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Independent component analysis-based method for electroencephalogram analysis during photic stimulation

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HIGHLIGHTS

- The method is capable of providing a good estimation of the ongoing EEG activities.
- The method is capable of providing a good estimation of the ongoing EEG activities.
- The ongoing EEG activity is provided on both time and frequency domains.
- Results have shown that the proposed method outperformed the coherence-based method.
- The contribution of the stimulation can be removed at a specific harmonic frequency.

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ABSTRACT

Background: Intermittent photic stimulation (IPS) leads to phase- and time-locked activities in the electroencephalogram (EEG). While the first are easily obtained by means of averaging techniques (the evoked response), this latter reflects changes in the ongoing EEG that are important in event-related synchronization/desynchronization (ERS/ERD) studies. Techniques have been proposed for assessing such changes but they only provide the spectral estimate of the time-locked activities.
New method: An independent component analysis-based method is proposed for the EEG analysis during IPS. Artificially generated sinusoidal functions at the stimulation frequency and harmonics are used together with the acquired EEG signal to build the observed vector that is presented to the ICA algorithm.
Results: The proposed method was evaluated with simulated data and applied to EEG signals acquired on two electrodes placed over the occipital region showing that this method is capable of providing a suitable estimation of the ongoing EEG activities in both time and frequency domains.
Comparison with existing method(s): The results were compared with a coherence-based method, showing that the proposed method can estimate the power spectrum of the ongoing EEG activity as precisely as the coherence-based method with the advantage of allowing the ongoing EEG activity in time domain to be also obtained.
Conclusions: The application of the proposed method could be used for ERS/ERD studies, since it separates evoked responses, which are phase-locked to the stimuli, from those that change the ongoing EEG in a time-locked manner to the external stimulation.

Abbreviations: BCI, brain–computer interfaces; BSS, blind source separation; EEG, electroencephalogram; EP, evoked potential; ERD, event-related desynchronization; ERP, event-related potential; ERS, event-related synchronization; ICA, independent component analysis; IVM, intertrial variance; IPS, intermittent photic stimulation; JADE, joint approximate diagonalization of eigenmatrices; NAE, normalized average error; rmse, root mean square error; Sd, spectral difference; SSVEP, steady-state visual evoked potentials.

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1. Introduction

External rhythmic stimulations, such as those provided by tone clicks, flickering lights or electric shocks, usually lead to evoked responses in the electroencephalogram (EEG). These responses are phase-locked to the stimulation and exhibit small amplitude in comparison with the background EEG (Chiappa, 1997). However, since they do not change so much from stimulus to stimulus (i.e. they can be assumed to be arisen from weakly stationary random processes), averaging techniques can reveal them, provided the background EEG is zero mean and uncorrelated with the stimulation. Thus, the pro-mediated EEG signal under stimulation represents the estimate of the evoked response and is commonly referred to as the evoked potential (EP). This averaging procedure requires the evoked response to a given stimulus to vanish before the following stimulus is applied. Therefore this EP is commonly referred as transient evoked potential. On the other hand, steady-state evoked potentials occur whenever the stimulation rate is increased (e.g. greater than 5 Hz), so that a following stimulus is applied before the evoked response to the previous one vanishes, leading to a sinusoidal behavior of the resulting averaged signal (Chiappa, 1997).

The intermittent photic stimulation (IPS) with a stroboscopic light constitutes a common practice in the clinical routine. It may be either used as an activation method, i.e. a way of enhancing preexisting abnormalities and/or inducing abnormal behavior in an otherwise normal EEG (Takahashi and Chiappa, 2011), or as a neurophysiological exam to assess the integrity of the visual pathway (Celesia and Peachey, 2011). Although it is not one of the preferred stimulation methods for clinical investigations (Chiappa, 1997), such as the luminance fixed, pattern-shift stimulation, IPS is very useful in cases of noncooperative patients, such as very young children and subjects in coma or under anesthesia (Chiappa, 1997). Furthermore, in the scenario of Brain-Computer Interfaces (BCI), steady-state visual evoked potentials (SSVEP) have been used as a communication signal to allow disable people to perform tasks such as typing a text or controlling a wheelchair (Zhu et al., 2010). In this case, flickering lights at distinct frequencies may be presented to the subject, each one assigned to a different action (e.g. to turn right or left; to stop and move forward).

