Developing Stimulus Presentation on Mobile Devices for a Truly Portable SSVEP-based BCI

Yu-Te Wang, *Student Member*, *IEEE*, Yijun Wang, *Member*, *IEEE*, Chung-Kuan Cheng, *Fellow*, *IEEE*, and Tzyy-Ping Jung*, *Senior Member, IEEE*

Abstract—**This study integrates visual stimulus presentation and near real-time data processing on a mobile device (e.g. a Tablet or a cell-phone) to implement a steady-state visual evoked potentials (SSVEP)-based brain-computer interface (BCI). The goal of this study is to increase the practicability, portability and ubiquity of an SSVEP-based BCI for daily use. The accuracy of flickering frequencies on the mobile SSVEP BCI system was tested against that on a laptop/desktop used in our previous studies. This study then analyzed the power spectrum density of the electroencephalogram signals elicited by the visual stimuli rendered on the mobile BCIs. Finally, this study performed an online test with the Tablet-based BCI system and obtained an averaged information transfer rate of 33.87 bits/min in three subjects. The current integration leads to a truly practical and ubiquitous SSVEP BCI on mobile devices for real-life applications.**

I. Introduction

In the past two decades, electroencephalogram (EEG)-based brain-computer interfaces (BCIs) have gained increasing attention in fields of neuroscience and neural engineering. While researchers have made significant progress in their efforts to design and demonstrate BCI systems, moving a BCI system from a laboratory demonstration to real-life applications still poses great challenges to the BCI community [1].

Steady state visually evoked potential (SSVEP) [2] is a natural response to visual stimulation flickering at specific frequencies. It has been used for clinical research and practice, e.g. migraine detection and/or prediction [3]. Predicting or monitoring migraine attacks requires a user-acceptable, non-tethered, continuous and home-based SSVEP BCI system. Thus, a mobile device that can deliver steady-state visual stimuli and continuously collect and analyze EEG data at the same time is crucial for clinical applications such as migraine and seizure detection and monitoring.

Our recent study [4] demonstrated a cell-phone based BCI that took advantage of the robust SSVEP. The entire system consisted of three parts: (1) a near real-time data processing platform (e.g., a Bluetooth-enabled cell-phone or a Tablet), (2) a mobile and wireless EEG device (e.g., a customized EEG headband featuring Bluetooth module, amplifier circuits, and a microprocessor), and (3) a computer screen (e.g., a cathode ray tube (CRT) monitor). Though the cell-phone based EEG acquisition and near real-time data processing significantly increased the portability of an EEG system in the BCIs, the SSVEP-based BCI system was still not completely portable or ubiquitous because subjects have to equip a bulky screen for stimulus presentation.

Several approaches have been carried out to elicit SSVEPs from the subjects. For instance, CRT based visual stimulators have been widely used in previous studies [5]-[9]. Gao et al. [10] used light-emitting diodes (LEDs) to deliver visual stimuli in a BCI-based environmental controller. Shyu et al. [11] also designed a LED stimulation panel to display visual stimuli. Recently, liquid crystal display (LCD) based stimulators have become popular in SSVEP BCIs [12]. Although different methods have been proposed in the design of visual stimulator for eliciting SSVEPs, the current visual stimulators are still very inconvenient and bulky. Users have to equip a computer monitor or an isolated visual stimulator (e.g. LEDs). The bulky SSVEP stimulator reduces the practicability of the BCI system, hindering the BCI applications.

In short, although the SSVEP-based BCI has been well studied in the past decades, no one has implemented and integrated the visual stimuli and the near real-time EEG processing system in a single mobile device for ubiquity and portability.

This study proposes to implement the display of visual stimulus together with near real-time data processing in a single mobile and wireless device, such as a laptop, a Tablet, or even a cell-phone. Since the cell-phone or Tablet based online EEG processing has been reported in detail in our previous study [4], this study then focuses on the implementation, integration, and validation of the SSVEP stimulus presentation on a portable device. This study first examines the accuracy and stability of visual stimulus rendered on each device, and then evaluates the all-in-one SSVEP BCI by analyzing the power spectrum density (PSD) of the EEG recorded from three healthy subjects performing the SSVEP experiments. Finally, this study performs an online test with three subjects to evaluate the performance of a Tablet-based BCI. The goal of this study is to demonstrate the feasibility of eliciting reliable SSVEPs and processing the wirelessly acquired EEG data on a single mobile device. The results of this study may lead to a truly practical and ubiquitous SSVEP BCI for daily use.

