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A Half-field Stimulation Pattern for SSVEP-based Brain-computer Interface

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Abstract—**A novel stimulation pattern has been designed for brain-computer interface (BCI) using steady-state visual evoked potential (SSVEP) signals. Each target is composed of two flickers placed on right-and-left visual fields. The user is expected to concentrate his or her sight on the fixation point which is located in the middle of the two flickers modulated at specific frequencies respectively. Considering the role of optic chiasm, the two frequency components could be extracted from contralateral occipital regions. Canonical correlation analysis (CCA) was applied to distinguish the electroencephalography (EEG) frequency components from right-and-left visual cortex. The attractive feature of this method is that it would substantially increase the number of targets by a combination of frequencies. Based on this technique a nine-target SSVEP-based BCI system was designed using only three different frequencies. The test results with 8 subjects showed a classification accuracy between 40.0% and 96.3%.**

I. INTRODUCTION

Brain-computer interface (BCI) is a direct communication channel between human brain and external world [1]-[2]. A great progress has been made in BCI research over the past 10 years. Brain signals can be detected and measured in many ways, like functional MRI (fMRI), positron-emission tomography (PET), electroencephalography (EEG) and near-infrared imaging (NIR). In this paper, we concentrate on EEG for its simplicity and non-invasive feature.

The commands for device control could be generated by self-regulated mu rhythm, P300, steady-state evoked visual potential (SSVEP) and so on. SSVEP is defined as periodic evoked potential induced by repetitive visual stimulation, typically at frequencies greater than 6 Hz [3]. Compared to BCIs based on other signals, SSVEP-based BCIs usually have faster information transfer rate (ITR) and less training time.

Several systems have already been proposed [4]-[5]. For SSVEP-based BCI systems, each target presented in the field of vision was modulated by a specific frequency. The users select one of the targets by looking directly at it. However, few targets could be presented when using screen display in SSVEP-based BCIs due to the restriction of screen refresh rate. Furthermore, good signal to noise ratio (SNR) can be obtained only in certain frequency range for a specific subject. For these reasons, increasing target number becomes a difficult problem in SSVEP-based BCI.

Some studies confirmed that the system performance of a SSVEP-based BCI would be improved by employing half-field stimulation. For example, SSVEP-based BCI system utilizing electrophysiological correlates of visual spatial attention mechanisms involves no dependency on peripheral muscles or nerves [6]. Alternative visual half-field stimulation allows significant SNR increase leading to a high transfer rate [7]. This paper presents a novel stimulation pattern which could increase target number remarkably. The method utilizes bilateral flicker stimuli to form each target; hence fewer frequencies could produce more targets by a combination of right-and-left frequencies. Based on this method, a 9 targets BCI system was designed and implemented by using only three different frequencies. Both offline and online experiments were carried out to evaluate the performance of this system.

II. METHOD

A. Subjects

Eight volunteers including five males and three females, aged 22-25 years, with normal or corrected-to-normal vision, participated in the experiments. All participants were seated in a comfortable armchair, about 70cm in front of the stimulation unit, in a shielded (for offline test) or unshielded (for online test), slightly dimmed and quiet room.

B. EEG recording

Multichannel EEG signals were recorded with a Synamps2 (NeuroScan Inc.) system using 64 channels placed according to international 10-20 electrode system. The reference channel was on the vertex. And the sampling rate was 200Hz. All the impedances were kept below 5K ohm. This set-up was used throughout all the experiments.

C. System configuration

Flicker stimuli displayed on a CRT monitor (See Fig.1.) were generated by a PC computer using MATLAB 7.0 (The MathWorks Inc.) in conjunction with the Psychophysics Toolbox [8].

