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Toward Binary Brain Computer Interface Using Steady-State Visually Evoked Potential under Eyes Closed Condition*

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Abstract— **It is highly difficult for severely amyotrophic lateral sclerosis and heavily spinal cord injury patients to use the brain computer interfaces (BCIs) based on the steady-state visual evoked potential (SSVEP) which need to control the direction of their eye gaze. We investigated amplitude change of the SSVEP associated with mental concentration on flicker to develop the SSVEP-based BCI usable under eyes-closed condition. Under the stimulus conditions of the flickering frequency of 10 Hz and the stimulus intensity of 5 lx, significant difference between the SSVEP amplitude in relaxed state and that in concentrated state was observed in the wide region of the scalp except the left frontal region, while such significance was also seen in the bilateral occipital lobes and left parietal region under the conditions of 14 Hz and 5 lx. Such an impact of mental concentration on the SSVEP amplitude was reproducible.**

I. Introduction

Recently many laboratories in the field of biomedical engineering are enthusiastically studying the brain computer interface (BCI) using EEG for communication tool and neural prosthetics for motor disabilities. This class of BCI detects changes of EEG and translates them into commands to computer or nurse robot to communicate and control. Recent progress in the BCI has accomplished outstanding results in the information transfer rate and classification accuracy [1]. Moreover, the BCI is also expected to apply to hands/voice-free games and control of home electronics .

A steady-state visual evoked potential (SSVEP) is an EEG component synchronized with flicker stimuli. Since the amplitude of the SSVEP is larger than other EEG components used for the BCI such as mu-rhythm, P300 and slow cortical potentials, there have been developed many BCIs based on SSVEP (SSVEP-BCI). The SSVEP-BCI utilizes increase of the SSVEP amplitude at a stimulus frequency of one flickering icon a user chooses and gazes among spatially-arranged icons flickering at different frequencies one another [2][3].

However, conventional SSVEP-based BCIs need eye-gaze of a user, which may elicit intensive fatigue. Furthermore, the eye-gaze action is very strenuous demands on severe physical disabilities, namely, “locked-in” patients such as serious amyotrophic lateral sclerosis and heavily spinal cord injury patients. Although superimposed two icons with different figures or colors have been used to avoid a shift of eye-gaze for users [4][5], classification accuracy may be deteriorated. It is still requisite to open and close user’s eyes even for such improved systems.

Thus the SSVEP-based BCI available for the locked-in patients who cannot open / close their eyes has not been developed yet. Recently we found that the amplitude of the SSVEP under eyes-closed condition was affected by mental concentration on flicker stimuli [6]. Mental focusing does not require eye-open / close and this observation suggests the possibility of a novel binary class of SSVEP-BCI under eye-closed condition which can be used for the locked-in patients. The present study investigated the inter-individual difference and stimulus-frequency-dependence of the impact of the mental concentration on the SSVEP amplitude.

II. Methods

A. Subjects and Experiments

We recruited 16 healthy male students aged from 21 to 44 years old as subjects. EEG was recorded from 13 electrodes placed at the sites determined using the 10-20 system of electrode placement. The linked-earlobe potential was used as the reference for the mono-polar derivation (Fig. 1). Informed consent was obtained from all the subjects in accordance with the tenets of the Declaration of Helsinki.

Eight red light emitting diodes (LEDs) (OptoSpply, OSHR516A-QR, half intensity angle: 30deg, wavelength: 625 nm) were used for the flicker stimuli. Four LEDs, arranged in a two-by-two matrix were located in front of both eyes with the distance of 70 mm from the top of LEDs, respectively. All the LEDs were flickered in synchronization with stimulus frequency. The light intensity was measured at the eye position by using a Topcon IM-5 illumination meter.

The electrooculogram (EOG) was also measured from the bilateral temples in order to check the eye-movement in the mental concentration on the flicker stimuli. In the present study, no obvious eye-movement to flicker stimuli was found in both the mental concentration and non-concentration (the latter will be referred as to be a relaxed state).

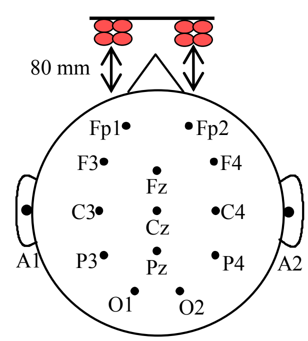

Figure 1. Electrode placement (10-20 system, Top view)

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The EEG-5532 (Nihon Koden) was used for measurement of EEG and EOG simultaneously. The EEG and EOG measured were digitized at a sampling rate of 200 Hz/ch and the 12-bit amplitude resolution.

