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A High Rate Online SSVEP Based Brain-Computer Interface Speller

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Abstract—**This paper presents an online steady-state visual evoked potential (SSVEP) based brain-computer interface (BCI). Stimuli are displayed on a liquid crystal display (LCD) screen with a frame based encoding method to elicit SSVEPs with a wide range of frequencies. This system focuses strongly on practicability and convenience, including an adequate alphabet (42 characters) that can allow a wide range of options. Four healthy subjects attain a mean information transfer rate (ITR) of 61.64±3.61 bits/min.**

I. INTRODUCTION

Brain-computer interface (BCI) systems provide direct communication pathway between brain and external devices without using peripheral nerves and muscular tissues[1], [2]. For disabled individuals who are unable to communicate through any classical nerves and muscular tissues, BCI systems can be used for them to establish a new channel between brain and outside world.

In recent decades, the BCI systems based on noninvasive scalp electroencephalograms (EEGs) have been widely used. Among several BCI systems, steady-state visual evoked potentials (SSVEPs) based BCI systems have received widespread attentions. SSVEP can be considered as a steady periodic response to a repetitive visual stimulus at frequencies higher then 6Hz. A SSVEP based BCI system has many advantages, including its higher information transfer rate (ITR) and little training [3] - [5].

Spelling device is a basic BCI application which allows users to type characters in computers or other devices [6] - [10]. Among several SSVEP BCI spelling system based on LCD/CRT monitor, the system proposed in [7] achieves ITR of 43.00 bits/min. The speller proposed in [8] with 9 targets has the ITR of 21.00 bits/min. A three-level menu speller with 5 targets proposed in [9] reaches ITR of 37.62 bits/min and another speller with 5 targets proposed in [10] has ITR of 29.68 bits/min. However, in these spellers, the ITR is not high enough and they only allow the users to spell a small number of characters, which are not enough in practical applications.

In general, large numbers of targets are required to be presented on the visual stimulator in the spelling applications. Therefore, the visual stimulator plays an important role in an SSVEP based BCI speller. Stimuli can be presented using light-emitting diode (LED) or liquid crystal display (LCD)/ cathode ray tube (CRT) monitors [11]. Compared with LCD/CRT, using LEDs as stimuli has some disadvantages. For instance, extra elaborate hardware is required for the LEDs to generate a stimulus with a constant frequency. Furthermore, it is also inconvenient to implement and configure. Therefore, presenting the stimuli on the LCD/CRT monitors is more convenience than LEDs.

To generate stable stimuli on LCD/CRT monitors, one general approach is traditional frame based method [4]. In this method, however, the number of stimuli is limited by the refresh rate of the LCD/CRT monitor. On the other hand, increasing the number of stimuli can enhance the performance of the BCI system in terms of ITR. Therefore the visual stimulator design is a critical problem. To solve this problem, two approaches can be used to generate more stimuli using LCD/CRT monitors. One is using high resolution timer such as Windows Multimedia Timer [12]. However, using this kind of resolution timer, the accuracy of stimuli frequencies will be affected by other Windows processes. The other method is frame based encoding method proposed in [13], which not only ensures the stability of flickers but also increases the number of targets. Therefore, we use this frame based encoding method to generate stimuli with wide range frequencies on LCD/CRT monitors to implement the spelling system. This speller provides adequate alphabet for users in daily work and communication.

II. METHODS

A. Visual Stimulator

Using traditional frame based method to generate stimuli on a LCD/CRT monitor is limited by the refresh rate of the monitor. For example, for a monitor with 60Hz refresh rate, 6.67Hz, 7.5Hz, 8.57Hz, 10Hz, 12Hz, 15Hz and 20Hz are usually used in practical design of visual stimulator. Both the number of stimuli and system performance will be limited due to the lack of modulation frequencies. Furthermore, the elicited SSVEPs have high amplitude at the harmonic frequencies and sometimes even stronger than the fundamental frequency. Hence the system may fail to discriminate the fundamental frequency from its harmonic frequencies (e.g. 10Hz and 20Hz SSVEPs). Consequently, this further limits the number of the stimuli frequencies. A 60Hz refresh rate monitor has 60 frames in one second and the number of frames in each cycle is a constant. For 10Hz flicker, the stimulus reverses between black and white every three frames; a 12 Hz flicker states in black for three frames and reverses to white for two frames. Therefore,

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the sequences of these two frequencies are combined together in a single sequence to approximate 10.5Hz, 11Hz and 11.5Hz with a varying number of frames in each cycle. Fig.1 (a) demonstrates the time series of 11Hz stimulus generated by frame based encoding method and its corresponding frequency spectrum, from which we can ensure the stability of the stimulus. The elicited SSVEP in time domain and frequency domain are illustrated in Fig.2 (b). From the frequency spectrum of elicited SSVEP, it is obvious that the 11Hz stimulus is able to elicit a reliable SSVEP. Therefore, frame based encoding method can be used to generate stimuli in this application.