The monitor (1024H×768V pixel resolution; 60 frames/s) located 70cm from the subject. The rectangular flicker was 80H×100V pixel size. Every two flickers which were situated bilateral to a white cross constituted one target. In our experiments, there were 9 targets (18 flickers) totally. Each flicker was modulated at a specific frequency. In traditional SSVEP-based BCIs, 9 frequencies are essential for nine-target system, while in our system 9 targets were

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realized by the combinations of 3 frequencies. In our experiments 10Hz, 12Hz and 15Hz which usually had a good SNR and could be displayed by a monitor (60 frames/s) easily were chosen. More details are illustrated in Table 1.

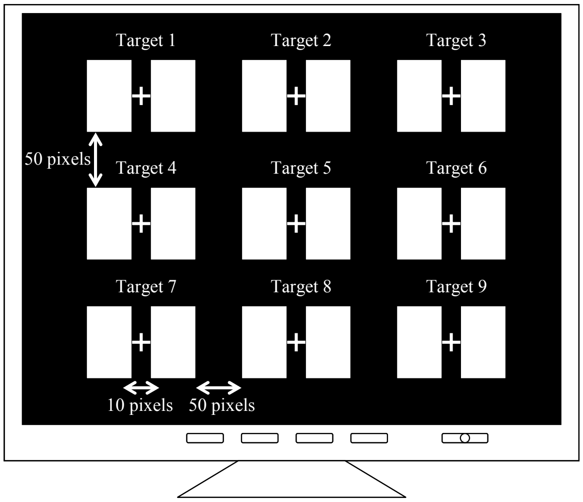

Fig.1. The visual display contained 18 flickers stimuli. In the horizontal direction every 2 adjacent flickers were placed bilateral to a central fixation cross on a black background.

Table 1. Nine target configuration: the combinations of three frequencies (10, 12 and 15Hz).

	Left/Right (Hz)	Left/Right (Hz)	Left/Right (Hz)
Target 1-3	10/10	10/12	10/15
Target 4-6	12/12	12/10	12/15
Target 7-9	15/15	15/10	15/12

D. Experiment paradigm

Each subject underwent both offline and online experiments. In figure 2, the right-and-left flicker stimuli were modulated at frequency f_1 and f_2 respectively. Subjects were requested to focus on the cross in the middle of the two flickers. This arrangement ensured the bilateral flicker stimuli were positioned on the right and left half of the retinas of each eye, so that the flicker frequencies could be projected to the contralateral occipital regions.

An offline study was carried out to investigate the phenomenon above mentioned before the online test. Subjects sitting in a shielded room were instructed to focus on one of the targets. The offline experiment consisted of 9 blocks (one for each target). Each block contained 10 trials. Each trial lasted 10s. The interval time between two trials was 2s. Hence, each block was 120s totally. The whole experiment lasted about 18 minutes (9 blocks×120s).

Unlike the offline tests, the online tests were taken in an unshielded room simulating daily life environment. Also we employed feedback to help subjects to control the interface easily. Subjects were informed to complete a specific task in online study. The task started when subjects pressed SPACE key. Then subjects selected targets to focus on according to pre-defined order. The recognition time had been tested before. We found that, for most subjects, a 3s of stimulation followed by a feedback lasting 0.5s was appropriate. During the feedback period, one of 9 white crosses turned to green color to indicate the identification result. The task kept going on until all 9 targets were detected successfully. Each subject repeated the task 10 times for calculating identification accuracy and ITR.

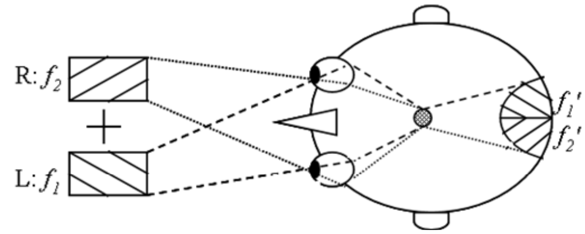

Fig.2. Schematic illustration of stimulation pattern.