Table I shows the experimental conditions for the stimulus frequency and mental state (concentration/relax). All the trials were conducted under the eye-closed condition. The duration of each trial is 20 s and the minimal duration of inter-trials is about 10 s. In runs of "relaxed" state ("R1" and "R2" in Table I), all the subjects were directed to be relaxed and not to be nervous about the flicker stimuli, whereas in "concentrated" runs (C1 and C2), the subjects were forced to mentally focus on the stimuli. All the subjects could perceive the flicker stimuli through their eyelids, but could neither gaze at the stimuli nor specify its location because the flickering light covered the entire skin of their eyelids. Thus note that "mental concentration" in the present study is essentially different from "eye-gaze" to choose an icon corresponding to a demand in the conventional SSVEP-based BCIs.

In Table I, the first 8 trials (Trial 1~8 in Table I) corresponded to preliminary mode for experiencing the flicker stimuli and mental concentration / relax on the flicker stimuli. Data measured in the second 8 trials (Trial 9~16 in the table) were analyzed to investigate the effect of the mental concentration on the SSVEP amplitude. The stimulus frequency was set at 10 Hz in Trial 1~4 and 9~13 and 14 Hz in Trial 5~8 and 13~16. The former was chosen to elicit the large SSVEP according to amplitude characteristics in the frequency response of the SSVEP [7]. The latter was introduced to elicit genuine SSVEP independently of the spontaneous and entrained alpha wave (8~13 Hz) which might considerably affect the SSVEP in the former case. Two trials in the resting state without flicker stimuli were conducted before the trial 1.

B. Analysis

The discrete Fourier transform was used to estimate the amplitude of SSVEP at the stimulus frequency, namely, the fundamental SSVEP. The SSVEP amplitude at the harmonic frequencies was not only smaller than the fundamental SSVEP amplitude at 10 and 14 Hz stimuli but also only as large as the amplitude of the background EEG activity near the stimulus frequency in the case of 14 Hz stimuli. We thus excluded the harmonic SSVEPs from analysis. A 10-s data window from 3 to 13 s after the beginning of each run was used to analyze in order to eliminate the effect of transient response to the onset of flicker stimuli. The effect of mental concentration on the flicker stimuli was assessed in the following aspects.

First, the SSVEP amplitude was evaluated with reference to the resting state; we used the ratio of average of the fundamental SSVEP amplitude at the stimulus frequency over 2 trials under the condition of the relaxed state (Trial numbers 1 and 2 in Table 1) to the average amplitude of the spontaneous EEG at this frequency over 2 trials each subject. Statistical significance in the amplitude between the relaxed and the resting states was tested using the nonparametric Wilcoxon signed-rank test because the amplitude of the EEG had large inter-individuality which showed no normal distribution.

Second, the impact of the mental concentration on the SSVEP amplitude was assessed by using the amplitude ratio of the average of fundamental SSVEP in the state of mental concentration to that in the state of relaxed state under each stimulus condition. This amplitude ratio, *R,* was given by

$$R = \frac{\frac{1}{2}(A_{C1} + A_{C2})}{\frac{1}{2}(A_{R1} + A_{R2})} \qquad --- (1)$$

where A_{Ci} and $A_{Rj}(i, j = 1,2)$ denote the spectral amplitude at the stimulus frequency (10 and 14 Hz) under the concentrated and relaxed (non-concentrated) states, respectively. Namely, Trial numbers corresponding to A_{C1}, A_{C2}, A_{R1} and A_{R2} are 11, 12, 9 and 10 for 10 Hz stimuli and 15,16, 13 and 14 for 14 Hz stimuli in Table I, respectively.

Moreover, reproducibility of the effect of mental concentration on the flicker stimuli was also evaluated by using normalized amplitude which was calculated in the following:

$$\overline{A}_i = \frac{A_i}{A_{R1} + A_{R2} + A_{C1} + A_{C2}} \qquad --- (2)$$

where A_i and $\overline{A}_i$ denote the amplitude at the stimulus frequency and its normalized amplitude in the *i*-th trial, $i = 9$, … , 12 for 10 Hz stimuli and $i = 13$, …, 16 for 14 Hz stimuli, respectively. Trial numbers corresponding to A_{C1}, A_{C2}, A_{R1}, and A_{R2} are the same as Eq. (1).

