

Brain-computer Interface based on the High-frequency Steady-state Visual Evoked Potential

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Abstract—Low-frequency steady-state visual evoked potentials (SSVEPs) are used as the input signal in the present SSVEP-based brain-computer interface (BCI). This prototype system has a high information transfer rate. On the other hand, it has some limitations including visual fatigue, false positive, and some possibility of causing a seizure. These drawbacks can be largely eliminated when using high-frequency stimulations. In this paper, we study the amplitude versus stimulation frequency response of SSVEPs. The signal-to-noise ratio versus frequency curve suggests that the high-frequency SSVEP (>20Hz) could help to construct a practical BCI system.

Keywords—Brain-computer interface (BCI), steady-state visual evoked potential (SSVEP)

I. INTRODUCTION

Brain-computer interfaces (BCIs) translate brain signals into a control signal without using muscles or peripheral nerves. Most BCIs use noninvasive scalp electroencephalogram (EEG) signals as inputs. Event-related potentials, mu and beta rhythms, event-related synchronization and desynchronization, slow cortical potentials, and visual evoked potentials are common signals used in EEG-based BCIs [1][2][3].

Visual evoked potentials (VEPs) recorded from scalp over visual cortex reflect the visual information processing mechanism in the brain. The steady-state visual evoked potential (SSVEP), which is characterized as an increase in amplitude at the stimulus frequency, occurs when stimulation frequency is higher than 6Hz. Current SSVEP-based BCIs harness low-frequency SSVEPs to determine gaze directions [4][5]. Several frequency-coded buttons flash on the monitor. The user looks at a button and the system determines the frequency of the photic driving response. The button, which matches the detected frequency, is the target the user wants to select. This BCI has the following advantages: high information transfer rates, wide subject applicability, and little training required for users.

The low-frequency SSVEP has a good signal-to-noise ratio (SNR), a wide distribution over the scalp, and it can be induced easily, but it also has some unavoidable limitations. First, visual fatigue evoked by durative stimuli will reduce the amplitude of response and make the user uncomfortable. Second, alpha rhythm (8-13Hz) of spontaneous EEG may cause false positive. Additionally, flickering stimuli have some possibility of causing a seizure in subjects. Considering that the high-frequency SSVEP can eliminate

the above disadvantages, we attempt to employ it as the communication medium in BCI research, though the system performance may be decreased due to a lower amplitude response and a restricted topographical distribution.

II. METHODOLOGY

A. Data acquisition

13 volunteers with normal vision (5 female and 8 male) participated in the experiments. The subjects sat in a comfortable chair facing the visual stimulus device. White light-emitting diodes (LEDs) were used as the blinking buttons. The flashing frequency of each LED was controlled by a programmable logic device [6]. 64-channel EEGs were recorded with a BioSemi ActiveTwo system at positions of the extended international 10/20 system. The repetition rates of stimulation covered the bandwidth from 21 to 43Hz (2Hz each step). For one subject, the stimulation frequency band was from 5 to 45Hz, including both low and high frequency bands for comparison. 60-second-long data in each session corresponding to different frequencies were acquired for offline analysis. Signals were sampled at 256Hz. During periods between sessions, subjects could relax in order to eliminate the reaction of visual fatigue.

B. Offline analysis

The feasibility of using the high-frequency SSVEP in BCI application is considered through offline data analysis. We compare the signal-to-noise ratio of SSVEPs in different frequency bands. The detailed procedures are described in three steps as follows:

1) Determine optimal electrode positions according to the spatial signal-to-noise ratio mapping of multichannel EEGs.

In order to detect the frequency components in SSVEPs accurately and conveniently during online applications, an optimal bipolar lead with high signal-to-noise ratio should be selected. In practice, channel with the most significant amplitude of SSVEP is considered as the signal channel which commonly locates over visual cortex. The difficulty is to select a reference channel for the bipolar lead. A correct choice of reference channel can greatly enhance the signal-to-noise ratio. A comprehensive consideration must be taken for optimal lead selection [7].

