Design and Implementation of a Brain-Computer Interface With High Transfer Rates

Ming Cheng*, Xiaorong Gao, Shangkai Gao, *Senior Member, IEEE*, and Dingfeng Xu

***Abstract*—This paper presents a brain-computer interface (BCI) that can help users to input phone numbers. The system is based on the steady-state visual evoked potential (SSVEP). Twelve buttons illuminated at different rates were displayed on a computer monitor. The buttons constituted a virtual telephone keypad, representing the ten digits 0–9, BACKSPACE, and ENTER. Users could input phone number by gazing at these buttons. The frequency-coded SSVEP was used to judge which button the user desired. Eight of the thirteen subjects succeeded in ringing the mobile phone using the system. The average transfer rate over all subjects was 27.15 bits/min. The attractive features of the system are noninvasive signal recording, little training required for use, and high information transfer rate. Approaches to improve the performance of the system are discussed.**

***Index Terms*—Brain-computer interface (BCI), electroencephalography (EEG), steady-state visual evoked potential (SSVEP), transfer rate.**

I. INTRODUCTION

A brain-computer interface (BCI) is a communication channel connecting the brain to a computer or another electronic device. The intrinsic feature of a BCI is that it does not depend on the brain's normal output pathways of peripheral nerves and muscles [1]. Two basic requirements are met for a communication channel between the brain and computer: 1) features that are useful to distinguish several kinds of brain state; 2) methods for the detection and classification of such features implemented in real time. Various techniques are now available to monitor brain function, e.g., electroencephalography (EEG), magnetoencephalography, functional magnetic resonance imaging, and positron emission tomography. The latter three techniques are technically demanding and expensive. At present, EEG is the optimal choice for BCI implementation.

Many laboratories in the world have begun research into BCIs over the past decade, and have built some prototype systems [1]. These systems differ greatly in their inputs, feature extraction and translation algorithms, outputs, and other characteristics such as speed, accuracy, and appropriate user population. Typical input signals of BCIs include slow cortical potentials [2], μ or β rhythms recorded over sensorimotor cortex [3]–[5], EEG patterns associated with different mental tasks [6], [7], P300 potentials [8], [9], and visual evoked potentials (VEPs) [10], [11]. Electrodes can be placed either on the scalp or on the cortex [10], [12], [13]. Typical BCI applications involve cursor movement, letter or icon selection, or device control. Currently, BCIs are mainly used as an augmentative communication technology for individuals with motor impairments, such as amyotrophic lateral sclerosis (ALS) or cerebral palsy.

Several issues are crucial to further development and expanded utilization of the BCI technology. The first issue is the information transfer rate. Current BCIs are relatively low bandwidth devices, offering maximum information transfer rates of 5–25 bits/min at best [1]. At this rate, it may take several minutes to input a simple word to a computer. If this rate could be increased, BCIs might offer all individuals useful ways to interact with their environment.

The second issue is the training time for users to develop competence. BCIs that do not depend on external stimuli provide direct control over the environment, but these BCIs often require extensive training, from several hours [14] to several months [6]. BCIs based on evoked potentials may not require extensive training, but do require a structured environment.

The third issue is medical invasiveness. The less invasive the technique the more likely it can be used in a wide range of applications. Implanted electrodes provide stability of location, freedom from artifacts, and much higher signal-to-noise ratio (SNR). But one difficulty in such a system is how to determine the locations and the number of the electrodes. Another difficulty is how to keep the system stable over long periods. A scalp EEG technique is noninvasive, but has a relatively low SNR and spatial resolution.

Based on the above considerations, our interests concentrate on high transfer rate, minimal training, and noninvasiveness. Steady-state visual evoked potentials (SSVEPs) recorded from the occipital scalp are used as the input of our BCI system. The system has the advantage of focusing on EEG activity that occurs at a specific frequency. This feature simplifies the feature extraction methods, and users require little or no training. SSVEP-based BCIs belong to dependent BCIs. An intact visual system is necessary, and it will be wholly devoted to EEG-based communication.

