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A potential real-time procedure to evaluate correlation of recordings among single trials (CoRaST) for mismatch negativity (MMN) with Fourier transformation

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HIGHLIGHTS

- CoRaST and ITC measure the correlation of 330 single trials' EEG recordings in 0.12 second and 45 seconds with the normal workstation, respectively.
- The correlation of ERP activity among single trials can be immediately inspected during the ERP data collection in a real-time system with CoRaST.
- CoRaST can be facilitated to study event-related potentials of evoked and induced brain activities simultaneously.

ABSTRACT

Objective: To design a fast algorithm that evaluates the degree of correlation of recordings among single trials (CoRaST) for mismatch negativity (MMN) activity.
Methods: The participants were 114 children, aged 8–16 years. MMNs were elicited by two deviants in duration that occurred in an uninterrupted sound within a passive oddball paradigm, and each trial lasted 650 ms with 130 samples. CoRaST was derived from the frequency-domain MMN model through Fourier transformation. To validate the effectiveness of the proposed method, the wavelet transformation-based inter-trial coherence (ITC) was taken as a reference.
Results: Performances of the proposed CoRaST and ITC were similar in evaluating the correlation of MMN activity among single trials. However, the analysis of electroencephalograph (EEG) recordings comprising approximately 330 trials at one channel took approximately 0.12 s with CoRaST, whereas ITC required approximately 45 s in our workstation.
Conclusions: CoRaST has the potential to evaluate the correlation of MMN activity among single trials in a real-time system. Furthermore, the new method can be facilitated to study other event-related potentials (ERPs) of evoked or induced brain activity.
Significance: The correlation of ERP activity among single trials can be immediately inspected during the ERP data collection in a real-time system.

1. Introduction

Mismatch negativity (MMN) was first identified by Professor Risto Näätänen and colleagues in 1978 (Näätänen et al., 1978). It is a negative event-related potential (ERP) (Luck, 2005), and describes an automatic process that detects the difference between a deviant stimulus and the preceding repeated stimuli (Näätänen, 1992). Today, MMN plays a pivotal role in research into cognition, clinical neuroscience and neuropharmacology (Duncan et al., 2009; Garrido et al., 2009). The peak amplitude of an MMN component is usually up to several microvolts. Consequently, the signal-to-noise ratio (SNR) of MMN in electroencephalograph (EEG) recordings is very low, and hundreds of trials are often collected to produce a satisfactory MMN component through the averaging of the single trials (Näätänen, 1992). Indeed, the well-structured MMN waveform corresponds to the expectation that the brain activities of MMN elicited by the same type of stimulus are similar among single trials. Furthermore, in this case, the EEG recordings that represent the responses from

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the same type of stimulus must be correlated among single trials. Thus, the revelation of such correlation becomes important in the study of MMN and other ERPs.

Currently, inter-trial coherence (ITC) is often used to measure the phase synchronism of EEG recordings among single trials at a certain frequency and time in the study of EEG/ERPs (Bardouille and Ross, 2008; Delorme and Makeig, 2004; Perez-Alcazar et al., 2010; Tallon-Baudry et al., 1996; Trujillo and Allen, 2007; Will and Berg, 2007). In fact, what ITC reveals is the degree to which EEG recordings correlate among single trials at a certain frequency and time. The value of ITC ranges from 0 to 1. Under perfect synchronization between EEG recordings and the time-locked event, the value of ITC approaches 1 and the value of 0 means that the synchronization does not exist and EEG recordings are independent of the stimulus (Delorme and Makeig, 2004). There are typically three steps to the calculation of ITC (Delorme and Makeig, 2004). The first implements the normalized time–frequency analysis (complex valued) on the recordings of each trial; the second obtains the average (complex valued) over the normalized time–frequency analysis of all trials; and the third achieves the magnitude of this average to gain the ITC. Thus, ITC is based on the time–frequency analysis. Furthermore, wavelet transformation is frequently used (Bardouille and Ross, 2008; Delorme and Makeig, 2004; Perez-Alcazar et al., 2010; Tallon-Baudry et al., 1996; Trujillo and Allen, 2007; Will and Berg, 2007). The calculation of this time–frequency transformation is the main computation of ITC. As one of the aims for MMN assessment is to take as little time as possible, particularly when the participants are children or the vulnerable groups, some MMN-elicitation paradigms have been designed to collect hundreds of trials in only a few minutes (Huttunen et al., 2007; Näätänen et al., 2004; Pakarinen et al., 2007, 2009, 2010; Pihko et al., 1995). This short time frame, coupled with a large number of EEG trials, places demands on the multichannel recording system hardware and presents a real challenge to the calculation of ITC online.

