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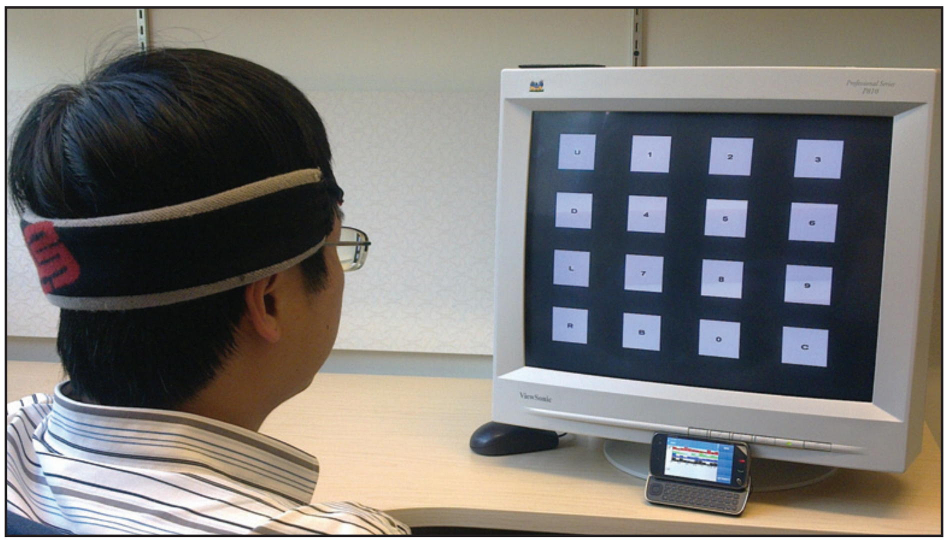
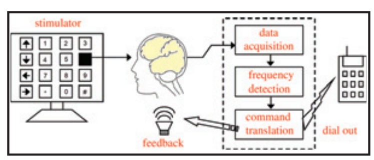
'Visual stimulus design for high-rate SSVEP BCI', Yijun Wang, Yu-Te Wang and Tzyy-Ping Jung

An easy, flexible and practical way to build a high-performance brain–computer interface using a monitor's refresh rate has been demonstrated by researchers in the US

tapping the brain*

Researchers at the University of California San Diego (UCSD) have built a brain–computer interface (BCI) system that uses a computer monitor's refresh rate to produce visual stimuli at varying frequencies. Their BCI design, in which the user controls a virtual keyboard, looks promising as a practical solution that will allow patients with motor diseases to communicate with other people or their environment.





TOP: A virtual keyboard is used as a substitute for the hardware equivalent and the user focuses on one of 16 virtual keys to make their selection
RIGHT: An SSVEP-based brain–computer interface

Visual control

Electroencephalogram (EEG)-based BCIs are being intensively researched for communication and control applications for people with spinal cord injuries, patients recovering from stroke and those with motor disabilities such as amyotrophic lateral sclerosis. BCIs bypass the traditional motor control pathway of peripheral nerves and muscles, and create a direct link between the human brain and output device. Common applications include word spellers, cursor control, wheelchair control and neuroprosthetic device control. Recently, BCIs have also been introduced to other fields like motor rehabilitation, video gaming and cognitive-state monitoring.

Visual evoked potential (VEP) BCIs, in which a stimulus is presented to the subject's visual field, can be applied to all these fields to realise high-speed communication. VEP BCIs have been under study for several decades, but the challenges relating to the required monitoring and analysis of subjects' EEGs in a natural environment have hindered the progress of real-life applications.

A refreshing change

To be useful and practical, a VEP BCI system has to be non-obtrusive, lightweight, non-tethered and low-cost, and demonstrate an accurate, reliable and robust performance. The UCSD research team has been working towards achieving a system with all these qualities. In this issue of *Electronics Letters* they present their development of a steady-state VEP (SSVEP) BCI using the flickers on a computer screen. Previously, the number of stimulus frequencies was limited to just a few by the refresh rate of the monitor, and if a more complicated control application was required, such as dialing a telephone, a special stimulus device such as an LED stimulator was needed. These custom hardware stimulators are not flexible and increase the overall system cost.

