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Sequence detection analysis based on canonical correlation for steady-state visual evoked potential brain computer interfaces

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HIGHLIGHTS

- A novel approach based on sequence detection (SD) is proposed for improving the performance of SSVEP recognition.
- In comparison with other resultful algorithms, experimental accuracy of the SD approach was better than those using other methods.
- It was implicated that our approach could improve the speed of BCI system in contrast to other methods.

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ABSTRACT

Background: Steady-state visual evoked potential (SSVEP) has been widely applied to develop brain computer interface (BCI) systems. The essence of SSVEP recognition is to recognize the frequency component of target stimulus focused by a subject significantly present in EEG spectrum.

New method: In this paper, a novel statistical approach based on sequence detection (SD) is proposed for improving the performance of SSVEP recognition. This method uses canonical correlation analysis (CCA) coefficients to observe SSVEP signal sequence. And then, a threshold strategy is utilized for SSVEP recognition.

Results: The result showed the classification performance with the longer duration of time window achieved the higher accuracy for most subjects. And the average time costing per trial was lower than the predefined recognition time. It was implicated that our approach could improve the speed of BCI system in contrast to other methods.

Comparison with existing method(s): In comparison with other resultful algorithms, experimental accuracy of SD approach was better than those using a widely used CCA-based method and two newly proposed algorithms, least absolute shrinkage and selection operator (LASSO) recognition model as well as multivariate synchronization index (MSI) method. Furthermore, the information transfer rate (ITR) obtained by SD approach was higher than those using other three methods for most participants.

Conclusions: These conclusions demonstrated that our proposed method was promising for a high-speed online BCI.

1. Introduction

Steady-state visual evoked potentials (SSVEPs) are elicited with one certain frequency by rapidly repetitive flickering stimulus. The SSVEP contains a series of discrete frequency components. The frequency component is derived from the fundamental frequency of the visual stimulus and its harmonics (Middendorf et al., 2000; Gao et al., 2003; Müller-Putz et al., 2005; Cecotti, 2010; Gollee et al., 2010). This signal is often extracted noninvasively from electroencephalography (EEG) for brain computer interfaces (BCIs). Recent studies indicated that SSVEPs had higher classification accuracy than other EEG patterns, such as P300 and event-related desynchronization/synchronization (ERD/ERS) (Friman et al., 2007; Parini et al., 2009; Guger et al., 2012). And a great number of SSVEP-based BCIs had been developed for human–computer communication (Wolpaw et al., 2000, 2002; Moore, 2003; Kelly et al., 2005; Xia et al., 2013).

Several classification methods based on frequency features had been proposed for SSVEP-based BCIs (Palaniappan et al., 2002; Lotte et al., 2007; Middendorf et al., 2000; Gao et al., 2003; Lalor

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et al., 2005; Mukesh et al., 2006; Muller-Putz and Pfurtscheller, 2008; Liavas et al., 1998; Müller-Putz et al., 2005, 2008; Wu and Yao, 2008). The traditional frequency domain analysis for SSVEP detection was power spectral density-based analysis (PSDA) (Middendorf et al., 2000; Gao et al., 2003; Lalor et al., 2005; Mukesh et al., 2006; Liavas et al., 1998). Power spectral density was evaluated from the user's EEG signal within a time window. It could be estimated by fast Fourier transform (FFT). Subsequently, the frequency corresponding to the peak value was considered as the evoked target stimulus. Müller-Putz et al. (2005, 2008) made use of distinctive sensitive learning vector quantization (DSLVQ) and lock-in analyzer system (LAS) to improve the feature extraction based on spectral information. This strategy significantly increased the classification accuracy compared to PSDA. Moreover, an assisted closed loop (ACL) algorithm was present for optimizing spectrum-based SSVEP recognition (Fernandez-Vargas et al., 2013). Wu and Yao (2008) proposed the stability coefficient (SC) model to improve the performance of SSVEP-based BCIs within a short time window of EEG signals.

In addition to spectral features, it was demonstrated that phase-coded information was feasible to decode SSVEP signals (Jia et al., 2011; Manyakov et al., 2012, 2013). Typically, Jia et al. (2011) presented frequency and phase mixed coding to improve the target identification accuracy. Although useful, this approach was still restricted by individual different phase-lags. The individual precise phase-lag was mainly dependent on the preliminary training for phase coding.