In 1991, Skidmore *et al.* discussed the possibility of establishing an evoked potential vision-tracking system [15]. They found that dual stimulating objects could generate separable responses. Two methods of using the SSVEP for control have been employed in the Air Force Research Laboratory [16], [17]. In the first, operators were trained to self-regulate the amplitude of SSVEP, and the control was binary. In the second, two virtual

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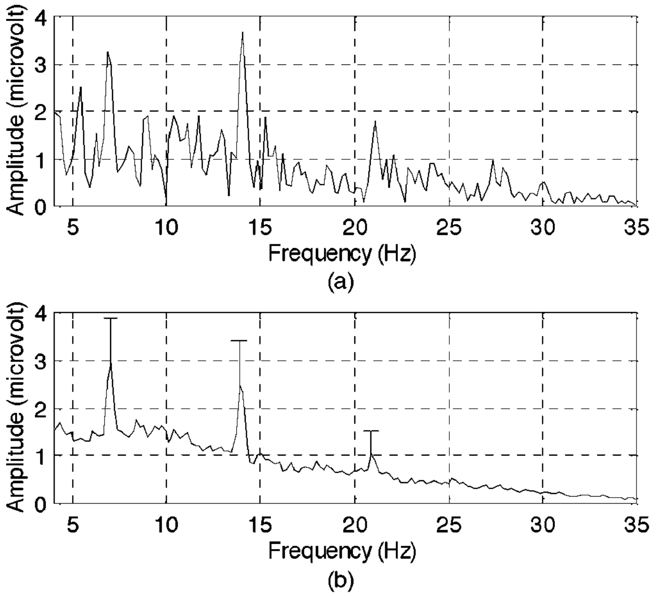

Fig. 1. Amplitude spectrum of SSVEP in response to 7 Hz stimulation. Three peaks at 7 Hz, 14 Hz, and 21 Hz can be found clearly. (a) Single trial amplitude spectrum. Sampling rate is 200 Hz and the trial has 512 data points (zero-padded to 1024 points before FFT). (b) Mean amplitude spectrum averaged over 40 trials. Vertical lines give standard deviation.

buttons modulated at 17.56 and 23.42 Hz were used to induce multiple SSVEPs.

We have applied SSVEP-based BCI to control cursor movements [18]. In that work, four buttons illuminated at different frequencies represented four directions; users could move the cursor to different directions simply by looking at the corresponding buttons. In this paper, we will introduce a new application of SSVEP-based BCI to show the system's ability to provide high transfer rates.

II. METHODS

A. Scientific Background

VEPs reflect, at least to some extent, the electrophysiological mechanisms underlying the processing of visual information in the brain. The signals are always in response to changes in the stimulus. A static stimulus in the visual field does not appear to effect any significant alterations in EEG activity. The signals evoked by changes in the visual input have been shown to reflect certain properties of the stimulus [10].

A distinction is made between transient VEP and SSVEP based on the stimulation frequency. The former arises when the stimulation frequency is less than 2 Hz. If the repetition rate of the stimulus is higher than 6 Hz, however, a periodic response called the SSVEP will result. It is composed of a series of components whose frequencies are exact integer multiples of the repetition frequency. The amplitude and phase of the SSVEP are highly sensitive to stimulus parameters such as repetition rate, contrast or modulation depth, and spatial frequency [19]. Fig. 1 shows the amplitude spectrum of 7 Hz-induced SSVEP. Three peaks at 7, 14, and 21 Hz can be found clearly.

The SSVEP was found to be strongly dependent on spatial attention, being substantially enlarged in response to a flickering stimulus at an attended versus an unattended location [20]. The increased SSVEP amplitudes reflect an enhancement of neural responses to a stimulus that falls within the range of spatial attention. This observation shows that SSVEP may provide an on-line method to identify the attentional target among a group of stimuli.