The key finding of the UCSD team is that SSVEP at any frequency lower than half of the refresh rate can be elicited using a computer monitor. They have used this to demonstrate that 16 stimulus frequencies (9–12.75 Hz with an interval of 0.25 Hz) can be accurately realised in Microsoft Windows. Their system uses a 'virtual keyboard' on the computer monitor, which consists of 16 frequency-coded flickers, and the subject focuses on a virtual key on the screen to operate it. In this study the researchers included the keys needed for a telephone: 10 digits, 'backspace' and 'confirm'; and also left, right, up and down keys for potential applications like cursor or wheelchair control. By solving challenges in the software design and signal processing relating to the accurate capture of the monitor's frame synchronisation signals, and the detection of the multi-channel EEG data, they achieved an average information transfer rate (ITR) of 75 bits/min which is significantly higher than the previous record of 58 bits/min. They are now exploring the possibility of using more targets on the screen, such as for a spelling system which may require higher frequency resolution, a wider frequency band and a higher monitor refresh rate to further improve the system performance.

Thinking mobile

The team is also collaborating with researchers at UCSD and National Chiao Tung University of Taiwan, led by Dr Chin-Teng Lin to conduct a pilot study on a mobile and wireless BCI platform for real-life applications that replace the bulky, wired EEG acquisition device and signal processing platform with a wearable and wireless EEG system integrated with a mobile phone. Their system consists of a multi-channel biosignal acquisition/amplification module, a wireless transmission module, and a Bluetooth-enabled mobile phone. Real-time data processing is implemented and carried out on the mobile phone. This BCI is easy to use, requires little user training and demonstrates a high ITR. In the near future, the team foresees an integration of new technologies, such as non-contact dry electrodes, wireless data transmission and real-time processing, into a nearly weightless and imperceptible BCI which will enable many more applications of BCIs in natural environments.

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Visual stimulus design for high-rate SSVEP BCI

Y. Wang, Y.-T. Wang and T.-P. Jung

A new approach to realise computer monitor flickers that can be used to elicit steady-state visual evoked potentials (SSVEP) at a flexible frequency is proposed. An SSVEP-based brain–computer interface (BCI) with 16 targets was then implemented using the proposed method. In an online test on three subjects, a high information transfer rate of 75.4 bits/min was achieved.

Introduction: Visual evoked potentials (VEPs) have been widely used in electroencephalogram (EEG) based brain–computer interfaces (BCI) owing to its advantages of high information transfer rate (ITR), little user training, and ease of use [1–3]. In current VEP BCI designs, frequency coding is the most commonly used method [1]. In such a system, each target is flickering at a different frequency. Through detecting the dominant frequency of the VEP, the system can recognise which target the user is gazing or attending. Recently, with advances in signal processing and machine learning, the performance of SSVEP BCIs has been significantly improved. An ITR of 58 bits/min was reported by Bin *et al.* [4].

The visual stimulator plays an important role in an SSVEP BCI. Visual stimuli can be presented using flashing lights/LEDs [1], or flickers on a computer screen [5, 6]. If considering stimulation parameters such as size, colour and position, presenting flickers on a computer monitor is more flexible than using stand-alone lights/LEDs. However, when using a frame-based design to ensure a flicker's frequency stability, the number of stimuli is always limited by the refresh rate of a monitor. For example, on a monitor with a 60 Hz refresh rate, the usable stimulus frequencies within the EEG alpha band (8–13 Hz) can only be at 8.57 Hz (7 frames per period), 10 Hz (6 frames per period) and 12 Hz (5 frames per period). An alternative approach is to program stimulus presentation using high-resolution timers such as the Windows Multimedia Timer [7]. However, when using a timer, the frequency resolution is limited by the timer's error which is always affected by other active Windows processes. In an SSVEP BCI, system performance is highly related to the number of targets. The ITR can always be improved with an increased number of targets. In addition, in some situations such as a phone dialling paradigm, the system needs at least 12 targets (10 digits, backspace, and confirm) to function [8]. Currently, visual stimulator design is the limiting factor of applications of SSVEP BCIs.

