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Research Report

A new dual-frequency stimulation method to increase the number of visual stimuli for multi-class SSVEP-based brain–computer interface (BCI)

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ABSTRACT

In the present study, we introduce a new dual-frequency stimulation method that can produce more visual stimuli with limited number of stimulation frequencies for use in multiclass steady-state visual evoked potential (SSVEP)-based brain–computer interface (BCI) systems. Methods for increasing the number of visual stimuli are necessary, particularly for the implementation of multi-class SSVEP-based BCI, as available stimulation frequencies are generally limited when visual stimuli are presented through a computer monitor. The new stimulation was based on a conventional black–white checkerboard pattern; however, unlike the conventional approach, ten visual stimuli eliciting distinct SSVEP responses at different frequencies could be generated by combining four different stimulation frequencies. Through the offline experiments conducted with eleven participants, we confirmed that all ten visual stimuli could evoke distinct and discriminable single SSVEP peaks, of which the signal-to-noise ratios were high enough to be used for practical SSVEP-based BCI systems. In order to demonstrate the possibility of the practical use of the proposed method, a mental keypad system was implemented and online experiments were conducted with additional ten participants. We achieved an average information transfer rate of 33.26 bits/min and an average accuracy of 87.23%, and all ten participants succeeded in calling their mobile phones using our online BCI system.

1. Introduction

Brain–computer interface (BCI) is a novel mode of communication that can help paralyzed individuals operate external devices or communicate with others using their brain signals (Wolpaw et al., 2002). Diverse types of experimental paradigms and tasks have been used to realize electroencephalography (EEG)-based BCI systems, e.g., steady-state visual evoked potential (SSVEP) (Bakardjian et al., 2010; Cheng et al., 2002; Volosyak, 2011), mu rhythm (Blankertz et al., 2007; Hwang et al., 2009; Pfurtscheller et al., 2006), slow cortical potential (SCP) (Birbaumer et al., 1999), and event-related p300 (Hoffmann et al., 2008; Sellers et al., 2010). Among them, SSVEP-based BCI systems have advantages over the other paradigms in that they

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provide a high information transfer rate (ITR), require relatively few electrodes, and generally do not need any training, compared to the requirements of other BCI systems (Vialatte et al., 2010; Zhu et al., 2010; Volosyak, 2011).

SSVEP is a periodic brain electrical response induced by the repetitive presentation of a visual stimulus, flickering or reversing at a certain frequency ranging from 1 Hz to 60 Hz (Zhu et al., 2010). Although SSVEP can be elicited by a broad range of frequencies, the available frequencies in practical BCI applications are often restricted by several factors. First, all available stimulation frequencies do not always evoke high SSVEP responses. The frequencies that elicit strong SSVEP responses are highly dependent upon the participants, as well as various properties of the visual stimuli, such as color, size, and contrast (Zhu et al., 2010). Second, the use of two frequencies, F_1 and F_2, in the same experiment has been typically avoided when F_1 is a multiple of F_2 or vice versa because of the harmonic SSVEP responses (Bakardjian et al., 2010; Cheng et al., 2002; Shyu et al., 2010); simultaneous use of those frequencies could significantly decrease the performance of SSVEP-based BCI systems. Third, the frequencies in the alpha band (8–13 Hz) should be carefully selected because its use has been attributed to a considerable number of false positives (Cheng et al., 2002; Zhu et al., 2010). Fourth, it is rare but sometimes possible that some visual stimuli with flickering frequencies in the 15–25 Hz frequency band may provoke epileptic seizures (Fisher et al., 2005). Most importantly, when using a monitor as a rendering device, stimulation frequencies have to be set as sub-harmonics of the monitor refresh rate (usually 60 Hz) to attain accurate SSVEP responses (Yan et al., 2009; Zhu et al., 2010). Therefore, one of the challenging issues in SSVEP-based BCI studies is to make the best use of available frequencies, particularly when using the computer monitor to implement a multi-class SSVEP-based BCI system.