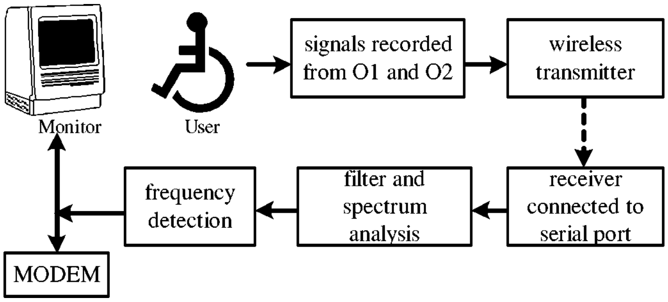

Fig. 2. Block diagram of the SSVEP-based BCI system for phone call.

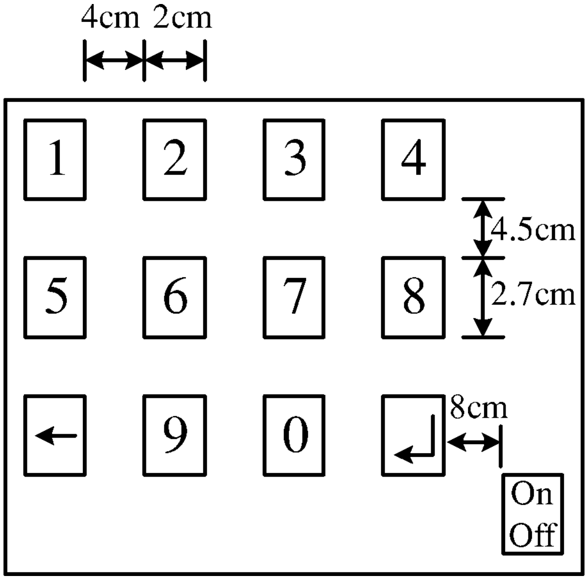

Fig. 3. Thirteen buttons widely spaced on the screen of a computer monitor. The 3 × 4 stimuli matrix constituted a virtual telephone keypad. The button ON/OFF was designed to control the start and stop of the other stimuli.

B. Hardware and Software

Fig. 2 shows the block diagram of the SSVEP-based BCI system. The system was designed to help users to input phone number. Thirteen buttons that flickered on and off at different frequencies were displayed on a computer monitor (Fig. 3). The on-off duty cycles were 50/50 for all frequencies. The 3 × 4 stimulus matrix constituted a virtual telephone keypad, representing the digits 0–9, BACKSPACE, and ENTER. Users could input phone numbers and correct input errors by gazing at these buttons. A beep was sent out from the loudspeaker of the computer after each selection, and the result was displayed on the monitor so that users could know whether the selection was correct. If the selection was wrong, users could delete it by gazing at the button BACKSPACE. The computer was connected to the telephone network through a modem. When ENTER was selected, the input number would be sent out. The button ON/OFF was designed to control the start and stop of the other stimuli.

It would be flickered all the time. If the stimulus matrix was static, the system only needed to detect the frequency of the button ON/OFF. A rigorous detection criterion was applied to this button to reduce the occurrence of false positives.

The buttons were widely spaced on the screen. Each button was a 2 cm × 2.7 cm rectangle. The distances between the neighboring buttons were 4 cm horizontally and 4.5 cm vertically.

Two-channel EEG signals were recorded from O1 and O2 according to the international 10–20 system and referred to the left and right ear lobes respectively. The electronic circuits provided signal amplification, A/D conversion (sampling rate = 200 Hz), and signal transmission. A wireless transmitter was adopted in the system to give users more freedom. Users could move their heads freely as long as their eyes were fixed on the desired buttons. A receiver connected to the serial port provided input data to the computer.

