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TMS Induced EEG Artifacts Analysis Based on the Partial Cross-Correlations

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Abstract

Combining Transcranial magnetic stimulation (TMS) and Electroencephaloraphy (EEG) offered insights into neural interaction during cognition which allows the investigation on the causal role of specific brain areas in behavior and the interactive connection between the brain areas. The TMS pulse in the TMS-EEG combining study introduces artifacts in the EEG electrodes which may mask the underlying neural activity lasting about 5 through even hundreds milliseconds after the pulse. In this study a statistical method on the removal of TMS induced EEG artifacts is presented based on partial cross-correlations. The method yields estimates of linear correlations between components obtained by Independent Component Analysis (ICA) and TMS signal that are not affected by linear correlations with other artifacts. We used the EEG data obtained from four healthy subjects without any neurological disorder, who were receiving single pulse TMS-EEG and sham-EEG stimulus on the left Broca's area. ICA filters trained on the reduced version of 60 channel EEG data collected during single pulse

TMS-EEG and sham-EEG recordings. It identified the reduced number of statistically independent source channels, in which the ICA components originating from the TMS-induced artifact are classified by estimating the partial cross-correlation coefficients between ICA components of single pulse TMS-EEG and sham-EEG stimulus after ICA decomposition. The results showed which ICA components are related to TMS induced EEG artifacts, suggesting the efficiency and the reliability of the method developed in this study.

Keywords: TMS-EEG, artifacts, ICA, partial cross-correlations, brain

1 Introduction

Transcranial magnetic stimulation (TMS) can be used to activate or deactivate a specific part of the brain non-invasively causing depolarization or hyperpolarization in cortical neurons by the electromagnetic induction. It is widely used to measure the connectivity of the primary motor cortex and a muscle to evaluate brain damage and other disorders related to the motor cortex [1] and also used to study the effects of phosphenes by stimulating the primary visual cortex [2] and the speech processing by disrupting momentarily the Broca's area [3]. TMS is divided into two types, single or paired pulse TMS and repetitive TMS depending on the stimulation mode. Single pulse TMS causes neurons in the neocortex under the site of stimulation to depolarize and discharge an action potential. Repetitive TMS can produce longer-lasting effects such as changes in synaptic efficacy by increasing or decreasing the excitability of the corticospinal depending on the intensity of stimulation, coil orientation, and frequency.

EEG, a non-invasive technique records spontaneous electrical activity of the brain by measuring the voltage fluctuations resulting from ionic current flows within the neurons of the brain [4]. EEG is used to clinically observe the type of neuronal oscillations and therefore can be used to diagnose Epileptic activity, brain death, or sleep disorders from their abnormal patterns of the EEG signals [5-6]. Furthermore, information on functional connectivity between the cortical areas involved in different cognitive tasks and processes can be extracted from the spectral properties and the cohesion of the spontaneous oscillations of EEG in different brain area by filtering and Fourier transformation.

Combining TMS and EEG offered insights into neural interaction during cognition which allows the investigation on the causal role of specific brain areas in behavior and the interactive connection between the brain areas [5-6].

EEG signals are typically contaminated with biological and environmental artifacts. Biological artifacts include eye-induced artifacts, cardiac artifacts, muscle activation-induced artifacts and glossokinetic artifacts [7]. Environmental artifacts include electrode spikes originating from a momentary change in the impedance of a given electrode due to body movement or settling of the electrodes, and 50 or 60 Hz line noise due to poor grounding of the EEG electrodes [8]. The TMS pulse in the TMS-EEG combining study introduces artifacts in the EEG electrodes. The magnetic pulse of TMS affects the muscles and motor nerves underneath the coil causing the muscle activation and eye movement, which results in the induction of EEG artifacts. The magnetic pulse of TMS can also excite the somatosensory nerve endings and the coil click activates the auditory system of the subject, which can be seen in EEG as auditory or somatosensory evoked potentials [9]. Independent Component Analysis (ICA) is applicable to separate EEG data into neural activity and artifact [10]. Many methods using ICA are applied to high-density EEG data to reject components of artifact [10-11]. However, there are few of them which resolve TMS induced artifact removal problem on EEG. In this study, a statistical method on the removal of TMS induced EEG artifacts is presented based on partial cross-correlations. The method yields estimates of linear correlations between components obtained by ICA and TMS signal that are not affected by linear correlations with other artifacts. The EEG data used in this study were obtained from four healthy subjects without any neurological disorder, who were receiving single pulse TMS-EEG and sham-EEG stimulus on the left Broca's area. ICA filters trained on the reduced version of 60 channel EEG data collected during single pulse TMS-EEG and sham-EEG recordings. The ICA components originating from the TMS-induced artifact are classified by estimating the partial cross-correlation coefficients between ICA components of single pulse TMS-EEG and sham-EEG stimulus after ICA decomposition. The results showed which ICA components are related to TMS induced EEG artifacts, suggesting the efficiency and the reliability of the method developed in this study.