This work was supported by a gift fund from Abraxis Bioscience Inc. Research was also sponsored in part by Office of Naval Research, Army Research Office (under contract # W911NF-09-1-0510) and Army Research Laboratory (under Cooperative Agreement # W911NF-10-2-0022).

Y. -T. Wang and C. K. Cheng are with Department of Computer Science and Engineering, University of California San Diego (UCSD), La Jolla, CA, USA (e-mail: ytwang@ucsd.edu and ckcheng@ucsd.edu).

Y. Wang and T. -P. Jung* are with Swartz Center for Computational Neuroscience, Institute for Neural Computation, and Center for Advanced Neurological Engineering, Institute of Engineering in Medicine, UCSD, La Jolla, CA, USA (e-mail: yijun@sccn.ucsd.edu, jung@sccn.ucsd.edu; phone: 858-822-7555; fax: 858-822-7556).

II. MATERIALS AND METHODS

A. The Platform of Rendering Visual Stimuli

Three portable platforms were selected to deliver the visual stimuli of a BCI: a laptop (Lenovo X200S), a Tablet (Motorola XOOM), and a cell-phone (Samsung Galaxy S). Table I lists the specifications of three devices. The flickering visual stimulation displayed on a laptop running Microsoft Windows operation system has been implemented and demonstrated in our previous study [4]. This section therefore only describes the details of the design and implementation of stimulus presentation on Android based mobile devices. For presenting SSVEP visual stimuli on a portable device, the stability of screen refresh rate is very important. This study first tests the screen refresh rate with a silicon NPN phototransistor (PNA1605F). The three devices have different refresh rates: 60.375Hz for the laptop, 59.975Hz for the Tablet, and 55.575Hz for the cell-phone

B. Software Architecture

The application of visual stimulation was written in Java under Eclipse integrate development environment. An Android Development Tools plugin to Eclipse facilitates the development and deployment of Android applications across different platforms. Fig. 1 shows the software architecture of the program delivering flickering visual stimulus. The OpenGL ES (OpenGL for embedded system) technology was used to realize a frame-based display. The stimulation application can display one or multiple flickering 3.5cm × 3.5cm squares on the screen over a black background according the screen resolution, accomplished by sequential rendering of black and white colors at a specific frequency [13].

The application of visual stimulus consists of two major programs and is shown in Fig.1. The Main Program is responsible for creating graphic user interfaces and calculating the stimulation sequence under a specific screen refresh rate. According to the approach proposed in [13], the stimulation sequence may vary due to the screen refresh rate. For instance, displaying an 11Hz flickering square on the screen refreshed at 60 Hz can be realized with 11-cycle black/white alternating patterns lasting [3 3 3 2 3 3 3 2 3 3 2 3 3 3 2 3 3 3 2 3 3 2] frames in a second. On the other hand, the Display Program is responsible for rendering the flickering animation. GLSurfaceView, a class of Android.opengl makes it possible to draw flickering animation frame-by-frame by creating and managing a separate thread. In general, multiple flickers flickering at different frequencies can be implemented at the same time.

C. Platform Testing and EEG Experiment

In order to test the stability of the flicker on each platform, the silicon NPN phototransistor was directly attached to the center of the flickering animation on the screen to examine the quality of the flickering stimulation. For each platform, 11-Hz flickering stimuli (one minute long) were recorded using an EEG amplifier. The EEG amplifier is a 16-channel bio-signal acquisition unit. Signals within the frequency band of 0-250 Hz were amplified and digitized by analog-to-digital converters (ADC) with a 24-bit resolution at a sampling rate of 1000 Hz.

TABLE I. SPECIFICATIONS OF STIMULATORS

	Lenovo X200s	**Motorola XOOM**	**Samsung Galaxy S**
OS	Windows XP SP3	Android 3.0	Android 2.1
CPU	Intel Core 2 Duo 1.4GHz	NVIDIA Tegra 2 Dual-Core 1GHz	ARM Cortex-A8 1 GHz
Software	Direct X	OpenGL ES	OpenGL ES
Screen refresh rate (Hz)	60.375	59.975	55.575
Screen size (inch)	13	10.1	4
Screen resolution (pixels)	800 × 1280	800 × 1280	400 × 800

To further validate the usability of each platform for eliciting SSVEPs, an EEG experiment was conducted on three subjects. Two of them were naive subjects to the SSVEP experiment (subjects 2 and 3), while subject 1 has experience in using an SSVEP-based BCI. Each subject repeated this task on each of the three platforms. The goal of this testing is to verify the presence of the 11-Hz brain activity induced by the visual stimulus. During the SSVEP experiments, the subjects gazed at a single flicker animation flashing at 11 Hz for one minute with no feedback. EEG signals were recorded from two electrodes placed over the occipital region, referenced to the forehead. The channel with higher signal-to-noise ratio (SNR) was selected for further analysis.