In this Letter we propose a new frame-based method to realise visual stimulus presentation for eliciting SSVEPs with a very high frequency resolution. A 16-target online system was implemented with a frequency resolution of 0.25 Hz, obtaining an average ITR of 75.4 bits/min in an SSVEP-based BCI.

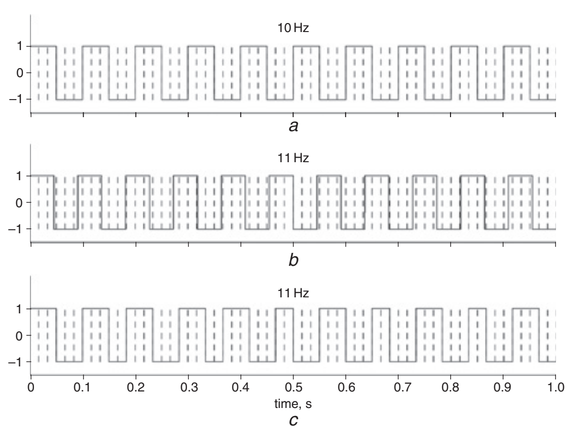

Fig. 1 *60-frame flickering signals of visual stimuli at 10 and 11 Hz*

a 10 Hz flicker reversing every 3 frames
b 11 Hz flicker reversing every 2.73 frames
c 11 Hz flicker reversing every 2 or 3 frames

Stimulus design: In conventional frame-based stimulus designs, the number of frames in each cycle is a constant. For instance, to produce a 10 Hz flicker with a 60 Hz refresh rate, the stimulus pattern reverses between black and white every three frames (Fig. 1*a*). In this regime, it is impractical to generate an 11 Hz stimulus because mathematically the stimulus presentation should reverse every 2.73 frames (Fig. 1*b*). However, it is feasible to approximate this presentation rate using a varying number of frames in each cycle (five or six, corresponding to 12 and 10 Hz, respectively). Fig. 1*c* shows a sequence for the 11 Hz stimulus. Generally, the stimulus signal at frequency *f* can be calculated as follows:

$$\mathrm{stim}(f, i) = \mathrm{square}[2\pi f(i/\mathrm{RefreshRate})] \tag{1}$$

where square(2πft) generates a square wave with frequency *f*, and *i* is the frame index. As shown in Fig. 1*c*, in a one-second stimulus sequence, the black/white reversing interval for the 11 Hz stimulus is: [3 3 3 2 3 3 3 2 3 3 2 3 3 3 2 3 3 3 2 3 3 2], which includes 11 cycles with a varying length of five or six frames. Based on this approach, a stimulus at any frequency up to half of the refresh rate can be realised.

Power spectrum analysis: Target detection is through detecting the dominant frequency of SSVEPs. Power spectrum analysis methods have been applied in many SSVEP studies owing to their simplicity and robustness [1]. To test the usability of the proposed method, fast Fourier transform (FFT) was performed to estimate the power spectra of the stimuli and the SSVEP signals. Fig. 2 shows the time series and power spectra of the 11 Hz stimulus (Fig. 2*a*) and the elicited SSVEPs (Fig. 2*b*). The one-second SSVEP waveform was obtained through averaging 10 one-second segments intercepted continuously from the EEG recordings measured at Oz from a subject. Data were bandpass filtered between 8–25 Hz. The time series show a typical stimulus-driven pattern of the SSVEPs which includes 11 cycles in one second. In the frequency domain, the power spectrum density (PSD) is peaking at 11 Hz with its second harmonics at 22 Hz. These results indicate that this stimulus approximation method can ensure frequency stability of the stimulus and the elicited SSVEPs.