Above algorithms required a mass of training samples to construct the classifier except for PSDA. However, PSDA was sensitive to external noise. Friman et al. (2007) proposed a minimum energy method (MEC) without calibration working for SSVEP detection. This method canceled the strong nuisance signals to obtain a better signal-to-noise ratio (SNR). Nevertheless, the computations cost had an adverse effect on the real-time BCI application. And canonical correlation analysis (CCA) method using channel covariance information was applied to increase the SNR and reduce the computational cost for online systems (Lin et al., 2006). CCA reflected the correlation relationship between EEG response signals and classical Fourier series at the stimulus frequency and its harmonics. Bin et al. (2009) used CCA algorithm to develop an online BCI system for detecting SSVEP signals without complicated training procedures. In addition, an unsupervised least absolute shrinkage and selection operator (LASSO) model was applied to recognize SSVEP signals to achieve the better effect than that of CCA in a short time window (e.g. 2 s) (Zhang et al., 2012). Recently, a new multivariate synchronization index (MSI) algorithm was proposed for SSVEP recognition (Zhang et al., 2014). This method showed better performance than CCA and MEC when using short length data and small number of channels. However, these methods just reflected the correlation between EEG time series and reference signals at a given time. It was difficult to judge the exact time point when the spectral feature achieved the steady state affected by individual difference, background noise and environmental factors. In this paper, we proposed an innovative frequency recognition approach based on sequence detection (SD), which made use of CCA coefficients for solving this problem. The method was widely used for predicting the exponent of the probability of symbol error in the communication engineering (Bussgang and Middleton, 1955; Hayes et al., 1982; Chaudhari et al., 2009).

The theory of SD was proposed by Wald in 1943 (Wald, 1943). The statistical hypothesis of this method was meant any statistical test procedure which gave a rule, at any time point of the experiment, for making one of the following three decisions: (1) to accept the hypothesis, (2) to reject the hypothesis, and (3) to continue the experimental procedure for receiving additional information. Note that such a test experiment was carried out sequentially. When the first or second decision was made at one certain time point, the experiment was terminated. Whereas the experiment was performed continuously while the third decision was made. This procedure had not been terminated until the first or second decision was made in one certain time window. In previous studies, Jin et al. (2011) regulated the time window of the average trial length to reduce the time costing of target detection for a P300-based BCI. Differently, another adaptive approach was used for regulating the time window of one subtrial and moving time window between consecutive calculations to reduce the recognition time (Wang et al., 2006). And a decision would be made if the same frequency was detected in several consecutive calculations. In our study, this SD method based on CCA coefficients was utilized for selecting the most probable stimulus frequency. The identical parameters were regulated for increasing the SNR and classification accuracy. Compared with the simple method of voting, our proposed method took advantage of the cumulative effect of multiple recognizing CCA coefficients to eliminate the noise disturbance. Then, a novel threshold strategy was used for making the decision of frequency detection. This methodology improved the systematical efficiency for SSVEP-based BCI under the condition of the simple parameters optimization.

2. Methodology

The flowchart of sequence detection analysis based on canonical correlation is illustrated in Fig. 1. Raw data are segmented in several subtrials based on sequence detection. Then, it is calculated by CCA method and frequency component analysis is performed for target recognition. Other comparative methods are also listed in this section.

2.1. Instantaneous probability analysis based on CCA

The instantaneous probability represents the probability that the frequency of the corresponding SSVEP component is recognized at the instantaneous time point. The effectiveness of CCA has been demonstrated in Bin et al. (2009). Thus, we use CCA coefficients to reflect the instantaneous state in our method. CCA is a well-known multivariable method for two sets of data, which may have the underlying correlation. The working hypothesis of the method is that the source signal for SSVEP, X, is the output of a linear system with the stimulus signal, Y, as the input. Y, at a certain frequency f can be decomposed into the Fourier series of its harmonics ($\sin(2\pi ft), \cos(2\pi ft), \sin(4\pi ft), \ldots$):

$$Y = \begin{cases} \sin(2\pi ft) \\ \cos(2\pi ft) \\ \sin(4\pi ft) \\ \cos(4\pi ft) \\ \sin(6\pi ft) \\ \cos(6\pi ft) \end{cases} \quad t = \frac{1}{S}, \frac{2}{S}, \ldots, \frac{T}{S} \tag{1}$$

where f is the fundamental frequency, T is the number of sampling points and S is the sample rate. The algorithm can find a pair of linear combinations, $x = X^T W_X$ and $y = Y^T W_Y$, for X and Y, to maximize the correlation between two canonical variables, x and y, by solving the following optimization problem:

$$\max_{W_X, W_Y} \rho(x, y) = \frac{E[x^T y]}{\sqrt{E[x^T x]E[y^T y]}} = \frac{E[W_X^T X Y^T W_Y]}{\sqrt{E[W_X^T X X^T W_X]E[W_Y^T Y Y^T W_Y]}} \tag{2}$$