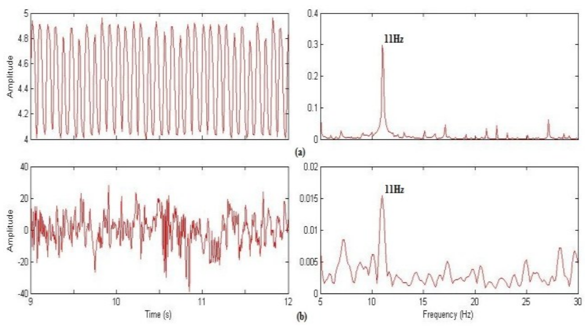

Fig.1. Time series and frequency spectrum of stimulus signal and elicited SSVEP at 11Hz.

The proposed speller allows input 42 characters (26 letters: '*A-Z*', 10 digits: '*0-9*' and 6 common used symbols). It has three pages and 16 targets in each page, 2 of the 16 buttons are reserved for turning page. The turning page buttons exactly show the character arrangement of that page so that the users can easily find the correct position of characters. Fig.2 presents the stimuli layout of each page. The frequencies of these 16 targets start from 8Hz to 15.5Hz with an interval of 0.5Hz. The visual stimulator is programmed in Microsoft Visual C++ 6.0 and DirectX DirectDraw 7.

B. *Canonical Correlation Analysis (CCA)*

CCA, as a multivariable statistical method, is used when there are two set of data, which may have some underlying correlation [5]. It focuses on a pair of linear combinations, for two certain data sets, such that the correlation between the two canonical variables is maximized. In our system, this approach is used to compare the EEG signals with reference signals which have been preinstalled in terms of sine and cosine expressions to calculate the CCA coefficients. Consider the multi-channel EEG signals X, the reference signal Y and their linear combinations $x = X^T W_x$ and $y = Y^T W_y$. CCA finds the weight vectors, W_x and W_y, which maximize the correlation between x and y, as shown in (1),

$$\max_{Wx,Wy} p(X,Y) = \frac{E[X^T Y]}{\sqrt{E[X^T X]E[Y^T Y]}} = \frac{E[W_x^T X Y^T W_y]}{\sqrt{E[W_x^T X X^T W_y]E[W_x^T Y Y^T W_y]}} \quad (1)$$

The user's command C in (2) is recognized as

$$C = \arg\max_i \rho_i \qquad i = 1,2,...,k \quad (2)$$

where ρ_i is the CCA coefficient, and command C is used to make a determination, more details refer to [5].

C. *Signal Processing*

The CCA is employed for extraction of frequency information of SSVEP signals. In our experiments, we apply CCA method for 1s length data, and then the coefficient is calculated every 0.2s. Therefore, 5 correlation coefficients will be obtained in a 2s length gazing interval. If more than 2 commands C of them are same, the corresponding command will be selected, otherwise the EEGs should be detected again. Then the corresponding correlation coefficients ρ_i are picked up to calculate the mean. If it is large than the threshold value, the selected command C will be chosen as the final result and the system will output a selection command.