Signal-to-noise ratio is used as the criterion to evaluate the efficiency of lead selection. The amplitude spectrum is

calculated by $y=|FFT(x)|$, where x is the temporal EEG data. $FFT(x)$ is the 1024-point fast Fourier transform (FFT) of x , and the frequency resolution is $256/1024=0.25\text{Hz}$. Here, when the stimulation frequency is f , signal-to-noise ratio is defined as the ratio of $y(f)$ to mean value of the n adjacent points:

$$SNR = \frac{n \times y(f)}{\sum_{k=1}^{n/2} [y(f + 0.25 \times k) + y(f - 0.25 \times k)]}$$

It can approximately reflect the signal-to-noise ratio of the SSVEP. Fig.1 illustrates the SNR mappings with different reference channels of one subject when the stimulation frequency is 21Hz. An optimal bipolar lead including a signal channel and a reference channel can be determined with the aid of these mappings. First, we use Fig.1(a), i.e. the SNR mapping with Cz as reference, to select the signal channel. According to Fig.1(a), Oz, the channel with the highest SNR, is selected as the signal channel with prominent SSVEP. Next, as shown in Fig.1(b), the SNR mapping with reference to the selected signal channel Oz is displayed to find the reference channel. The channel with the highest SNR is considered as the reference channel. The arrow indicates the selected optimal lead.

2) Plot the amplitude versus frequency response curve through amplitude spectra analysis.

According to human brain electrophysiological research, the amplitude of the SSVEP varies in a complex manner with the frequency of stimulation. The amplitude response has several peaks with three regions, often referred to as subsystems [8]: low-frequency region, medium-frequency region, and high-frequency region. The amplitudes of subsystems depend on many factors including electrode position, luminance, and flicker modulation depth.

The amplitude versus frequency response curves for the three SSVEP subsystems of one subject are shown in Fig.2. EEG data of the optimal lead are used to calculate the amplitude response through amplitude spectra analysis. Filled dots indicate the original results and solid lines denote the polynomial fitting results. The three subsystems are centered on 15Hz-low frequency, 31Hz-medium frequency, and 41Hz-high frequency, respectively. The lower frequency region has the larger amplitude response.

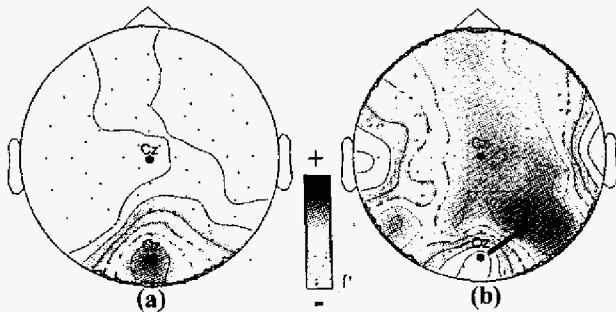


Fig.1. SNR mappings with reference to (a) Cz and (b) Oz respectively.

3) Compare the signal-to-noise ratios of different frequency regions and select the usable high-frequency bands for online application.

The lower amplitude response may decrease the signal-to-noise ratio if the amplitude of background noise is unchanged. Fortunately, the noise, i.e. spontaneous EEG, also decreases in higher frequency bands. So the signal-to-noise ratios of the three subsystems are almost on the same level (as shown in Fig.3). Offline frequency detection in higher frequency region has been done on this subject. The frequency corresponding to the maximum of amplitude spectra should be the stimulation frequency when the detection is accurate. The length of data section for FFT is 1024 points, and the frequency resolution is 0.25Hz. The detection accuracy is about 97% when the stimulation frequencies are in the medium-frequency region (31-35Hz). In the high-frequency region (39-45Hz), the average accuracy remains as 95%. The total usable bandwidth is about 10Hz, leading to about 40 targets at most.

For the other subjects, we analyze the SSVEPs with the stimulation frequencies from 21 to 43Hz. With the proper selection of electrode position and stimulation frequency bands, the average accuracy of all the 13 subjects is about 96%. The results of the individual are listed in Table I.