E. Data processing

1) Canonical correlation analysis (CCA) method for SSVEP-based BCIs: CCA was implemented to extract frequency components from right and left occipital regions. CCA developed by H. Hotelling is a multivariable statistical method used when there are two sets of data, which may have some underlying correlation [9]-[10]. It finds two linear transformations, one for each dataset, that maximize the correlation of the two datasets in the new coordinates. Ordinary correlation analysis is dependent on the coordinate system in which the variables are described, whereas CCA finds the coordinate system that is optimal for correlation analysis. Given that characteristic of CCA, it has been widely used in real-life problems [11]-[12]. CCA is also applicable in analyzing the relationship between stimulus signals and EEG signals from multiple channels in a local area [13]. In our method, one set of variables were the signals $\boldsymbol{x}(\mathrm{t})$ recorded from n channels, and the other set $\boldsymbol{y}(t)$ were from stimulus signals. Where $\boldsymbol{y}(t)$ is defined as below:

$$\boldsymbol{y}(t)=\begin{pmatrix}\boldsymbol{y}_1(t)\\ \boldsymbol{y}_2(t)\\ \boldsymbol{y}_3(t)\\ \boldsymbol{y}_4(t)\\ \boldsymbol{y}_5(t)\\ \boldsymbol{y}_6(t)\end{pmatrix}=\begin{pmatrix}\cos(2\pi ft)\\ \sin(2\pi ft)\\ \cos(4\pi ft)\\ \sin(4\pi ft)\\ \cos(6\pi ft)\\ \sin(6\pi ft)\end{pmatrix} \quad (1)$$

CCA analysis can be defined as the problem of finding two sets of basis vectors, one for $\boldsymbol{x}(\mathrm{t})$ and the other one for $\boldsymbol{y}(t)$, so that the correlations between the projections of the variables onto these basis vectors are mutually maximized. Considering the linear combinations $X=\boldsymbol{x}^{\mathrm{T}}\hat{\boldsymbol{W}}_{\boldsymbol{x}}$ and $Y=\boldsymbol{y}^{\mathrm{T}}\hat{\boldsymbol{W}}_{y}$ of the two variables respectively, the function to be maximized is:

$$\rho=\frac{E[XY]}{\sqrt{E[X^2]E[Y^2]}}=\frac{E\left[\hat{\boldsymbol{W}}_x^{\mathrm{T}}\boldsymbol{x}\boldsymbol{y}^{\mathrm{T}}\hat{\boldsymbol{W}}_y\right]}{\sqrt{E\left[\hat{\boldsymbol{W}}_x^{\mathrm{T}}\boldsymbol{x}\boldsymbol{x}^{\mathrm{T}}\hat{\boldsymbol{W}}_x\right]E\left[\hat{\boldsymbol{W}}_y^{\mathrm{T}}\boldsymbol{y}\boldsymbol{y}^{\mathrm{T}}\hat{\boldsymbol{W}}_y\right]}}=\frac{\boldsymbol{W}_x^{\mathrm{T}}\boldsymbol{C}_{xy}\boldsymbol{W}_y}{\sqrt{\boldsymbol{W}_x^{\mathrm{T}}\boldsymbol{C}_{xx}\boldsymbol{W}_x\boldsymbol{W}_y^{\mathrm{T}}\boldsymbol{C}_{yy}\boldsymbol{W}_y}} \quad (2)$$

The maximum of ρ with respect to $\boldsymbol{W}_x$ and $\boldsymbol{W}_y$ is the maximum canonical correlation. The projections of $\boldsymbol{x}(t)$ and $\boldsymbol{y}(t)$ onto $\boldsymbol{W}_x$ and $\boldsymbol{W}_y$, i.e. X and Y, are called canonical variates.

2) Offline feature extraction: Before offline analyses the data were checked by visual scoring. Signals contaminated by artifacts were excluded from further analyses. The SSVEP topographies for the responses to the frequencies were plotted to investigate the maximal SSVEP amplitudes distribution. CCA analysis was performed to extract the feature.