TABLE I. EXPERIMENTAL CONDITIONS

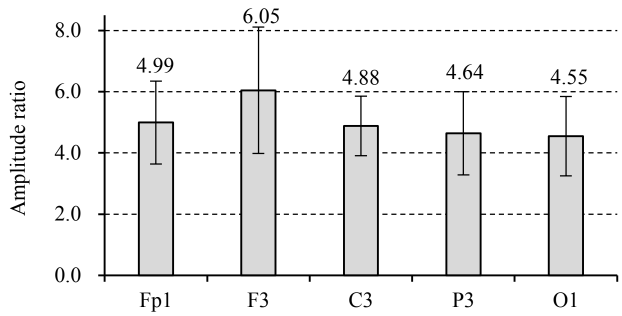
Trial No.	Mode	Frequency (Hz)	Mental State
1	Pre[a]	10	R1[b]
2	Pre	10	R2[c]
3	Pre	10	C1[d]
4	Pre	10	C2[e]
5	Pre	14	R1
6	Pre	14	R2
7	Pre	14	C1
8	Pre	14	C2
9	Ana[f]	10	R1
10	Ana	10	R2
11	Ana	10	C1
12	Ana	10	C2
13	Ana	14	R1
14	Ana	14	R2
15	Ana	14	C1
16	Ana	14	C2

a. Preliminary trial, b. First relaxed state in each stimulus frequency condition,
c. Second relaxed state, d. First concentrated state on flicker stimuli in each stimulus frequency condition, e. Second concentrated state and f. Trial analyzed.

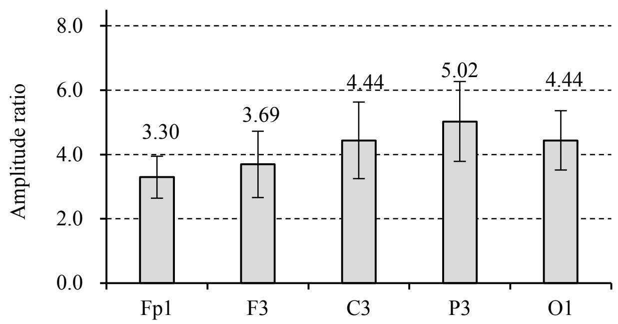
III. RESULTS

A. Response of EEG at stimulus frequency to flicker stimuli

Figure 2 illustrates the grand mean of the ratio of the average of the spectral amplitude at the stimulus frequency over 2 trials in the relaxed state under the flicker stimuli to the average amplitude of the spontaneous EEG at this frequency over 2 trials along the left hemisphere. The grand mean of the amplitude ratio of the SSVEP in the relaxed state to the amplitude in the resting state reached the values more than 3 (in the range from 3.3 to 6.1) indicating the enhancement of

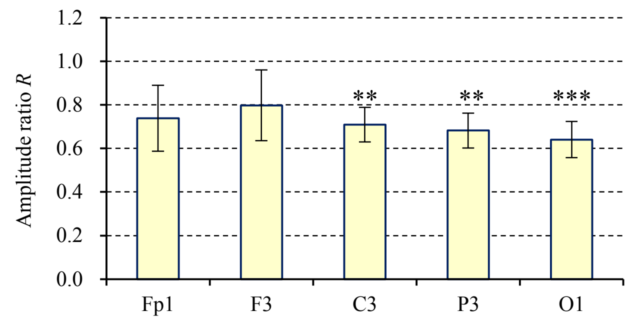


(a) 10 Hz stimuli

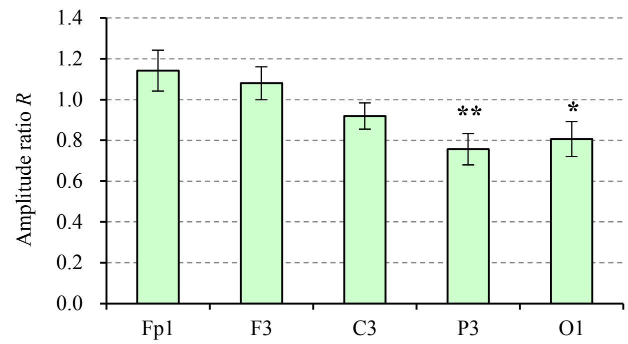


(b) 14 Hz stimuli

Figure 2. Grand mean of amplitude ratio of average of SSVEP amplitude at with standard error over 2 trials under flicker stimuli without concentration to average of spectral amplitude in the spontaneous state at (a) 10 Hz and (b) 14 Hz across 16 subjects; (a) 10 Hz stimuli and (b) 14 Hz stimuli.