In addition to the evoked responses, paced events result also in non-phase locked changes of the ongoing EEG (Pfurtscheller and Lopes da Silva, 1999). Such time-locked changes (i.e. the ones occurring during the period stimulation is being applied) are often referred to as event-related synchronization (ERS) and desynchronization (ERD), depending on whether there is an increase or decrease in the EEG power spectrum. ERD/ERS patterns may be also used in BCI applications, since the planning or even the intention to perform a certain movement or task may reflect in time-locked spectral changes (Wolpaw et al., 2002).

The classical approach for assessing the ERD/ERS consists of first bandpass filtering each event-related trial, squaring next the amplitude samples and then averaging the pre-processed set of trials (Pfurtscheller and Lopes da Silva, 1999). Finally, this time evolution of an instantaneous band power is compared to that of the EEG without stimulation. This is often accomplished throughout the calculation of an index of the percent power difference. However, using this classical ERD/ERS computation method to SSVEP signals, the resulting EEG power change includes both phase-locked and non-phase-locked responses. Thus, during rhythmic stimulation, this latter may be hidden by the first due to the averaging carried out to obtain the EP. This may constitute a problem in the analysis of the EEG acquired during IPS, since one might be concerned, for example, with only the EEG activation. In such a case, the photic driving activity constitutes a confounding signal. The intertrial variance (IVM) of bandpass filtered EEG data (Kalcher and Pfurtscheller, 1995) was proposed as a way of overcoming this problem. This method consists of subtracting from the bandpass filtered EEG data the mean value of each window previously to calculating the ERD/ERS indexes. Since this mean value reflects an estimate of the phase-locked response in the frequency band under consideration, the IVM method enhances hence non-phase-locked activities. Although such method allows assessing the time evolution of the ERD/ERS, it cannot be considered a fully time-domain technique, since the ongoing EEG is not obtained.

Infantosi and Miranda de Sá (2006) proposed a frequency-domain approach for separating the ongoing EEG activity spectrum from that of the ERP during IPS. The methodology is based on the coherence estimate between the stimulation signal and the EEG. It has been proved in such work that this coherence-based method is asymptotically equivalent to the IVM one, with the additional benefit of not requiring bandpass filtering the signal. Furthermore, a statistical criterion was applied to reduce spurious spectral peaks. The performance of this procedure was assessed throughout simulation and illustrated with EEG during photic stimulation. However, as the IVM method, this one does not allow the ongoing EEG to be obtained, but rather only its power spectrum estimate.

In Miranda de Sá and Infantosi (2007), the partial coherence (i.e. the coherence between two signals after removal of the linear contribution from a group of other signals) for taking away the contribution from the stimuli has been proposed, in order to quantify the similarity between two EEG activities that are not phase-locked to the stimulating signal. The method should allow a more suitable evaluation of the ongoing multichannel EEG relationship. Thus, this partial coherence estimate, together with simple coherence, might be useful in order to quantify the relationship between cortical activities that would not be completely synchronized to the stimulating signal, but that could reflect time-locked spectral changes.

Blind source separation (BSS) techniques may also be used for separating time-locked and phase-locked activities. In general, such techniques use acquired data for obtaining sources that had been previously mixed with no a priori knowledge on the sources and neither on the mixing process. They are typically based on second order and/or higher order statistics. As a matter of fact, BSS techniques have been widely used in the EEG analysis (Congedo et al., 2008). Independent Component Analysis (ICA) (Hyvärinen et al., 2001) is one of the most BSS used techniques. It assumes the sources to be mutually independent.

ICA has been successfully applied to the EEG for denoising and non-cephalic artifacts removal purposes (Akhtar et al., 2012; Klados et al., 2011; McMenamin et al., 2010). It has also been applied to the multi-channel EEG (Onton et al., 2006) and to event-related potentials (Lemm et al., 2006). In this latter work, it was proposed the use of prior information about the phase-locked activity to bias the ICA algorithm toward improving the separation of single-trial event-potentials. Although the technique could enhance the signal-to-nose ratio in the extracted evoked responses, it might not apply to time-locked activities. This is because it had been tailored as a trade-off between single-trial decomposition and the separation of average responses, which is not the scenario of time-locked activities. Additionally, there is some evidence that multi-trial evoked EEG data from different electrodes may not fulfill the independence assumption of the hidden components (Metsomaa et al., 2014). Thus, the separation of phase-locked and non-phase locked EEG activities based on the ICA applied to the multichannel EEG may not lead to suitable results.

Ferreira et al. (2009) proposed a methodology to investigate ERD/ERS, which uses the stimulation signal as an observed source to be presented to the ICA algorithm along with two EEG signals acquired from two homologue EEG deviations. Results with simulated signals showed that the methodology allows separating the