Recently, a few methods based on dual-frequency stimulation have been studied for the production of more distracters than the number of stimulation frequencies (Mukesh et al., 2006; Shyu et al., 2010; Yan et al., 2009). For example, one study showed that a single visual stimulus modulated with two different frequencies, F_1 and F_2, could elicit SSVEP responses at F_1, F_2, F_1+F_2, and their harmonics (Mukesh et al., 2006). Based on this phenomenon, three different types of visual stimuli could be generated using two flickering frequencies F_1 and F_2 (first stimulus modulated with a single frequency F_1, second stimulus modulated with F_2, and third stimulus modulated with both F_1 and F_2). This study demonstrated the possibility of increasing the number of selections using fewer numbers of frequencies; however, unfortunately, the concept was not expanded to more than two frequencies.

More recently, two other studies used two closely-spaced visual stimuli each flickering at different frequencies (Shyu et al., 2010; Yan et al., 2009). Although these studies used different rendering devices and different strategies for extracting SSVEP features, they used a common stimulation strategy. In both studies, participants were asked to focus their eyes on the middle of the two flickering points, and the SSVEP responses at two main frequencies were used as the main feature vectors for classification (Shyu et al., 2010; Yan et al., 2009). However, it was observed in both previous studies (Shyu et al., 2010; Yan et al., 2009) as well as in preliminary experiments of our study that the spectral powers at two stimulation frequencies were not consistent with respect to time, which was because the participants shifted their attention from the middle of the visual stimuli to one of the two stimuli (Gao et al., 2000; Yan et al., 2009). Indeed, in Yan et al.'s (2009) study, two out of eight participants had difficulty in maintaining their concentration on the middle of two visual stimuli, and thereby they did not show high classification accuracy. Consequently, this type of visual stimuli could cause a number of false positives and requires more complicated classification algorithms to enhance the detection accuracy.

The goal of the present study was to provide an efficient dual-frequency stimulation method that can address the 'attention-shift' problems of the conventional dual-frequency stimulation methods. To this end, a pattern-reversal checkerboard stimulus consisting of black and white squares was modulated with two stimulation frequencies. In the offline study, EEG signals were recorded from 11 participants while they were staring at the new checkerboard pattern stimuli modulated with two frequencies. The power spectral analysis was applied to the recorded EEG data and SSVEP signal-to-noise ratios (SNRs) were evaluated to verify the feasibility of the proposed dual-frequency stimulation method. For the online experiment, we implemented a mental keypad system consisting of twelve visual stimuli generated by the proposed dual-frequency stimulation method, and evaluated the performance of the mental keypad system with ten additional participants.

2. Results

2.1. *Offline experimental results*

2.1.1. *The conventional dual-frequency stimulation method*

Before the main experiments, a conventional dual-frequency stimulation method was replicated to demonstrate the limitation of the conventional dual-frequency stimulation approach. In order to observe the SSVEP responses evoked by the conventional dual-frequency stimulation method, two flashing squares, each of which subtended a visual angle of 1.43° both vertically and horizontally, were placed in a row, with a 0.5 cm inter-stimulus distance, on a gray background. Fig. 1 shows the conventional dual-frequency visual stimulus used in this study. Each square flashed with white (ON) and black (OFF) colors at given stimulating frequencies, respectively. Six dual-frequency visual stimuli were generated by combining four different flickering frequencies (Shyu et al., 2010). The selected four stimulation frequencies were 6 Hz, 6.66 Hz, 7.5 Hz, and 8.57 Hz, which corresponded to the frequencies of classical pattern reversal checkerboard stimuli used in our offline studies.

Fig. 2(a)–(d) shows the representative examples of the time–frequency spectral power maps acquired while a participant (P1) was focusing on the conventional dual-frequency visual stimuli for 30 s. In those examples, it was observed that the frequency evoking a strong SSVEP response was time-varying. For example, in the first example (Fig. 2(a)), the