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Validation of SOBI components from high-density EEG

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Second-order blind identification (SOBI) is a blind source separation (BSS) algorithm that can be used to decompose mixtures of signals into a set of components or putative recovered sources. Previously, SOBI, as well as other BSS algorithms, has been applied to magnetoencephalography (MEG) and electroencephalography (EEG) data. These BSS algorithms have been shown to recover components that appear to be physiologically and neuroanatomically interpretable. While some proponents of these algorithms suggest that fundamental discoveries about the human brain might be made through the application of these techniques, validation of BSS components has not yet received sufficient attention. Here we present two experiments for validating SOBI-recovered components. The first takes advantage of the fact that noise sources associated with individual sensors can be objectively validated independently from the SOBI process. The second utilizes the fact that the time course and location of primary somatosensory (SI) cortex activation by median nerve stimulation have been extensively characterized using converging imaging methods. In this paper, using both known noise sources and highly constrained and well-characterized neuronal sources, we provide validation for SOBI decomposition of high-density EEG data. We show that SOBI is able to (1) recover known noise sources that were either spontaneously occurring or artificially induced; (2) recover neuronal sources activated by median nerve stimulation that were spatially and temporally consistent with estimates obtained from previous EEG, MEG, and fMRI studies; (3) improve the signal-to-noise ratio (SNR) of somatosensory-evoked potentials (SEPs); and (4) reduce the level of subjectivity involved in the source localization process.

Keywords: Blind source separation (BSS); Second-order blind identification (SOBI); Independent component analysis (ICA); Electroencephalography (EEG); Source modeling; Equivalent current dipole (ECD); Event-related potentials (ERP); Median nerve; Somatosensory; Source localization

Introduction

Electroencephalography (EEG) and magnetoencephalography (MEG) are noninvasive tools that offer millisecond temporal resolution for the study of neural mechanisms underlying mental phenomena. Both EEG and MEG signals recorded at the scalp are mixtures of signals from multiple intra- and extracranial sources, thus such sensor signals do not necessarily reflect brain activity immediately below the sensors. To extract underlying sources of interest from such mixtures, blind source separation (BSS) algorithms (Hyvarinen et al., 2001; Jutten and Herault, 1991) have been increasingly applied to EEG and MEG data (Jung et al., 2001; Stone, 2002; Tang and Pearlmutter, 2003; Vigario and Oja, 2000; Vigario et al., 2000) collected during a range of sensory and motor activation tasks, including signals recorded during activation of visual (Makeig et al., 1999a,b, 2002; Tang et al., 2000, 2002a,b), auditory (Cao et al., 2002; Makeig et al., 1997; Tang et al., 2000, 2002a,b; Vigario et al., 2000; Wubbeler et al., 2000), somatosensory (Sutherland et al., 2004; Tang et al., 2000, 2002a,b; Vigario et al., 2000; Wang et al., 2004), and motor systems (Mackert et al., 2001), and during the performance of complex real world tasks (Tang et al., 2003).

Several advantages of using BSS as a preprocessing tool for analyzing EEG and MEG data have been demonstrated. First, more effective artifact removal than that offered by conventional approaches can be achieved (Barbati et al., 2004; Culpepper and Keller, 2003; Ikeda and Toyama, 2000; Iriarte et al., 2003; Joyce et al., 2004; Jung et al., 2000a,b; Kobayashi et al., 2001; Tang et al., 2000, 2002b; Tong et al., 2001; Vigario, 1997). Second, weak or highly variable neuronal activations that were otherwise undetectable can be recovered (Tang et al., 2002b). Third, higher effective signal-to-noise ratios (SNRs) can be achieved at the level of single trial to allow for increased single-trial response onset time detection (Loring et al., 2004; Tang et al., 2002a) and for improved single-trial event-related potential (ERP) classification (Wang et al., 2004). Fourth, neuronal sources with slow DC changes in their activations can be recovered (Mackert et al., 2001; Wubbeler et al., 2000). Fifth, synchronization and desynchronization at specific brain locations can be more effectively studied (Makeig et al., 2004). Most recently, we have

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shown that by using BSS, single-trial ERPs from visual and frontal cortices can be extracted from EEG collected during video game play where continuous free eye movement was permitted (Tang et al., 2003). Despite these promising findings made over the last decade, some reported in highly visible journals, BSS algorithms have not been adopted by the EEG or MEG communities as part of routine analysis. Aside from the normal delays one might expect for new methods to become a part of routine analysis, what hinders the wide use of BSS algorithms appears to be a perceived lack of attempts to validate BSS-recovered putative sources prior to their interpretations. While some BSS algorithms have been applied to simulated EEG and MEG data (Cao et al., 2002; Makeig et al., 2000), in this paper we considered alternative ways for validating BSS-recovered putative sources.

