Research on Steady-State Visual Evoked Potentials in 3D Displays

Yu-Yi Chien*[a], Chia-Ying Lee[a], Fang-Cheng Lin[a], Yi-Pai Huang[a],
Li-Wei Ko[b] and Han-Ping D. Shieh[a]
[a]Dept. of Photonics and Display Institute, National Chiao Tung Univ., 1001 University Rd., Hsinchu, Taiwan 30010; [b]Dept. of Biological Science and Technology, National Chiao Tung Univ., 1001 University Rd., Hsinchu, Taiwan 30010

ABSTRACT

Brain-computer interfaces (BCIs) are intuitive systems for users to communicate with outer electronic devices. Steady-state visual evoked potential (SSVEP) is one of the common inputs for BCI systems due to its easy detection and high information transfer rates. An advanced interactive platform integrated with liquid crystal displays is leading a trend to provide an alternative option not only for the handicapped but also for the public to make our lives more convenient. Many SSVEP-based BCI systems have been studied in a 2D environment; however there is only little literature about SSVEP-based BCI systems using 3D stimuli. 3D displays have potentials in SSVEP-based BCI systems because they can offer vivid images, good quality in presentation, various stimuli and more entertainment. The purpose of this study was to investigate the effect of two important 3D factors (disparity and crosstalk) on SSVEPs. Twelve participants participated in the experiment with a patterned retarder 3D display. The results show that there is a significant difference (p-value<0.05) between large and small disparity angle, and the signal-to-noise ratios (SNRs) of small disparity angles is higher than those of large disparity angles. The 3D stimuli with smaller disparity and lower crosstalk are more suitable for applications based on the results of 3D perception and SSVEP responses (SNR). Furthermore, we can infer the 3D perception of users by SSVEP responses, and modify the proper disparity of 3D images automatically in the future.

Keywords: Brain-computer interface (BCI), steady-state visual evoked potential (SSVEP), three-dimension (3D) display, visual stimulation

1. INTRODUCTION

Brain-computer interface (BCI) is a connection between the brain and the external devices. The user's thoughts can be directly converted to control or operate the external devices through the BCI. Over the past decade, BCI systems have already been used in assistive living [1]. For human, vision is our most dominant sense; hence, BCI-enabled interactive displays will have a broad range of potential applications in gaming and e-learning, especially for stereoscopic 3D displays. 3D technologies are now widely available and frequently used in virtual reality and augmented reality applications. Based on the idea of combining a liquid crystal display and an intuitive interface, this study proposed the concept of a brain-display interactive (BDI) system, as shown in Figure 1 [2].

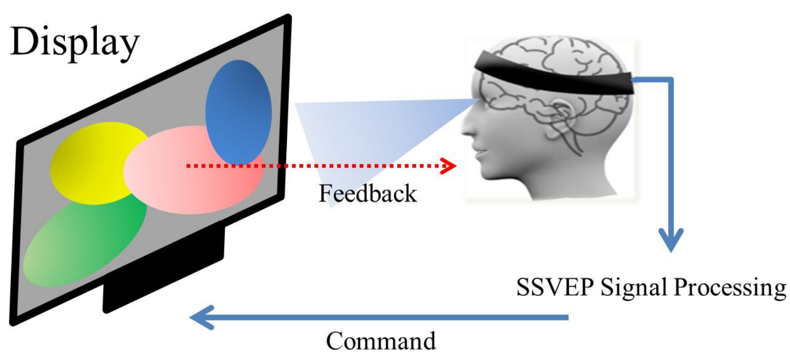


Figure 1. SSVEP-based BCI integrated with a liquid crystal display.

*yuyichien.eo95@nctu.edu.tw; phone 886 3 571-2121#59210; fax 886 3 573-7681; adolab.ieo.nctu.edu.tw

Three-Dimensional Imaging, Visualization, and Display 2015, edited by Bahram Javidi,
Jung-Young Son, Proc. of SPIE Vol. 9495, 94950U · © 2015 SPIE
CCC code: 0277-786X/15/$18 · doi: 10.1117/12.2184373

Steady-state visual evoked potentials (SSVEPs) are responses to repetitive visual stimuli modulated at a constant frequency on the central retina, and they usually contain the same fundamental frequency as the stimulus and some harmonics [3]. SSVEP is one of the most common inputs of BCI systems, and SSVEP-based BCI systems have become popular in the past decade, because of the attractive features such as noninvasive signal recording, little user training and high information transfer rate [4].