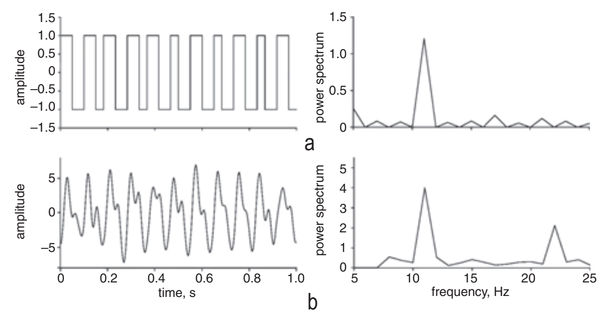

Fig. 2 *Time series and power spectra of stimulus signal and elicited SSVEPs at 11 Hz*

a Stimulus signal
b SSVEP signals

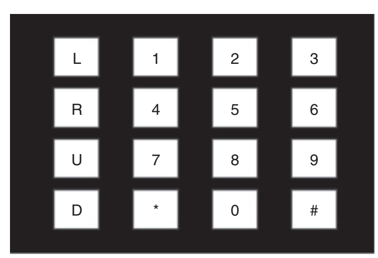

Fig. 3 *Distribution of 16 targets on screen*

BCI paradigm: To demonstrate the practicability of this method, we designed a virtual keypad consisting of 16 targets (10 digits, backspace, confirm, left, right, up, down) for an SSVEP BCI. Frequencies from 9 to 12.75 Hz with an interval of 0.25 Hz were selected because SSVEPs in the alpha band (8–13 Hz) have a relatively high signal-to-noise ratio [8]. The distribution of the targets on the screen is shown in Fig. 3. A CRT monitor (ViewSonic, 21 inch, 60 Hz refresh rate, 800 × 600 screen resolution) was used for stimulus presentation. The stimulus program was developed under Microsoft Visual C++ using the Microsoft DirectX 7.0 framework.

Three healthy right-handed adults with normal or corrected-to-normal vision participated in this study test after giving their informed consent. They were randomly selected from subjects in a previous BCI study. The EEG signals were recorded using a BioSemi ActiveTwo system (BioSemi Inc.). Real-time data recording and processing was performed using DataRiver (A. Vankov) and MatRiver (N. Shamlo). Eight electrodes were placed over the occipital region. The sampling rate was 256 Hz. Subjects were seated in a comfortable chair approximately 60 cm from the screen in a normal office room. After 1.5 s from the beginning of each trial, the dominant frequency was detected at 0.2 s steps using SSVEPs within an expanded time window. The trial ended after the same frequency was detected three times consecutively. Visual feedback was then provided through displaying a red rectangle over the centre of the selected target. A 0.5 s interval following feedback was given to the subject to shift gaze to the next target. The canonical correlation analysis (CCA) method used in [4] was adopted in our system for frequency detection using multi-channel EEG data. In each of three bouts, each subject was asked to input the 16 characters on the keypad consecutively. The accuracy and ITR were used to evaluate the performance of the BCI.

Results: Table 1 lists the task performance of the three subjects. An averaged ITR of 75.4 bits/min was achieved. Two subjects made two errors of 48 selections, the other subject made no error. The mean accuracy was 97.2%. Mean time for selecting a target was 3.08 s.

Table 1: Online test results of three users of SSVEP-based BCI

Subjects	ITR (bits/min)	Accuracy (%)	Time per selection (s)
S1	94.5	100 (48/48)	2.54
S2	76.6	95.8 (46/48)	2.81
S3	55.2	95.8 (46/48)	3.90
Mean	75.4	97.2	3.08

Conclusion and discussion: We propose a presentation approximation approach for the frame-based visual stimulus design in an SSVEP BCI. Using this method, the number of targets is no longer limited by the refresh rate of the monitor. The resultant online SSVEP BCI comprised 16 targets with a frequency resolution of 0.25 Hz. The averaged ITR across three subjects was 75.4 bits/min, exceeding current SSVEP-based BCIs. Considering the flexibility of using a higher frequency resolution and a wider frequency band, the BCI system may achieve an even higher ITR provided more targets were used, such as a spelling program which uses more than 30 targets.

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Y. Wang, Y.-T. Wang and T.-P. Jung (*Swartz Center for Computational Neuroscience, University of California, San Diego 92122, CA, USA*)

E-mail: yijun@sccn.ucsd.edu

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