The main obstacle for satisfactory validation is that the nature of neuronal activation recorded at the scalp by EEG or MEG is inherently unknown. Even with intracranial recordings, it is difficult and impractical to precisely position electrodes to capture the center of neuronal activations among functionally unique brain regions. The aim of the present study was to determine whether the putative sources recovered by a BSS algorithm adequately approximated the true sources. We do so by providing objective spatial and temporal validation of BSS components recovered using second-order blind identification (SOBI) (Belouchrani et al., 1993, 1997; Cardoso and Souloumiac, 1996). First, we took advantage of the presence of known sources such as 60-Hz line noise and artificially induced noise to provide objective validation. Secondly, because primary somatosensory (SI) cortex activation by median nerve stimulation has been well characterized both spatially and temporally (for reviews, see Allison et al., 1991; Hari and Forss, 1999; Kakigi et al., 2000; McLaughlin and Kelly, 1993), we further used SI activations as known sources to validate the SOBI decomposition process.

Through this validation process, we provide a step by step description of the application of SOBI to high-density EEG with sufficient details to allow new users of SOBI to replicate the analysis process. We demonstrate that the SNRs of somatosensory-evoked potentials (SEPs) associated with the SOBI-recovered SI components were significantly larger than the SNRs measured at the EEG sensors. Spatially we show how the location of the recovered putative sources can be determined using a dipole modeling method. We demonstrate that SOBI-aided source localization does not require the step of generating an averaged event-related potential (ERP) and significantly reduces the subjectivity involved in the source modeling process. We also expand our previous work by demonstrating that SOBI is not only useful for analyzing data of relatively poor SNR obtained under unfavorable experimental conditions but can also further improve SNR even when data are collected under relatively optimal experimental conditions.

Methods

Subjects

Four right-handed subjects (two males), aged between 20 and 25 years, volunteered to participate in the present study. All subjects were free of any history of neurological or psychological disorders. The experimental procedures were conducted in accordance with the Human Research Review Committee at the University of New Mexico.

Stimuli

Constant current square-wave pulses were delivered transcutaneously to the median nerve at the wrist using a pulse generator (S88) and a photoelectric stimulus isolation unit (Model SIU7) from Grass Instrument (Astro-Med, Inc. West Warwich, RI). Stimulation intensity was adjusted slightly below motor threshold to selectively activate somatosensory cortex while minimizing activation of motor cortex (Spiegel et al., 1999) as well as to minimize nonspecific somatosensory activation associated with finger movement. Stimulus duration was 0.25 ms and intensity ranged from 4.5 to 8.5 mA (M = 6.5 mA). The perceived intensities of left and right stimulation were reported to be similar by the subjects. Subjects were instructed to keep their eyes closed during stimulation.

Unilateral (L: left; R: right) and bilateral (B) stimuli were delivered intermixed and pseudorandomly with no more than three consecutive identical stimulations. Bilateral stimulation was used to generate temporally overlapping activation in both hemispheres, thus providing a challenge for the source separation of left and right SI activation. The number of stimuli per condition was 400 for two subjects, 200 and 150 for the remaining two. The intertrial intervals (ITIs) were uniformly distributed, ranging from 0.75 to 1.25 (for the two subjects with 400 trials), 1.25 to 1.75 (for the subject with 200 trials), and 1 to 2 s (for the subject with 150 trials) with increments of 0.05, 0.05, and 0.1 s, respectively. These variations allowed us to determine whether source separation results were dependent upon particular stimulation parameters[1]. Stimulation lasted less than 20 min. No behavioral responses were required.

Data acquisition

EEG signals were recorded in an electrically shielded room from the whole head with a 128-channel EEG system (SymAmps, Neuroscan, El Paso, TX) using tin electrodes mounted in a custom-made cap (ElectroCap International, Eaton, OH). The sensor (electrode) locations are indicated in Fig. 1C. The signals were continuously sampled at 1000 Hz and bandpass filtered between 0.1 and 200 Hz. All channels were referenced to the nose and impedances were maintained below 10 kΩ. Electrode and landmark positions (nasion, left and right pre-auriculars) were digitized (Fastrack, Polhemus Inc., Colchester, VT) and used for subsequent source localization. In conventional sensor-based data analysis, the continuous EEG signals from each sensor are typically epoched, baseline corrected, possibly filtered, and averaged. Data length is typically reduced after rejecting epochs containing visually identified artifacts. Here, the SOBI BSS algorithm was applied directly to the continuous EEG data as it had been collected without epoching, artifact rejection, baseline correction, filtering, removal of bad channels, or signal averaging, similar to previous applications of SOBI to MEG data (Tang et al., 2002a,b).

[1] SOBI analysis did not indicate noticeable differences produced by these different block sizes or ITIs.