2 Methods for TMS induced EEG artifact detection and removal

A total of 4 healthy male subjects (L1, L3, L5 and L9 with ages: 25 ± 2.5) without any neurological disorder were selected in this study. Subjects were screened with the TMS Screening Questionnaire. Once informed consent was obtained, the inclusion and exclusion criteria were reviewed. Baseline measures included the modified Edinburgh Handedness Inventory and a baseline Minimental State Exam (MMSE).

Subjects visited 2 times separately for the TMS-EEG study visit with at least two days interval. One of the two TMS-EEG study visits were for single pulse TMS-EEG, the other were for sham-EEG. Subjects were included in either the sham-EEG first or the single pulse TMS-EEG first group by random assignment by using a random number generation method. 60 Channel EEG were recorded at a total of 4 TMS-EEG and 4 sham-EEG data. The single pulse TMS stimulus was treated on the left Broca's area. Trains of single TMS pulses were administrated at intervals of 300 ms for a 1 minute period at 80% of active motor threshold on left Broca's area (area 44) for the single pulse TMS-EEG group. Sham-EEG underwent the same procedure for identifying stimulus location used in subjects receiving single pulse TMS-EEG. Simulated TMS were administered using Magstim Placebo 70 mm figure-of-8 shaped coils producing discharge noise and vibration similar to a real 70 mm coil without stimulating the cerebral cortex. The electrical stimulation of the scalp, which is induced in the single pulse TMS-EEG experiment, was simulated by attaching surface electrodes underneath the sham coil and in contact with the scalp and using Nerve Conduction Study devices routinely to administer electrical shocks to the scalp simultaneous to each simulated TMS train.

Figure 1 represents the flowchart of the overall processes of this method. EEG data were sampled preliminary at 1.45 kHz and then re-sampled at 0.725 kHz before filtering. The EEG data initially referenced to site Fz which is the 14th channel in this study. The referenced EEG data were filtered offline using a bandpass filter between 1 Hz and 95 Hz with a notch at 50 Hz to remove environmental noises. Next, artifactual channels are statistically classified, removed and interpolated based on their distributions and correlations to each other. The data were referenced to the average of all scalp electrodes. Then, ICA was performed with FastICA algorithm on the data and the decomposed components were analyzed for biological artifacts and TMS induced artifact using partial cross-correlations. Finally, the ICA components originating from biological artifacts and TMS-induced artifact were subtracted from each channel data.