D. Data Analysis

The flickering animation signals rendered on the three different platforms were recorded and filtered with a (8-20 Hz) band-pass filter. Secondly, one-minute recording was partitioned into fifteen 4-sec trials. Fast Fourier Transform (FFT) was then applied to the averaged waveforms of the segmented data and the resultant PSDs were plotted to

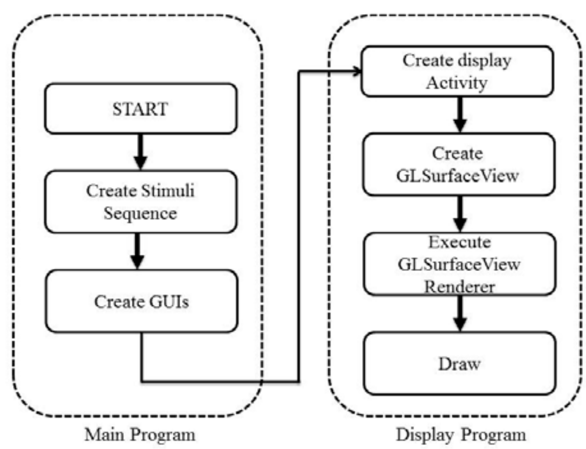

Figure 1. The stimulation software consists of two saperate programs

evaluate the flickering frequencies on different platforms and elicited SSVEPs.

E. On-line Testing

A Tablet-based system integrating visual stimulus presentation and data processing was tested on an online BCI experiment. Three subjects performed a phone-dialing task, in which they need to dial 10-digit numbers using their brain activities as described in [4]. An EEG headband, which features miniature amplifier, Bluetooth module, and a microprocessor [4], was used for data collection. A virtual keypad comprised 12 targets on the screen of the Tablet. Each target was a 3.5cm × 3.5 cm square. The frequencies ranged from 9-11.5Hz with a 0.25Hz interval. Each subject sat in a comfortable chair in a dim room. The Tablet was placed ~60cm in front of them. They were asked to gaze at the targets sequentially with the following sequence: #, 1, 2, 3, 4, 5, 6, 7, 8, 9, 0, #. The SSVEP frequencies in the 4-channel EEG from the headband were detected by the canonical correlation analysis (CCA) algorithm [12]. The target stimulus on the screen would change to a red background (as visual feedback) for about 200ms once the target had been identified. The subject was instructed to switch to the next target immediately following the feedback. Each subject repeated the task five times and the averaged information transfer rate (ITR) was used to evaluate the BCI performance.

III. Results and Discussion

A. Accuracy and Stability of Flickering Signals

Fig. 2 shows the averaged time series and PSDs of the acquired flickering animations from three different platforms. The stimulus signals (Fig. 2(a)) on the laptop and the Tablet are more stable than those rendered on the cell-phone. More precisely, the signal waveforms flashed from the laptop and the Tablet had almost same phases in each second, while the phase of 11-Hz stimulus signals on the cell-phone shifted back and forth slightly. The normalized PSD (Fig. 2(b)) shows that the stimulus signal on all platforms contained the correct fundamental frequency (11 Hz). The normalized amplitude of the stimulation frequency on the cell-phone is smaller than that of other platforms due to the phase jitter of the screen refresh rate. Although the flickering signal on the cell-phone is not as stable as other platforms, the stimulation frequency is still accurate.

B. SSVEP Signals

Fig. 3 shows the averaged SSVEPs and their PSDs elicited by the flickering stimuli on the three platforms for all the subjects. Fig. 3(a) exhibits characteristic sinusoidal SSVEPs. Because the stimulus signal and the EEG signal were not synchronized, SSVEPs of the three subjects had different initial phases. Fig. 3(b) plots the PSDs of SSVEPs elicited by the flickering stimuli, all showing very consistent and accurate 11-Hz peaks. For all subjects, the amplitudes of the 11-Hz SSVEPs elicited by the laptop and Tablet screens were higher than those elicited by the cell-phone.