The data were filtered with a bandpass of 4–35 Hz. A 1024-point fast Fourier transform (FFT) was performed every 0.3 s using the latest 512 points EEG data padded with zeros, and the frequency resolution was 200/1024 $\approx$ 0.195 Hz. As only 60 points of new data were received in 0.3 s, there was substantial overlap of the data used in consecutive FFTs. The intensity of the response for each stimulation frequency was defined as the sum of the amplitudes of its fundamental frequency and the second harmonic, which would be taken as the feature for target detection. The threshold for detection was twice the mean value of the amplitude spectrum between 4 Hz and 35 Hz, determined empirically. If the largest intensity was over threshold, the corresponding button was considered as the target that the subject was gazing at. To improve the reliability, a selection was made only if the same stimulation frequency was detected in several consecutive FFTs. For the button ON/OFF, this number was six, and for the others it was four. The same detection parameters were used for all users.

Considering that the refresh rate of the CRT monitor was only 70.14 Hz, the stimulation frequencies were selected within the frequency band between 6 and 14 Hz. To reduce the interference of spontaneous EEG, the frequency band of the α rhythms was excluded from the stimulation frequencies (see below). Furthermore, all the stimulation frequencies were odd multiples of the frequency resolution so that it was impossible that one stimulation frequency was twice another stimulation frequency. The minimal difference between stimulation frequencies in our experiments was twice the frequency resolution; i.e., 0.39 Hz.

C. *Experiment Conditions and Tasks*

Thirteen volunteers (two female and eleven male) with normal or corrected to normal vision participated in the experiments. Their mean age was 24 (range 10 to 39) years. Before the experiments, the spontaneous EEG with eyes closed was recorded for each subject, and the mean amplitude spectrum was calculated. The frequency band above twice the mean value of the spectrum between 4 Hz and 35 Hz was considered the α rhythms, and would be excluded from the stimulation frequencies.

The subjects were seated comfortably facing the computer monitor. The visual angles of each button were 1.9 degrees in horizontal and 2.6 degrees in vertical at a viewing distance of 60 cm. At the beginning of the experiments, each subject had three minutes to adapt to the blinking stimuli and to remember the function of each button. Nothing was recorded in this step.

The first task in the experiments was to input an 11-digit phone number: 13 901 075 272. The initial state of the virtual keypad was static. The subjects were instructed to begin the procedure by using the button ON/OFF, and then to input the digits one by one. If a wrong selection appeared, they should delete it via BACKSPACE and input again until the digit was correctly input. The number was transmitted by selecting ENTER when input was finished. After that, the subjects were to stop the stimuli by again using the button ON/OFF, and wait three minutes without facing the monitor to see if a false positive would occur.

The second task was to measure the information transfer rate. The functions of BACKSPACE and ENTER were changed to "input letter A" and "input letter B". The subjects were asked to input 24 randomly arranged alphanumeric characters without input error correcting. These characters included ten Arabic numerals, letter A, and letter B; each character appeared twice. The input of each of the 24 characters constituted a trial. Each subject was tested in two blocks of 24 trials using different character arrays with a three minute interval between blocks. If the button ON/OFF was misselected, the subjects should select it again and go on with the test.

The third task was to test the influence of the distance between buttons on transfer rates. The buttons were displayed more and more closely until there were no gaps between them, and the subjects repeated the work of the second task. The horizontal distance and vertical distance pairs were 3.2 cm/3.6 cm, 2.4 cm/2.7 cm, 1.6 cm/1.8 cm, 0.8 cm/0.9 cm, and 0 cm/0 cm. The sizes of the buttons did not change. Four subjects performed this test.

D. *Performance Measure*

A standard measure of communication systems is bit rate, the amount of information communicated per unit time. Bit rate depends on both speed and accuracy. If a trial has N possible selections and each selection has the same probability of being the one that the user desires, if the probability P that the desired selection will actually be selected is always the same, and if each of the other (i.e., undesired) selections has the same probability of being selected (i.e., $(1-P)/(N-1)$), then bit rate B can be expressed as

$$B = \log_2 N + P \log_2 P + (1-P) \log_2 \left[\frac{1-P}{N-1}\right]. \qquad (1)$$

More details about (1) can be found in [1].

III. RESULTS

In the first task, eight of the thirteen subjects succeeded in ringing the mobile phone, the others failed. No false positives occurred for any subjects. In the second task, the average transfer rate over all subjects was 27.15 bits/min. The results could be classified into three grades.