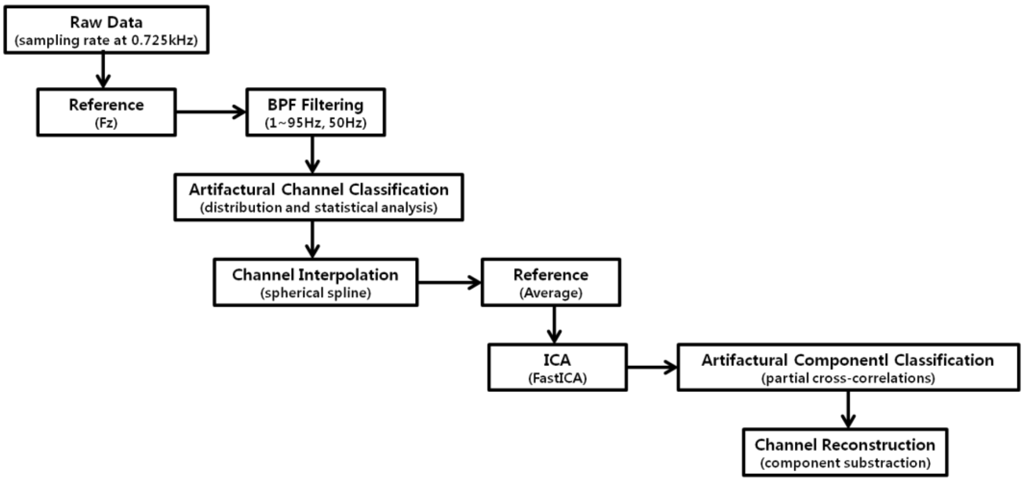

Fig. 1. The flowchart of the overall processes of this method

Artifactural channels are statistically classified by estimating the median $M(r_{x_i,x_j})$ of the Pearson correlation coefficients r_{x_i,x_j} of each channel x_i to other channel, x_j, $j=1,\cdots,n$. A contaminated channel usually has low correlation with other channels. A channel is removed and then reconstructed by interpolating with neighboring channels if the median $M(r_{x_i,x_j})$ of it lies out of 99% confidence interval range. The interpolation was performed by using EEGLAB spherical spline interpolation function. The correlation r_{x_i,x_j} between two channels x_i and x_j can be estimated by Eq. (1).

$$r_{x_i,x_j} = \frac{<(x_i - <x_i>)(x_j - <x_j>)>}{\sigma_i \sigma_j} \tag{1}$$

Where $<x_i>$ is the average of x_i and σ_i is its standard deviation and likewise for x_j.

The mathematical model of ICA is described as the following equation, $x = As$ where x is the random vector whose elements are the mixture of $x_1,\cdots,x_n$, s is the random vector with elements $s_1,\cdots,s_n$ and A is the matrix with elements $a_{i,j}$. The components can be classified to signals from brain activities and artifacts induced by TMS stimulation as well as those by body movements or electrode mismatching.

The partial correlation coefficient $r_{s_i,s_j/s_\alpha}$ between ICA components s_i and s_j is defined as Eq. (2), in which the linear effect of s_α the sum of sources accounting for typical EEG artifacts is to be removed and r_{s_i,s_α}, r_{s_j,s_α} and r_{s_i,s_j} are cross-correlation coefficients.

$$r_{s_i,s_j/s_\alpha} = \frac{r_{s_i,s_j} - r_{s_i,s_\alpha} \cdot r_{s_j,s_\alpha}}{\sqrt{(1-r_{s_i,s_\alpha}^2)(1-r_{sj,s_\alpha}^2)}} \tag{2}$$

Linear correlations between s_i and s_α and between s_j and s_α are removed from r_{s_i,s_j} by subtraction, and the difference is normalized by the geometric average of the deviations of these correlations from one. This is conceptually similar to estimating the correlation between s_i and s_j, whereas s_α is held constant experimentally. The ICA component of TMS induced EEG artifact is statistically classified by estimating the median $M(r_{s_i,s_j/s_\alpha})$ of the partial correlation coefficients $r_{s_i,s_j/s_\alpha}$ of each ICA source s_i to others, s_j, $j=1,\cdots,m$ within 99% confidence interval limit criteria, where m is the total number of ICA components after typical EEG artifact removal.

3 Results and Discussions

Figure 2 (a) and (b) show the time series of the single pulse TMS-EEG and sham-EEG data, respectively, of subject L5 with 0.725 kHz of re-sampling rate before (top) and after (bottom) bandpass (1~95Hz) and notch (50 ± 3Hz) filtering, where the x axis represents time (sec) and y axis, voltage (μV). Figure 3 (a) and (b) show the power spectra of the single pulse TMS-EEG and sham-EEG data, respectively of subject L5 with 0.725 kHz of re-sampling rate after bandpass (1~95Hz) and notch (50 ± 3Hz) filtering and interpolating artifactural channels, where the channel maps for frequencies of 2.1, 5.7, 9.2, 19.8, and 39.6 Hz are shown for each power spectrum and the x and y axes represent the frequency (Hz) and the power intensity ($10\log_{10}$ μV^2/Hz), respectively. The TMS-induced artifacts are noticeable at figure 3 showing long lasting disruption in the EEG data. The linear trends and 50 Hz line noises are removed from EEG data as shown in figure 2 (b) and 3 (b). Figure 4 (a) and (b) represent the time courses of channels for single pulse TMS-EEG data and sham-EEG data, respectively after ICA decomposition analysis (top) and TMS induced EEG artifact removal (bottom) based on the partial cross-correlations. The TMS-induced artifacts of TMS-EEG data are shown to be removed in the bottom of figure 5.represents the time courses of channels for single pulse TMS-EEG data and sham-EEG data, respectively after ICA decomposition analysis (top) and TMS induced EEG artifact removal (bottom) based on the partial cross-correlations.1 represents the flowchart of the overall processes of this method. EEG data were sampled preliminary at 1.45 kHz and then re-sampled at 0.725 kHz before filtering