3) Online system recognition strategy: In our online experiment, EEG signals measured from 8 channels which located near the occipital regions were used to extract the feature (See Fig.3(a)). The EEG signals recorded were divided into two groups: PO3, PO5, PO7 and O1 placed over left occipital part of the head ($\boldsymbol{x}_{\mathrm{L}}$); PO4, PO6, PO8 and O2 placed over right occipital part ($\boldsymbol{x}_{\mathrm{R}}$). The periodic stimulus signal at a certain frequency can be decomposed into the Fourier series of its harmonics. By the decomposition, we got stimulus datasets, $\boldsymbol{y}_{10}$, $\boldsymbol{y}_{12}$ and $\boldsymbol{y}_{15}$ corresponding to 10Hz, 12Hz and 15Hz stimulations. CCA coefficients ρ between EEG signal datasets and stimulus datasets were calculated, so that we could recognize the frequencies components through a comparison between different ρ (See Fig.3(b)). In Fig3 (b) $\rho_{\mathrm{L-10}}$, $\rho_{\mathrm{L-12}}$ and $\rho_{\mathrm{L-15}}$ indicates CCA coefficients of $\boldsymbol{x}_{\mathrm{L}}$ and $\boldsymbol{y}_{10}$ / $\boldsymbol{y}_{12}$ / $\boldsymbol{y}_{15}$ respectively. Similarly, $\rho_{\mathrm{R-10}}$, $\rho_{\mathrm{R-12}}$ and $\rho_{\mathrm{R-15}}$ indicates CCA coefficients of $\boldsymbol{x}_{\mathrm{R}}$ and $\boldsymbol{y}_{10}$ / $\boldsymbol{y}_{12}$ / $\boldsymbol{y}_{15}$. And $\rho_{\mathrm{L-max}}$ =max $\{\rho_{\mathrm{L-10}}, \rho_{\mathrm{L-12}}, \rho_{\mathrm{L-15}}\}$; $\rho_{\mathrm{R-max}}$ =max $\{\rho_{\mathrm{R-10}}, \rho_{\mathrm{R-12}}, \rho_{\mathrm{R-15}}\}$. The target can be selected by using $\rho_{\mathrm{L-max}}$ and $\rho_{\mathrm{R-max}}$ according to right-left stimulation frequencies in Table 1.

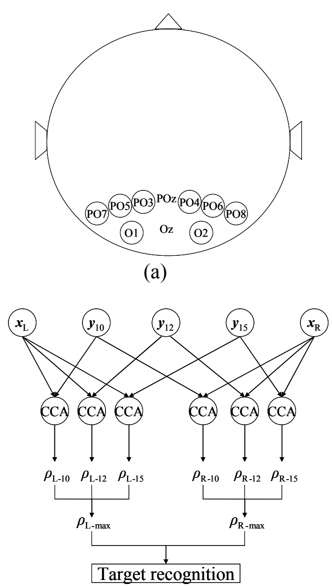

Fig.3. (a) Channel location used in CCA analyses.
(b) Recognition procedure.

III. RESULTS

A. CCA analysis of offline experiments

For each target, ten time segments of 10s length were extracted from corresponding trial. After averaging of ten segments, a 10s length dataset was obtained finally. The SSVEP amplitudes for the responses to specific frequency were computed and plotted. Take subject1 (s1) as an example, the SSVEP amplitudes distribution was plotted using the function 'topoplot.m' in EEGLAB [14]. Fig.4 shows that for the target 6 and target 9, maximal SSVEP amplitudes occurred at contralateral to the stimulus over occipital cortical regions.

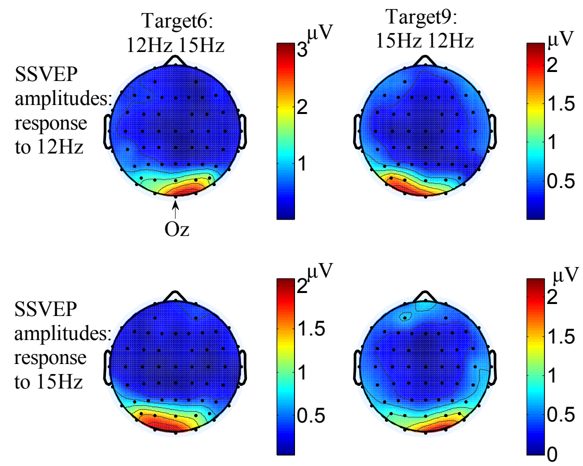

Fig.4. Topographic plots: SSVEP amplitudes for responses to 12Hz and 15Hz (Target 6 and 9 of s1).