(a) 10 Hz stimuli



(b) 14 Hz stimuli

Figure 3. Grand mean of amplitude ratio R with standard error across 16 subjects with reference to amplitude in nonconcentration state on flicker under 10 Hz stimuli. The symbols *, ** and *** designate $p < 0.05$, $p < 0.01$ and $p < 0.001$ by using one-sample t-test for population mean of R with null hypothesis that the population mean is equal to 1, respectively; (a) 10 Hz stimuli and (b) 14 Hz stimuli.

the amplitude at the stimulus frequency in the relaxed state under both of 10 Hz and 14 Hz flicker stimuli.

The range of the amplitude ratio falls within the range from 4.6 to 5.0 along the left hemisphere except F3 having large standard error for 10 Hz stimuli, whereas there exists larger difference in the amplitude ratios between the frontal region (3.3 at Fp1 and 3.7 at F3) and the centro-occipital region (more than 4.4 at C3, P3 and O1) under 14 Hz stimuli.

The average of spectral amplitude at the stimulus frequency demonstrated significant differences over all of the electrode sites between the resting state and 10 Hz stimuli and also between the resting state and 14 Hz stimuli by using the Wilcoxon signed rank test ($p < 0.01$ for all the pairs of the average amplitude). Thus the SSVEPs were significantly elicited over the entire scalp in the relaxed state with eyes closed under the flicker stimuli of both 10 Hz and 14 Hz. Similar result was obtained from the electrode sites along the right hemisphere.

B. Impact of mental concentration on SSVEP amplitude

Figures 3 illustrates the grand means of the amplitude ratio R across 16 subjects under (a) 10 and (b) 14 Hz stimuli. Under the condition of 10 Hz stimuli, the grand means of R were less than 0.8 over all the electrode sites, indicating that the amplitude reduction occurred in connection with the mental concentration on the flicker stimuli. In particular, such a phenomenon was remarkable in the posterior region where the amplitude was decreased by more than 30 % corresponding $R < 0.7$. For reference, significant difference was found between the relaxed and concentrated states at Fp2, F4, Fz, C3, C4, P3, P4, Pz, O1 and O2 by using the one-sample t-test with null hypothesis that the population mean of R was equal to 1.

On the other hand, under 14 Hz stimuli, the amplitude decrease associated with the mental concentration was localized in the parieto-occipital region where the amplitude ratio R reached significant difference between the relaxed and concentrated states at P3, O1 and O2. One reason for not large impact of the mental concentration on the SSVEP amplitude at the stimulus frequency may be due to the fact that the average of the amplitude at the stimulus frequency under 14 Hz stimuli was smaller than that under 10 Hz stimuli by 40 % and the SSVEP is likely to be affected by spontaneous EEG and its voluntary fluctuation.

The amplitude in the parieto-occipital regions was seen to be significantly changed in association with mental concentration on the flicker stimuli under 10 and 14 Hz stimuli, respectively. The SSVEP is generally well elicited in the occipital region and its response to the mental concentration on the flicker stimuli may be responsible for making significant difference between the relaxed and concentrated states. The parieto-occipital cortex corresponds to the visual and visual association area where the retinal neuronal excitability elicited by the flicker stimuli projects via the lateral geniculate nucleus. Thus the mental concentration on the flicker stimuli is considered to considerably affect the SSVEP in the parieto-occipital regions.

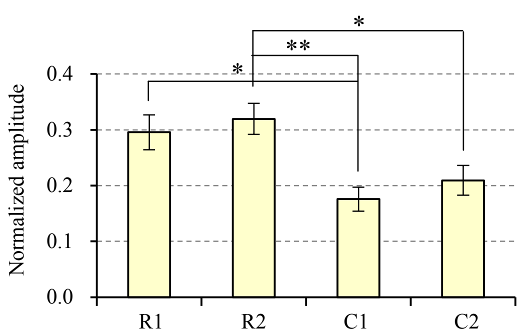
C. Evolution of normalized amplitude

Figure 4 depicts the evolution of normalized SSVEP amplitude at P3 with standard error from R1 to C2 under (a) 10 Hz and (b) 14 Hz stimuli, respectively. Under both stimulus conditions, any of the normalized SSVEP amplitudes in the relaxed state (R1 and R2) were larger than any of that in the concentrated state (C1 and C2) on the flicker stimuli. A main effect of trial was significant under both stimulus conditions, $F(3,45) = 4.9$, $p < 0.01$ for 10 Hz stimuli and $F(3, 45) = 3.9$ and $p < 0.05$ for 14 Hz stimuli.