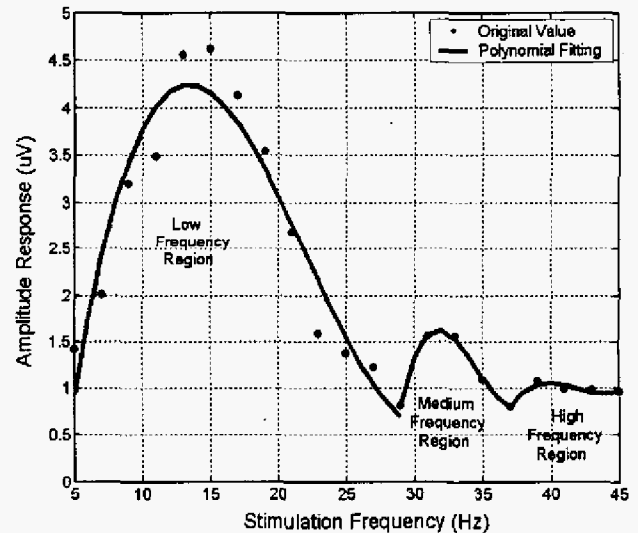


Fig.2. The three SSVEP subsystems of one subject.

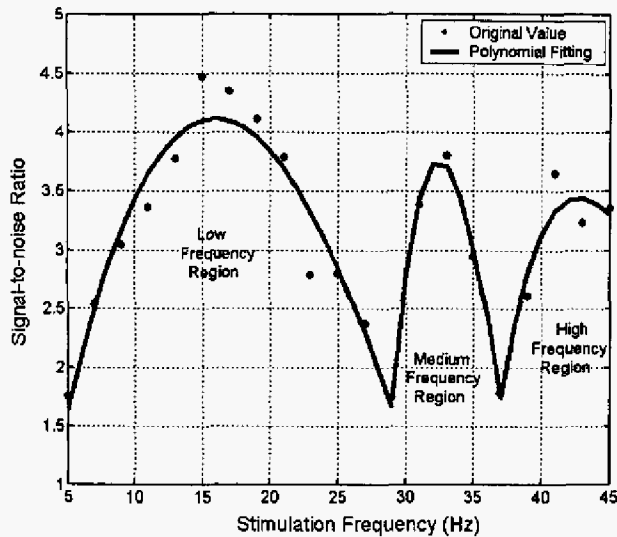


Fig.3. SNR curves corresponding to the three SSVEP subsystems.

TABLE I
OFFLINE ANALYSIS RESULTS OF ALL SUBJECTS

Subjects	Frequency Bands (Hz)	Accuracy (%)
CSQ	31 - 37	97
CSS	27 - 35	99
LH	21 - 27	90
LL	21 - 31	100
LY	23 - 37	100
NTS	27 - 43	100
SZJ	31 - 37, 41 - 43	95
WH	21 - 43	100
WMH	31 - 43	100
WW	31 - 35, 39 - 45	96
YH	21 - 27	76
YJ	31 - 35, 39 - 43	100
YY	21 - 23, 33 - 43	95
Mean		96

III. CONCLUSION AND DISCUSSION

Our results suggest that the high-frequency SSVEP has a lower background noise as well as a lower amplitude response, so it has a signal-to-noise ratio almost the same as the low-frequency SSVEP. The offline analysis demonstrates that the high-frequency SSVEP could be employed as a good medium in SSVEP-based BCIs. With great decrease of visual fatigue, possibility of causing a seizure, and interference of alpha rhythm, it makes the SSVEP-based BCI a more comfortable and stable system.

The standard method for measuring BCI performance is information transfer rate. It is the amount of information communicated per unit time. The bit rate (B) of each selection can be expressed as

$$B = \log_2 N + P \log_2 P + (1 - P) \log_2 [(1 - P)/(N - 1)]$$

N is the number of targets and P is the accuracy of target selections. B multiplied by selecting speed is the transfer rate (bits per minute) [1]. Assume that there are 8 visual targets, selection is performed every 4s, the expected information transfer rate of the online system could exceed 30bits/m if the detection accuracy is 90%.

Other effective signal processing methods for enhancing signal-to-noise ratio, e.g. adaptive filtering, could be used in future systems. The system parameters such as electrode position, number of targets, stimulation frequencies, and operating speed, should be optimized for each user individually. To implement a practical BCI, a higher information transfer rate should be expected, and moreover, the research on a portable system realized with digital signal processor is ongoing.

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