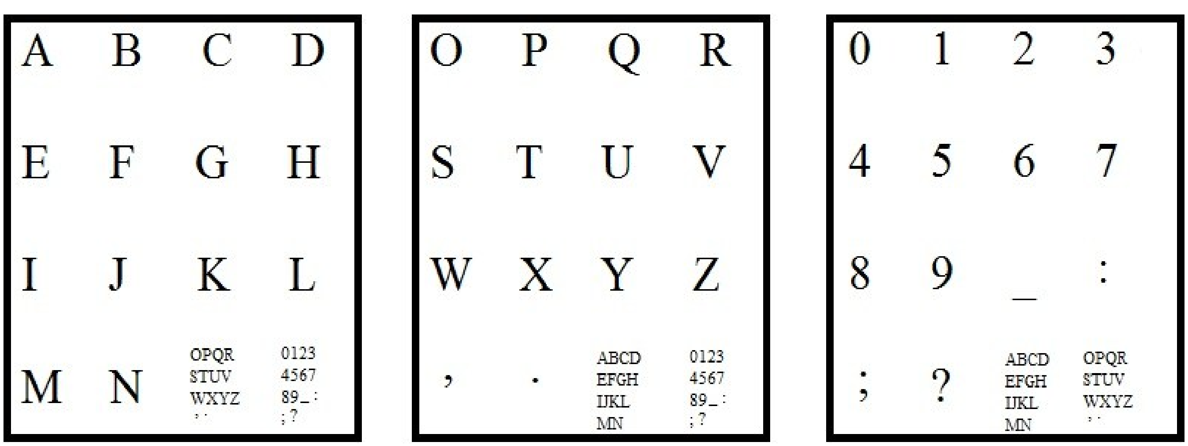

Fig.2. Graphical user interface of SSVEP based BCI speller.

III. Experimental Results and Discussion

A. Experimental Setup

In this experiment, we used a LCD monitor as the visual stimulator (ViewSonic 22", refresh rate 60Hz, 1680×1080 pixel resolution). Four subjects, from 22 to 27 years old, with normal or corrected-to-normal vision participated in the experiments and were selected from the subjects with BCI experience. The subjects were seated in a comfortable chair in front of the visual stimulator about 60 cm. 6 standard EEG electrodes placed on PO_Z, P_3, P_4, O_Z, O_1, and O_2 were used as input channels. EEG signals were collected by an amplifier (g.USBamp, Guger Technologies, Graz, Austria) and online data processing was based on Matlab Simulink. All the signals were filtered by 0.5Hz to 60Hz band-pass filter and sampling rate was 256Hz. The dominant frequency was detected every 0.2s and the threshold value in CCA was 0.2. During the experiments, the stimulus was flickering for 2s for target identification and the following 1s interval was left for the subject to shift his gaze to next target.

Before the experiment, the offline analysis for four subjects was performed to determine which stimulus frequencies will elicit a SSVEP with high amplitude. Then the corresponding frequencies were chosen for two turning page buttons. Subjects were asked to input the characters in a random sequence and the total experiment time was 6 minutes. The selected character was fed back and displayed on the LCD monitor. If subject intended to spell the characters on other pages, he needed to gaze on turning page button first, and then selected the correct characters on that page.

B. Results

The ITR, given in bits per minute, is used as an evaluation measurement for BCI systems which is defined in (3).

$$ITR = \frac{60}{S} \times [\log_2 N + p\log_2 p + (1-p)\log_2(\frac{(1-p)}{N-1})] \quad (3)$$

where S is calculated as the time to complete total tasks over the total number of the input characters. p is the probability to input characters correctly and N is the number of the possible characters which equals to 42.

Table I presents the accuracy, the average ITR over the sessions and the average input speed of the experiments. The best performance is obtained by subject 1, with an average of 99.01% and an ITR of 62.49 bits/min. The average accuracy and ITR over all subjects are 98.78% and 61.64 bits/min respectively. Table II presents the performances of other SSVEP based BCI spelling systems which are also using LCD/CRT monitors as visual stimulators. Compared with them, the presented speller has highest ITR and highest accuracy.

Fig.3 presents the average commands distribution for each subject to complete a task. The most frequently selected command are target 15 and target 16, which severed as the turning page buttons. As shown in Fig.3, nearly 33% of commands distribution is occupied by the turning page buttons, hence it is crucial to select the values for certain targets like turning page buttons. However, in practical BCI applications, it is inconvenient to specify the stimuli frequencies for each user. In order to solve this problem, every subject is asked to gaze each targets for 10 times and the accuracy for all subjects is presented in Fig.4, from which it is observed that the stimuli frequencies in the range of 8.5Hz to 12.5Hz and 15Hz have higher accuracy. Since frequency band

TABLE I
Summarized Results for 2s, 1s Combination

Subject	Average Speed (cps)	Average Accuracy (%)	Average ITR (bpm)
S1	5.06±0.25	99.01±1.48	62.49±3.83
S2	5.12±0.25	99.29±0.99	62.23±3.21
S3	5.13±0.13	98.99±1.53	61.70±2.95
S4	5.15±0.24	97.83±2.47	60.15±4.46
Mean	5.12±0.22	98.78±1.62	61.64±3.61