TABLE I
RESULTS OF PHONE NUMBER INPUT. IF THE SUBJECTS COULD NOT START OR STOP THE STIMULI IN 30 s, THE TESTER WOULD PERFORM THIS OPERATION USING KEYBOARD. RESULTS FROM SEVEN OF THE 13 SUBJECTS ARE SHOWN. THE LAST TWO SUBJECTS IN THE TABLE FAILED IN THE TEST. ←: BACKSPACE. ↙: ENTER. TIME UNIT: SECOND

Subject	Time for start	Input results (wrong underlined)	Total / Wrong	Time	Time for stop	False positive
GXR	3.9	13901075272 ↙	12/0	45.0	4.2	No
CM	3.9	13901075272 ↙	12/0	46.2	4.2	No
CHM	6.0	13901075272 ↙	12/0	56.1	5.1	No
GYH	4.2	$13901\underline{1} \leftarrow 07\underline{8} \leftarrow \underline{2} \leftarrow 5272 \swarrow$	18/3	110.1	6.3	No
XDF	7.5	$13901\underline{375} \leftarrow\leftarrow\leftarrow$ $075272\underline{0} \leftarrow \swarrow \ \underline{00}$	22/6	135.0	7.2	No
LY	25.5	$1\underline{213} \leftarrow\leftarrow\leftarrow \underline{4} \leftarrow \underline{\swarrow}$	10/5	95.4	By hand	No
LXL	By hand	$\underline{03} \leftarrow\leftarrow \underline{3} \leftarrow 1\underline{72 \swarrow}$	10/6	90.9	By hand	No

TABLE II
INFORMATION TRANSFER RATES FROM THE SAME SUBJECTS AS TABLE I. TIME UNIT: SECOND. UNIT OF TRANSFER RATE: BITS/MIN

Subject	Block 1			Block 2			Average transfer rate
	Correct trials	Average time	Transfer rate	Correct trials	Average time	Transfer rate	
GXR	24	3.95	54.46	24	3.95	54.46	54.46
CM	24	3.90	55.15	24	3.83	56.23	55.69
CHM	23	4.70	40.74	24	5.36	40.11	40.42
GYH	19	4.66	27.36	20	6.33	22.37	24.87
XDF	19	6.18	20.66	18	6.44	17.79	19.22
LY	8	10.95	1.97	7	10.23	1.55	1.76
LXL	13	8.78	6.87	11	7.49	5.74	6.30

Good: The results from six subjects were encouraging. They could input the phone number without errors. In the second task, zero or one error occurred in each block of 24 trials. Their mean transfer rate was 48.93 bits/min (range 40.42 bits/min to 55.69 bits/min).

Moderate: The results from another two subjects were moderate. They both finished the phone number input successfully, but made some mistakes. In the second task, the number of wrong trials was between four and six in each block of 24 trials. Their transfer rates were 24.87 bits/min and 19.22 bits/min.

Bad: Performances of the rest were unacceptable. They could not input the phone number correctly; some subjects could not even start or stop the stimuli. In the second task, the input accuracy was not more than 50%; the lowest input accuracy was only 16.7%. Their mean transfer rate was 3.05 bits/min (range 0.76 bits/min to 6.30 bits/min).

Tables I and II show the results of task one and task two from seven of the thirteen subjects. In each table, rows 2 to 4 are examples of *good* results, rows 5 and 6 are *moderate* results, and the last two rows are examples of *bad* results.

Fig. 4 shows the performances of the four subjects in the third task. To keep a transfer rate not less than the result in the second task, the minimal distances were 0 cm/0 cm for GXR and GYH, and 0.8 cm/0.9 cm for DGY and CHM. The results suggest that the stimuli can be placed more closely for the subjects with *good* and *moderate* results.

IV. DISCUSSION

A. Information Transfer Rate

The transfer rate of a BCI system depends on three factors: number of selections, accuracy and speed.