Furthermore, stereoscopic 3D technology is a popular trend in the future. Compared to two-dimensional (2D) visual stimuli, stereoscopic visual stimuli contain the depth information. The applications of 3D displays have been developed widely, because 3D displays can provide a more realistic sensation to observers. However, until now most SSVEP-based BCIs are studied in a 2D environment. Fortunately, Mun *et al.* observed that 3D visual stimuli in SSVEP-based BCI systems could enhance the BCI performance by increasing users' motivation and decreasing the task complete time [5]. Calore *et al.* stated that SSVEP-based BCI applications in 3D virtual reality environments could implement integrated flickering stimuli having a non-zero stereoscopic disparity, without affecting the SSVEP response strength [6]. Since the BCI systems allow users to experience more natural and intuitive interaction, the next step is to integrate BCI systems with 3D displays to provide immersive feelings and an enhanced sense of reality to viewers.

2. METHODOLOGY

The visual stimulation was a white circular pattern with different disparity angles and crosstalk levels flickering at 30 Hz to reduce the flicker sensation [7] on a stereoscopic 3D display using patterned retarder. In this study, we expected to learn suitable stereoscopic visual stimulation, and set them as targets in SSVEP-based BCI systems.

2.1 Subjects

Twelve subjects (two females) ranging in age between 22 to 28 years old (mean: 24.3, SD: 2.06) participated in this experiment. All of them have normal or corrected-to-normal visual acuity and suffer no vision impairment. The experimental procedures (except for research purpose) were explained, written informed consent was acquired from all subjects before the experiment. The consent was approved by the Research Ethics Committee for Human Subject Protection of National Chiao Tung University (NCTU-REC-102-003).

2.2 Apparatus

To reduce the potential contamination of visual stimuli and EEG signals, this experiment was conducted in a dark and quiet room. The apparatus with a 23 inch 3D polarized display and an EEG recorder is illustrated in Figure 2. EEG signals were acquired by using a 64-channel electrode cap (Quik-Cap, NeuroScan, USA), and the reference electrodes were placed on the mastoids behind the ears. The EEG signals were received and amplified by the EEG acquisition device (SynAmps2, NeuroScan, USA), as well as saved by the computer with installed EEG software (Scan 4.5, NeuroScan, USA). The location of scalp electrodes were placed according to the International 10–20 System.

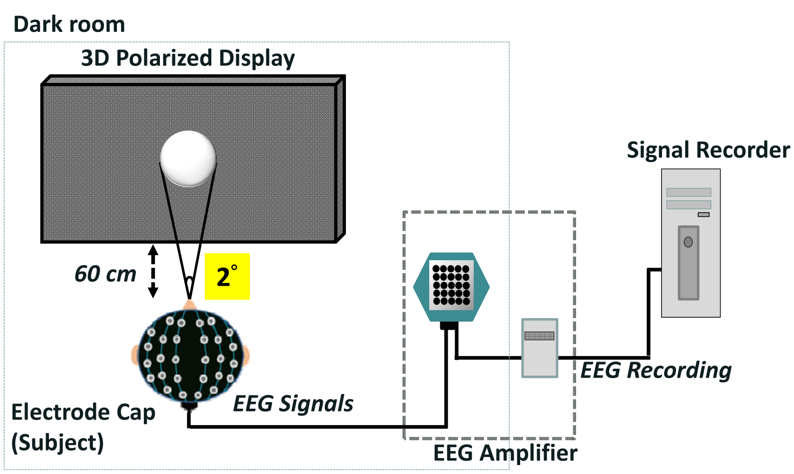


Figure 2. Block diagram of the experimental setup.

2.3 Stimulation

The stereoscopic stimulation pattern was a white circle displayed on a 1920×1080 screen with 60 fps refresh rate. The viewing distance was 60 cm and the circular stimuli were spanned a 2° viewing angle. The target color can be specified as coordinates in the CIE 1931 xyY system (x, y, Y) = (0.321, 0.354, 46.5), where x, y are the chromaticity coordinates and Y is the luminance. The stimulation frequency was 30 Hz, as shown in Table 1, and the background color was gray (x, y, Y) = (0.300, 0.342, 3.5), as shown in Figure 2. A Spectroradiometer (SR-UL1R, Topcon, Japan) was located in front of the screen to measure the flicker luminance, which was set to 46.5 nits in the experiment. The luminance contrast or "modulation depth" is defined as $(L_{max} - L_{min})/(L_{max} + L_{min}) \times 100\%$, where L_{max}, L_{min} are the maximum and minimum luminance respectively [8]. In the experiment, the modulation depth was 86%, which can be specified as:

$$\text{Modulation depth} = \frac{L_s - L_b}{L_s + L_b} \times 100\% \quad (1)$$

where Y_s is the luminance of the stimulation, and Y_b is the static background luminance.

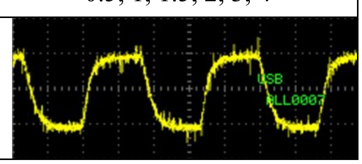
Disparity and crosstalk are dominant factors of 3D displays [9]: disparity angle refers to the difference in image location of an object seen by the left and right eyes; crosstalk level refers to the light leakage due to imperfect light separation from 3D displays. In its simplest form, crosstalk can be mathematically defined as [10]:

$$\text{Crosstalk} = \frac{L_{leakage}}{L_{signal}} \times 100\% \quad (2)$$

where $L_{leakage}$ is the luminance of light that leaks from the image for the other eye, and L_{signal} is the luminance of the correct information received by the viewer's eyes.

Therefore, this study used 13 various disparity angles from -4 to 4 degree and two different crosstalk levels for 3D visual stimuli on SSVEPs in the experiment. Most importantly, the user's 3D perception can be affected by these two factors. Severe accommodation-convergence mismatch and the light leakage resulted from large disparity angle and high crosstalk level will make it more difficult for the users to generate 3D perception.

Table 1. Experimental parameters.

Parameters	
Frequency (Hz)	30
Luminance (nits)	46.5
Modulation depth (%)	86
Crosstalk (%)	1.7 / 15.4
Disparity Angle (°) ***negative/positive: in front of /behind the display**	-4, -3, -2, -1.5, -1, -0.5, 0, 0.5, 1, 1.5, 2, 3, 4
Waveform in 100 ms	

2.4 Recording

There were six runs in the SSVEP experiment, including three low crosstalk runs and three high crosstalk runs. The order of stimuli was randomized to avoid the order effect. Each trial included four sections: (1) 10-second baseline, (2) 10-second stimulation, (3) subjective evaluation of the 3D image perception, and (4) 10-second rest, as shown in Figure 3. During the subjective evaluation, the participant was asked to score the 3D pattern according to the situation when they watched the 3D image. There were three different situations for their 3D perception: (1) the participant could perceive the 3D image successfully, (2) the participant could only perceive the 3D image sometimes, and (3) the participant could not perceive the image in the stimulation stage.

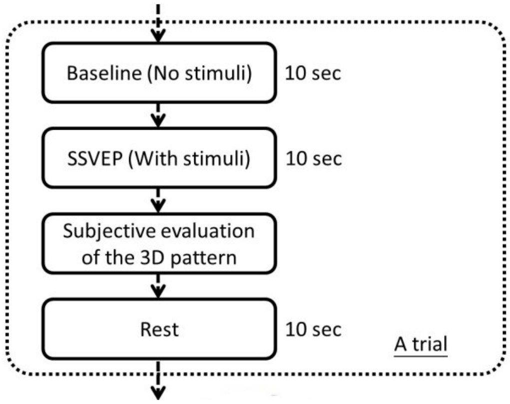


Figure 3. Flow chart of each trial in the SSVEP experiment

2.5 Analysis

The analysis procedures are depicted in Figure 4. This study used the automatic artifact removal (AAR) including clean artifacts, signal segmentation, independent component analysis (ICA), EyeCatch [11] and ADJUST [12] to remove muscle activity and eye movement signal. After that, the normalization was to eliminate the difference from different participants and channels. