps from the cICA-extracted EEG data. Figs. 9 (a) and (b) were acquired with the experimental protocol I at the eyes-closed period. Fig. 9 (c) shows the fMRI activation maps which include the alpha activated regions with the protocol I.

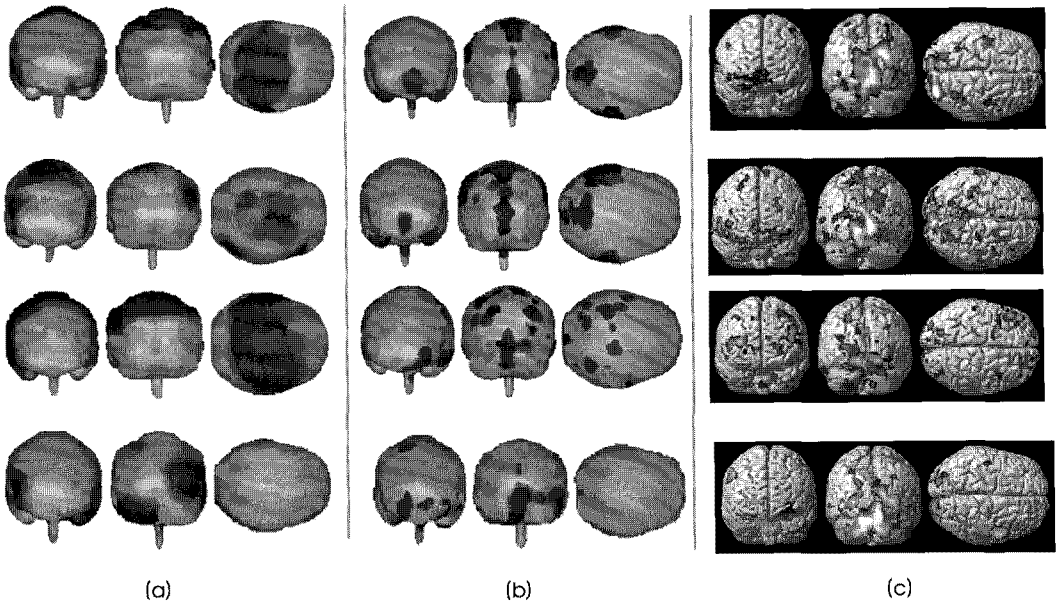

Fig. 9. EEG cortical source maps and fMRI activation map from four other subjects (each row represents one subject). (a) Cortical source maps from the band-pass filtered data, (b) From the cICA filtered data, and (c) fMRI activation maps.

Ⅳ. DISCUSSION

Regarding the true sources of alpha activity, although there have been many studies using EEG, fMRI, and simultaneous EEG-fMRI [1-7], general consensus has not been made yet. However, the studies by Laufs et al. [1], Goldman et al. [5], and Moormann et al. [16] reported multiple regions, based on the negative BOLD of fMRI, including occipital (occipital gyri, precuneous), parietal (pre and post-central gyrus), and inferior frontal or prefrontal lobes (orbitofrontal cortex, superior frontal gyrus), responsible for the generation of alpha activities. Alpha source localization studies based on EEG or combined EEG-fMRI are rare. Nevertheless, both the first EEG localization study [17] and the ICA preprocessed EEG distributed imaging study [2] reported very similar source regions in the precuneous gyrus of the middle occipital lobe, the angular gyrus of the parieto-occipital lobe, and the middle frontal gyrus of the frontal lobe. Our findings in this work match very closely these regions, supporting our approaches.

However, there is one concern remaining in our results regarding the spatial correspondence of the activated regions between EEG and fMRI. There is some discrepancy of the source locations in the parietal regions: the recovered sources in EEG tend to be located toward the posterior part of the brain, but the activated regions in fMRI tend to show up more toward the anterior portion of the brain. We consider this discrepancy is due to two factors. One factor is the mapping of the EEG sources onto the standardized brain surface model and the normalization process in data processing for fMRI which might cause some shift of the activated regions. The other is the alpha generating sources which are identifiable by EEG, but not by fMRI or vice versa. In facts, the previous studies have not report the consistent sources in the parietal regions of the brain yet, but they do clearly indicate the involvement of the frontal and occipital lobes of the brain for the brain alpha activities.

Our results suggest that cICA seems to be capable of extracting the alpha-related signals more effectively from raw EEG data, resulting in more focalized alpha generating regions or sources in the alpha power and source maps. The results also suggest that the conventional band-filter based approaches might not reveal the true alpha generating areas of the brain, although they seem to recover the alpha generating regions which are very much blurred and enlarged. We think that the technical differences are the cause of our results: the conventional band-pass filtering is performed each EEG channel independently (i.e., channel-by-channel processing) whereas the cICA extraction looks at the EEG signals across all channels simultaneously and extracts the alpha signals that are independent from the rest of the data.

Ⅴ. CONCLUSION

We have presented a new approach of extracting alpha activity related signals from EEG data utilized cICA. We consider that the cICA approach could be more useful in the analysis of alpha activities of EEG and extended to extract other kinds of brain activities upon the availability of some *a priori* information.

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