C. On-line Results

The ITR in bits/minute was calculated as follows [14]:

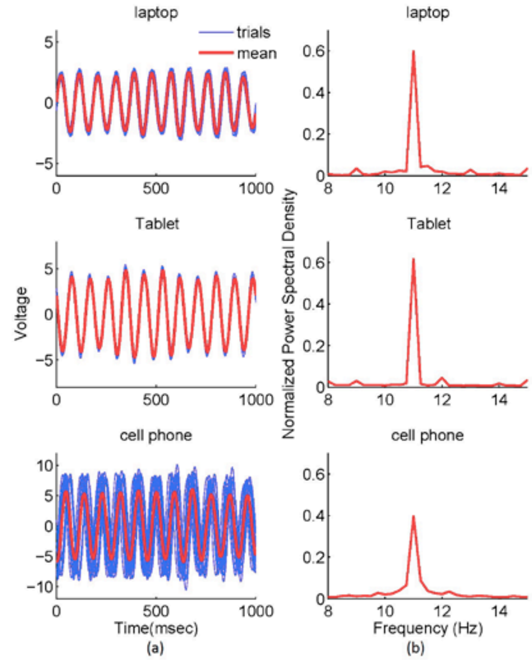

Figure 2. The waveforms and power spectra of the flickering signals. (a) Time series of averaged flickering signals from the laptop, the Tablet and the cell-phone. (b) The normalized power spectral density of the flickering signal on each platform.

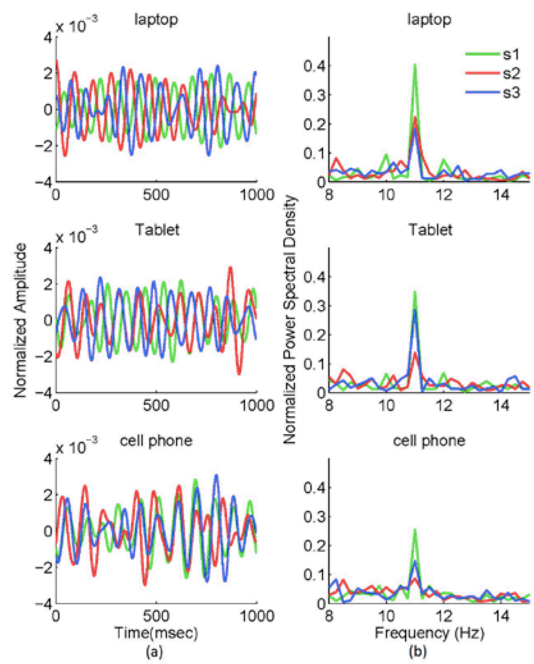

Figure 3. EEG signal acquired and averaged during visual stimulation presenting with a frequency of 11 Hz and its power spectrum. (a) Sample SSVEP signal obtained from the three subjects on different platforms. (b) The frequency spectrum corresponding to the signal in left. The SSVEP manifests itself in oscillations at 11 Hz.

TABLE II. ON-LINE TESTING RESULTS

Experiment run	Subject 1	Subject 2	Subject 3
1	49.64	28.13	31.15
2	45.66	35.76	22.54
3	41.64	25.17	33.26
4	50.74	29.89	25.05
5	49.64	20.99	18.74
Average	47.46	27.99	26.15
Standard deviation	±3.39	±4.92	±5.38

$$\text{ITR} = log_2 N \ + A\ log_2 A + (1-A) log_2 \left[\frac{1-A}{N-1}\right]$$

where N is the number of targets, and A is the accuracy of frequency detection. Table II shows the ITR in bits/minute for all subjects. All subjects fulfilled the tasks. The averaged ITR is 33.87 bits/min, which is comparable to previous studies using a separate stimulating device [4], [7].

IV. CONCLUSION

This study implemented and demonstrated a practical and ubiquitous SSVEP-based BCI system for real-world applications. The feasibility of using a mobile stimulus presentation was suggested by the accuracy and stability of flickering frequencies and the elicited SSVEP signals. As the feasibility of using a mobile device (a cell-phone or a Tablet) to acquire and process EEG signals from unconstrained individuals in real-world environments has been demonstrated in our previous studies [4] [13], the integration of stimulus presentation and real-time data analysis on a single mobile device leads to a truly practical, online SSVEP-based BCI for real-life applications that require continuous and ubiquitous monitoring of the brain.

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