CCA was performed to extract the frequencies components. According to Fig.3 (b) $\rho_{\mathrm{L-10}}$, $\rho_{\mathrm{L-12}}$, $\rho_{\mathrm{L-15}}$, $\rho_{\mathrm{R-10}}$, $\rho_{\mathrm{R-12}}$ and $\rho_{\mathrm{R-15}}$ were computed for each subjects' 9 blocks. Again, taking s1's results of target 6 and target 9 as example to evaluate SSVEP contralateral response function. Fig.5 shows that the results of CCA analysis are consistent with the SSVEP amplitudes topographies. For target 6, the right-and-left flicker stimuli were modulated at 12Hz and 15Hz respectively. Fig.5 (a) indicates that the maximum CCA correlation is $\rho_{\mathrm{L-15}}$ for left occipital region and $\rho_{\mathrm{R-12}}$ for right occipital region. The results confirm that the left and right frequency components were projected to contralateral occipital regions. The same results are testified in Fig.5 (b).

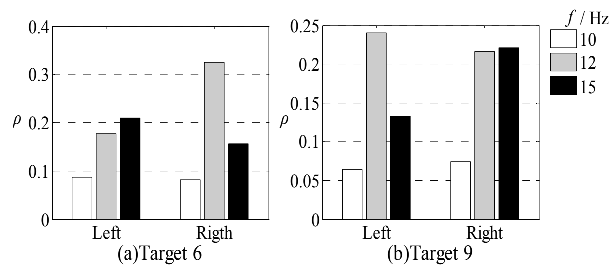

Fig.5. CCA analysis results of target 6 and target 9 for s1.

B. Results of online test

Eight subjects participated in the online test. In table 2, the accuracies and ITR results are given. The ITR measured in bits per minute is used to evaluate the performance of BCI systems [2]. In our system, the number of targets was 9, and a BCI command was posted once every 3.5s except for s4 and s7 test2. The 3s stimulation made s4 feel fatigue so that we adjusted it to 2.5s including a 2s stimulation and additional 0.5s feedback. Due to s7's high performance in test 1, another test identical to s4 was carried out. During test 2 of s7, the BCI system attained the ITR of 64.6 bit/min.

Table 2. Online test results

Subject	Accuracy (%)	ITR (bit/min)
s1	70.0	23.8
s2	86.7	37.8
s3	88.9	40.0
s4*	71.1	34.5
s5	84.4	35.6
s6	40.0	6.8
s7 test1	96.3	48.5
s7 test2	94.4	64.6
s8	51.1	12.1

IV. Discussion and conclusion

The traditional power spectral density (PSD) analysis method might be sensitive to noise, whereas array signal processing like CCA, using channel covariance information could improve the SNR [15]. Therefore, CCA rather than PSD method was used in our system.

Some subjects, s6 in particular, reported that it was difficulty to focus on the cross in the middle of the two flicker stimuli. We guessed it was the reason for the low performance of s6. A better online feedback strategy may solve this problem.

A nine-target SSVEP-based BCI system was designed and implemented based on a method proposed in this paper. It utilized right-and-left visual field stimulation with two frequencies, so that more targets could be acquired by combinations of frequencies. CCA was applied to extract the SSVEP responses occurred at contralateral occipital area. The results showed that the accuracy of 6 in 8 subjects was acceptable. Meanwhile, the system could increase the number of targets significantly. Under certain circumstances, like using CRT or LCD as visual stimulation unit, more targets could be obtained by the proposed method.

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