The goal of this study is therefore to develop a fast algorithm that measures the extent of correlation of recordings among single trials (CoRaST). The EEG recordings of one trial at one electrode can be represented by a vector of samples. Mathematically, it is very convenient to acquire the correlation of two vectors by calculating their correlation coefficient. In short, it is simple to calculate the correlation of EEG recordings between two single trials. However, as mentioned earlier, the production of a satisfactory MMN component often requires hundreds of trials for the averaging and, consequently, the problem turns to measure the extent of correlation among hundreds of vectors. To achieve this goal, we implement a frequency-domain MMN model in this study. The model has been developed in our previous report and is composed of a complex-valued vector at each frequency bin within the MMN frequency range (Cong and Ristaniemi, 2008). This vector consists of the Fourier-transformed data of all trials at the same frequency bin. Then, the correlation coefficient of the real part and the imaginary part of this complex-valued vector represents the extent of correlation of MMN activity among single trials at a given frequency bin. The advantage of the proposed parameter is that it requires much less computation with Fourier transformation than is required by ITC for wavelet transformation.

For completeness, the frequency-domain MMN model will be illustrated in detail within Section 2. This study will contrast the effectiveness of both the CoRaST method and the ITC method in measuring the extent to which EEG recordings correlate among hundreds of single trials from the MMN recordings of children. The computational complexity of CoRaST and ITC methods is naturally of interest. It is expected that the computing efforts are reduced dramatically when considering CoRaST, even though the performances of CoRaST and ITC are otherwise quite the same.

2. Methods

2.1. CoRaST

Assume $s(n,l)$ is the nth sample of the recording at the lth trial. The Fourier transformation (Mitra, 2005) of the recordings of one trial can be defined as

$$S_k(l) = \sum_{n=1}^{N} s(n,l)\exp\left(-2\pi i\frac{n}{N}k\right) = \sum_{n=1}^{N}\left[s(n,l)\cos\alpha_k^n - i\cdot s(n,l)\sin\alpha_k^n\right], \quad (1)$$

where $\exp(\cdot)$ is the exponential function, k $(k=1,\ldots,K)$ denotes the frequency bin, $i^2=-1$, $\alpha_k^n = 2\pi\frac{n}{N}k$, n represents the sample index of the recordings, and N is the number of samples recorded within one trial. The real and imaginary parts of $S_k(l)$ are written as $S_k^R(l)$ and $S_k^I(l)$, respectively, as below:

$$S_k^R(l) = \sum_{n=1}^{N} s(n,l)\cos\alpha_k^n, \quad (2)$$

$$S_k^I(l) = -\sum_{n=1}^{N} s(n,l)\sin\alpha_k^n. \quad (3)$$

Then, the frequency-domain MMN model at the kth frequency bin can be represented as

$$\mathbf{S}_k = [S_k(1),\ldots,S_k(l),\ldots,S_k(L)], \quad (4)$$

where L denotes the number of trials. At the kth frequency bin, the two row vectors are defined as

$$\mathbf{S}_k^R = [S_k^R(1),\ldots,S_k^R(l),\ldots,S_k^R(L)], \quad (5)$$

$$\mathbf{S}_k^I = [S_k^I(1),\ldots,S_k^I(l),\ldots,S_k^I(L)]. \quad (6)$$

Cong and Ristaniemi (2008) have shown that $\mathbf{S}_k^R$ and $\mathbf{S}_k^I$ correlate with each other when the waveform of a signal has the temporal structure and property. Furthermore, each vector contains the information of all single trials at a certain frequency bin in the study of ERPs. As a result, the correlation coefficient of $\mathbf{S}_k^R$ and $\mathbf{S}_k^I$ reveals the coherence of EEG recordings among all single trials at a certain frequency bin. This is defined below in this study as

$$\rho(k) = \left|\frac{\frac{1}{L}\sum_{i=1}^{L}\left[S_k^R(l)-\mu_k^R\right]\cdot\left[S_k^I(l)-\mu_k^I\right]}{\sigma_k^R\cdot\sigma_k^I}\right|, \quad (7)$$

$$\mu_k^R = \frac{1}{L}\sum_{l=1}^{L} S_k^R(l), \quad (7\text{-}1)$$

$$\sigma_k^R = \sqrt{\frac{1}{L}\sum_{l=1}^{L}\left[S_k^R(l)-\mu_k^R\right]^2}, \quad (7\text{-}2)$$

where μ_k^R and μ_k^I are the means of $\mathbf{S}_k^R$ and $\mathbf{S}_k^I$, respectively, σ_k^R and σ_k^I correspondingly represent the standard derivations (SDs) of $\mathbf{S}_k^R$ and $\mathbf{S}_k^I$ and $|\cdot|$ stands for the absolute value operation. After the correlation coefficients at all frequency bins of interest are computed, the CoRaST is defined by averaging those coefficients through,

$$\text{CoRaST} = \frac{1}{k_2-k_1+1}\sum_{k_1}^{k_2}\rho(k), \quad (8)$$

where k_1 and k_2 are the frequency bins corresponding to the frequency band of the studied ERP. The goal of measuring the correlation of EEG recordings among more than two trials is then achieved.