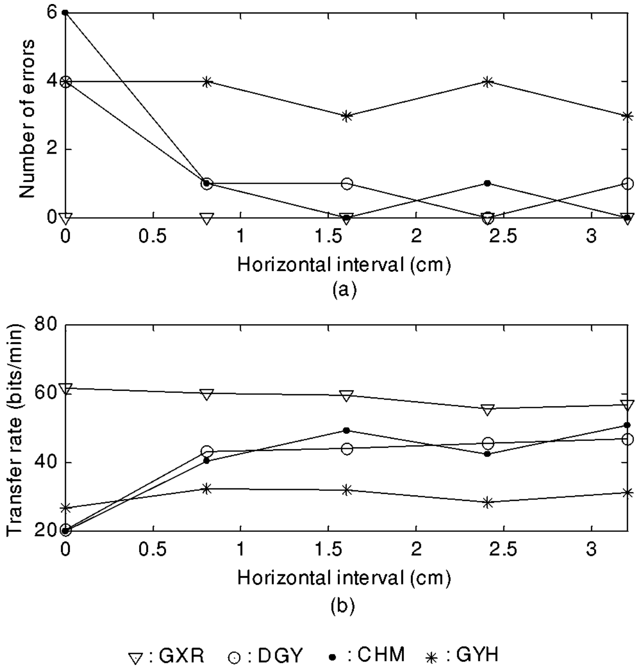

Fig. 4. Performances of four subjects when using different distances between buttons. (a) The number of wrong trials in a total of 24 trials. (b) The corresponding transfer rate.

Currently, many BCIs are designed to control one1-dimensional or two-dimensional cursor movements. Only two or four EEG patterns are needed for this kind of task. It is relatively simple to increase the number of selections in VEP-based BCI systems. The system introduced in [10] could provide up to 64 visual stimuli modulated with m-sequences. One trained subject with implanted electrodes reached communication rates of 10–12 words/min. In our system, each trial had 12 possible selections, which was crucial to the realization of high transfer rates. The results of task three suggest that it is possible to place more visual stimuli in a small area so that the transfer rate can be further improved. High stimulation frequencies can be realized using LEDs or CRT monitor with high refresh rate.

In any real time system, there is a tradeoff between accuracy and speed. In our system, a selection was made only if the same repetition frequency was detected in four consecutive FFTs. To increase the speed, it is better to optimize the detection criteria for each user individually. For subjects with strong SSVEP, a higher threshold can be used, and a selection can be made based on only two or three consecutive FFTs. Furthermore, advanced signal processing methods should be used; e.g., the prewhitening of the background brain activity is expected to improve the SNR of SSVEP [21], [22].

B. *Appropriate Applications*

SSVEP-based BCIs are essentially EEG-based vision-tracking systems. These systems rely on the user's ability to control eye movements. This prerequisite restricts the possible applications. It might not be effective, e.g., for some severe ALS patients.

The subjects could move their heads and blink freely in the experiments, but they should concentrate on the tasks. We have observed that the input accuracy would decrease when the subject was listening to other people's conversation.

V. CONCLUSION

The frequency-coded SSVEPs elicited by multiple flickered visual stimuli can be used to determine where the eyes are directed. This methodology was used to construct a BCI system that could help users to input phone numbers. Users could operate the system with little training. Eight of the thirteen subjects gave promising results in the tests. A higher performance can be expected when using more visual stimuli and more sophisticated signal processing methods, optimized for each user individually. There are many disabled persons who have no motor control left for communication besides eye movements. The system introduced in this paper can help them to achieve an acceptable level of communication. Future systems will reduce the dependence on a general-purpose computer. For example, LEDs can be used in the stimulus device, and data analysis can be realized in special digital signal processor. The practical system will be compact and portable.

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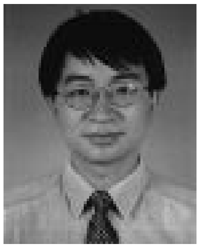

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