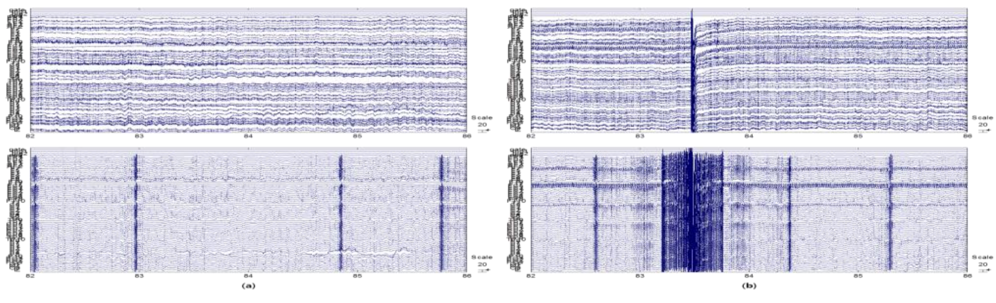

Fig. 2. The time series of (a) the single pulse TMS-EEG and (b) sham-EEG data, of subject L5 with 0.725 kHz of re-sampling rate before (top) and after (bottom) bandpass (1~95Hz) and notch (50 ± 3Hz) filtering

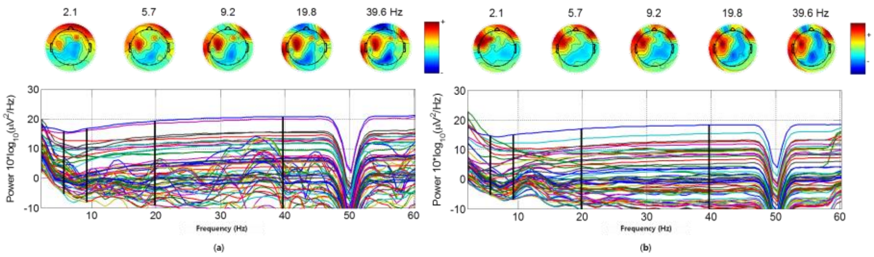

Fig. 3. The power spectra of the single pulse TMS-EEG and sham-EEG data, respectively of subject L5 with 0.725 kHz of re-sampling rate after bandpass (1~95Hz) and notch (50 ± 3 Hz) filtering and interpolating artifactural channels

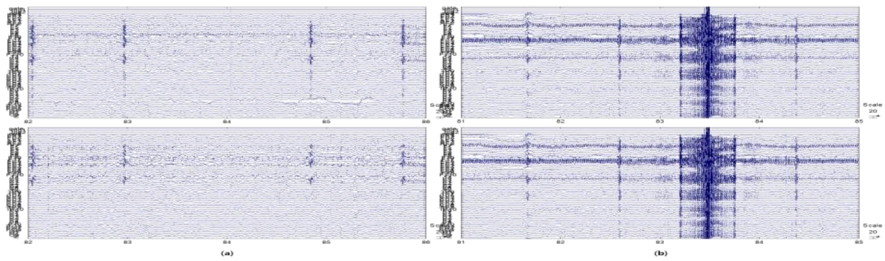

Fig. 4. the time courses of channels for single pulse TMS-EEG data and sham-EEG data, respectively after ICA decomposition analysis (top) and TMS induced EEG artifact removal (bottom) based on the partial cross-correlation.

4 Conclusions

In this study, a statistical method on the removal of TMS induced EEG artifacts is presented based on partial cross-correlations. The method yields estimates of linear correlations between components obtained by ICA and TMS signal that are not affected by linear correlations with other artifacts. The EEG data used in this study were obtained from four healthy subjects without any neurological disorder, who were receiving single pulse TMS-EEG and sham-EEG stimulus on the left Broca's area. ICA filters trained on the reduced version of 60 channel EEG data collected during single pulse TMS-EEG and sham-EEG recordings. The ICA components originating from the TMS-induced artifact are classified by estimating the partial cross-correlation coefficients between ICA components of single pulse TMS-EEG and sham-EEG stimulus after ICA decomposition. The results showed which ICA components are related to TMS induced EEG artifacts, suggesting the efficiency and the reliability of the method developed in this study.

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