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"Eyes-Closed" SSVEP-Based BCI for Binary Communication of Individuals With Impaired Oculomotor Function

J.-H. Lim[1], H.-J. Hwang[1], C.-H. Han[1], C.-H. Im[1]
[1]*Hanyang University, Seoul, Korea*

Correspondence: C.-H. Im, Department of Biomedical Engineering, Hanyang University, 222 Wangsimni-ro, Seongdong-gu, Seoul, 133-791, Republic of Korea. E-mail: ich@hanyang.ac.kr

Abstract. In this study, we propose a new paradigm for steady-state visual evoked potential (SSVEP)-based brain-computer interface (BCI), which can be potentially suitable for disabled individuals with impaired oculomotor function. The proposed electroencephalography (EEG)-based BCI system allows users to express their binary intentions without a need to open their eyes. A pair of glasses with two light emitting diodes (LEDs) flickering at different frequencies was used to present visual stimuli to 12 participants with their eyes closed. Through offline experiments performed with 11 healthy participants, we confirmed that human SSVEP could be modulated by visual selective attention to a specific light stimulus penetrating through the eyelids. After customizing the parameters of the proposed SSVEP-based BCI paradigm based on the offline analysis results, binary intentions of five healthy participants and one ALS patient were classified in real time. The average ITR of five healthy participants reached 10.83 bits/min, and the ITR of the ALS patient was 2.78 bits/min, demonstrating the feasibility of our BCI.

Keywords: Steady-State Visual Evoked Potential (SSVEP), Brain-Computer Interface (BCI), Eyes-Closed BCI, EEG, ALS Patient

1. Introduction

One of the most widely studied EEG-based BCI paradigm is the SSVEP, which is a periodic neural response elicited by a certain visual stimulus flickering or reversing at a specific frequency. The conventional SSVEP-based BCI systems can provide a high information transfer rate (ITR) and do not require extensive training procedures, but commonly require the basic assumption that the users have normal oculomotor function and are thus able to maintain an open gaze at a given visual stimulus consistently. In practice, however, it has been reported that some patients suffering from serious neuromuscular disorders have difficulty controlling their eyes [Balaratnam et al., 2010]. In particular, many ALS patients have oculomotor impairments causing abnormal visual perception [Okuda et al., 1992]. The main goal of the present study was to develop a new SSVEP-based BCI system that can be potentially used for classifying binary intentions of individuals who have impaired oculomotor function and thus cannot easily use the conventional SSVEP-based BCI systems.

2. Material and Methods

2.1. Design of A Visual Stimulation System

In order to present flickering visual stimuli to eyes-closed participants, we implemented a new visual stimulation system using a pair of glasses, LEDs, and an LED controller as shown in Fig. 1(a). As shown in Fig. 1(b), each LED channel attached at the lateral side of each eye flickered at different frequency. A frequency band of 7-17 Hz was empirically selected as the stimulation frequency band. The frequency band was then divided uniformly into increments of 1 Hz, leading to 11 candidate stimulation frequencies. Since the stimulation frequencies modulating the strongest SSVEP responses differ from one individual to another, different combinations of two stimulation frequencies were determined for each participant.

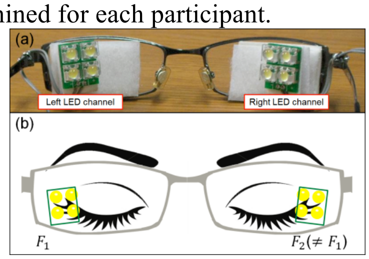

Figure 1. *(a) The newly developed visual stimulation system. (b) A schematic representation of the visual stimulation system.*

2.2. Experimental Procedures

Eleven healthy participants (P1-P11) were recruited for our preliminary offline experiments. They were required to gaze on either the left or right LED for 10 s with their eyes closed, this procedure was repeated 100 times to obtain 50 epochs of SSVEP responses for each of the 'left' and 'right' trials. To acquire EEG data, eight electrodes (POz, PO1, PO2, PO3, PO4, Oz, O1, and O2) were attached to the participants' scalps. We used a simple classification algorithm that searches for the frequency with the largest SSVEP amplitudes.

Five healthy participants (P7-P11) took part in online experiments. According to online experimental paradigm, the participants should begin concentrating on the designated visual stimulus for a certain period. We tested four time periods (2, 3, 4, and 5 s) to investigate changes in the performance of our BCI paradigm. An experimental session consisting of 10 trials (five for left stimulus and five for right stimulus) was repeated three times for each of four different time periods. In addition, an ALS patient (male) who can hardly move his eyeballs and eyelids was recruited, and answered ten yes/no questions using our system. He was asked to attend on the left LED to answer 'yes' and the right LED to answer 'no'. In the online experiments, we used the same classification strategy as in the offline study.

3. Results

In the offline experiments, the average classification accuracy was 74.8% when the analysis window size was 1 s, and it exceeded 90% when the analysis window size was longer than 4 s, demonstrating that the SSVEP responses obtained from individuals with their eyes closed can be classified with high accuracy.

Table 1 shows the results of online experiments with respect to different time periods. The time listed in the second row in the table is that allotted for gazing at each designated stimulus. As shown in the table, the average classification accuracy increased as the time period increased (2 s: 81.3%, 3 s: 90.0%, 4 s: 95.3%, and 5 s: 96.0%). It is worthwhile to note that the average classification accuracy was 81.3% even when the time period was only 2 s, demonstrating that our paradigm could be used for a BCI system requiring quick responses. The highest average ITR was obtained when the given time period was 4 s, suggesting that the trade-off between classification accuracy and ITR should be carefully considered. In the case of the ALS patient, the classification accuracy and ITR were 80% and 2.78 bits/min (the time period: 6 s), demonstrating the practical feasibility of our BCI paradigm.

Table 1. *Results of online experiments with respect to different time periods.*

Participants	Electrodes	Classification accuracy (%)			
		2 s	3 s	4 s	5 s
P7	PO2, O2	80.0	100.0	93.3	100.0
P8	Oz, O2	80.0	80.0	93.3	90.0
P9	POz, PO2	96.7	96.7	100.0	100.0
P10	Oz, O1	73.3	83.3	96.7	93.3
P11	POz, PO2	76.7	90.0	93.3	96.7
Average		81.3	90.0	95.3	96.0
ITR (bits/min)		9.21	10.62	10.83	9.09

4. Discussion

In this paper, we developed a new SSVEP-based BCI system that can be potentially used for classifying binary intentions of individuals who have impaired oculomotor function. Our experimental results demonstrated that the proposed SSVEP-based BCI paradigm for 'eyes-closed' individuals could be used for a practical BCI system.

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