TABLE II
Performances of SSVEP-Based BCI Spelling Systems

Reference ID	Average Accuracy (%)	Average ITR (bpm)	Numbers of targets
[7]	-	43.00	12
[8]	79.74	21.00	9
[9]	92.25	37.62	5
[10]	94.66	29.68	5
Ours	**98.78**	**61.64**	**16**

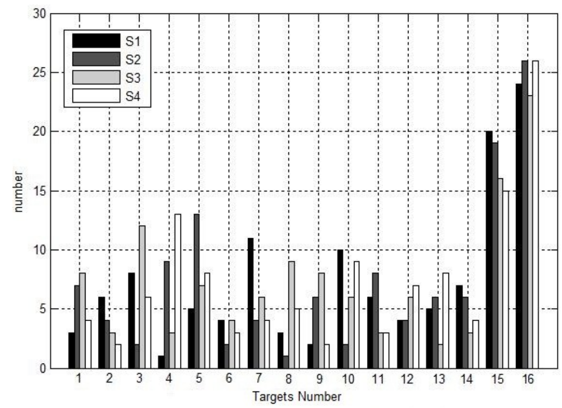

Fig.3. Average commands distribution of each subject.

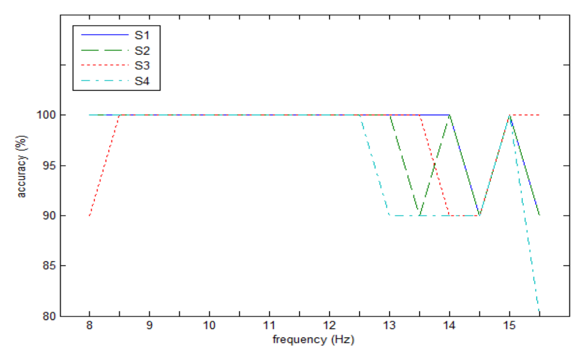

Fig.4. Accuracy of each frequency for all subjects.

from 8.5Hz to 12.5Hz overlaps with alpha rhythms, this frequency range is recommended for the subjects who have intensive SSVEP in alpha rhythm. In additional, for traditional frame based method, the number of frames in each cycle is a constant which ensures the stability of the SSVEPs. Compare with the traditional approach, the frame sequence generated by frame based encoding method has a varying length of frames in each cycle and leads the unstable of stimulus. Therefore, the frequencies generated by traditional framed based method should be chosen for the turning page buttons for most users.

The false positive of the system means when the system accidentally performs an action that the subject does not intend. In practical applications, it is undesirable to output an incorrect character with a speller. Compared with this, it is more tolerant that the system does not output any control command when the user is gazing at targets, which is regarded as false negative of the system. In real life applications of BCI systems, it is more important to limit false positive in a low level to increase the stability. A higher threshold value will reduce the percentage of error detecting of SSVEP but increase the false negative rate as well. In additional, exorbitant threshold value will also lead to a lower sensitivity in system. For this purpose, the threshold value is considered serious in this system. Based on the above, the threshold value in this system is selected as 0.2 to make the tradeoff of the performance between the sensitivity and stability. The false positive rate and false negative rate over all subjects are listed in Table III. The average false positive rate of this system is 1.23% while the false negative rate is 3.06%.

TABLE III
FALSE POSITIVE AND FALSE NEGATIVE RATE

Subject	False Positive Rate (%)	False Negative Rate (%)
S1	1.08	2.58
S2	0.75	2.50
S3	1.25	3.17
S4	1.83	4.00
Mean	1.23	3.06

IV. CONCLUSION

In this paper, a high rate online SSVEP based BCI speller is presented. The motivation of this work is to apply the online SSVEP BCI system with certain application like speller. Through online experiments, four subjects achieve an average spelling speed of 5.12±0.22 seconds per character, average accuracy up to 98.78±1.62%, and ITR of 61.64±3.61 bits/min. The further work may focus on optimization of menu configuration. For instance, list the characters which most commonly used in one page or change the position of characters. Besides, we will explore threshold parameter selection algorithms to obtain a better performance. The proposed system can be further improved by dealing with the idle states detection.

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