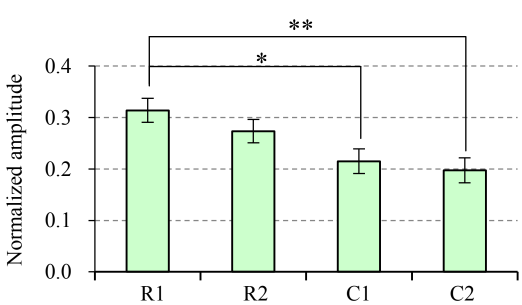
A two-tailed paired *t*-test as a *Post hoc* test showed significant difference between R1 and C1, R2 and C1 and R2 and C2 for 10 Hz stimuli and between R1 and C1 and R1 and C2 for 14 Hz stimuli, respectively ($p < 0.01$ for the pair of R2 and C1 and $p < 0.05$ for R1 and C1 and also R2 and C2 under 10 Hz stimuli and $p < 0.01$ for R1 and C2 and $p < 0.05$ for R1 and C1 under 14 Hz stimuli), whereas the paired *t*-test revealed no significant difference between R1 and R2 and between C1 and C2 under 10 and 14 Hz stimuli. This result may suggest the reproducibility of the impact of mental concentration on the stimuli. However, note that no significant difference was also found between R1 and C2 under 10 Hz stimuli and between R2 and C1 and R2 and C2 under 14 Hz stimuli, respectively. The reproducibility of the effect of mental concentration on the flicker stimuli is being examined through the repetition of mental concentration and relaxation many times and will be reported in the conference.

Causality from the mental concentration on flicker stimuli to the amplitude decrease of SSVEP with eyes closed remains to be elucidated. One possibility is that the mental concentration on the stimuli may evoke a stressed state which elicits the suppression of the SSVEP similar to the event-related de-synchronization (ERD) of the alpha wave. In particular, the ERD of the 10 Hz alpha wave may contribute to the amplitude decrease of SSVEP and make a larger amplitude difference between the relaxed and concentrated states than that under 14 Hz stimuli. However, the amplitude at 10 Hz in the concentrated state was much larger than that in the free run. Although it seems impossible to discriminate between the 10 Hz alpha (background) and SSVEP, the ERD of the 10 Hz alpha may be limited impact.

However, there exists considerable inter-individuality and inter-site difference; three and four subjects had one or two electrode sites in the parieto-occipital region showing the amplitude increase in the concentrated state under 10 Hz and 14 Hz stimuli and there were also three and four subjects whose SSVEP decreased at some electrode sites but increased at other sites under 10 and 14 Hz, respectively. It is thus needed to user-specific calibration for developing the BCI It should be also considered some other parameters including stimulus frequency [8] and analyses including time-frequency analysis in addition to the amplitude of fundamental SSVEP to improve the classification accuracy and information transfer rate. Future works includes validation and establishment of the concept of mental concentration/relaxation methods to effectively concentrate on the flicker stimuli to control the SSVEP amplitude.



(a) 10 Hz stimuli



(b) 14 Hz stimuli

Figure 4. Grand mean of normalized amplitude $\overline{A_i}$ at P3 under the stimulus frequency of (a) 10 Hz and (b) 14 Hz, respectively. The symbols * and ** designate $p < 0.05$ and < 0.01 for two-tailed paired *t*-test as *Post-hoc* test.

IV. Conclusion

Response of SSVEP to mental concentration on flicker stimuli was investigated in the presents study under the conditions of the stimulus frequency of 10 and 14 Hz with the stimulus intensity of 5 lx in order to consider a novel SSVEP-based BCI available in the eyes-closed state for locked-in patients. The mental concentration on the flicker stimuli significantly suppressed the SSVEP amplitude under both 10 and 14 Hz flicker stimuli. Repeatability of the response should be verified to develop the binary class of SSVEP-BCI available in the eyes-closed state.

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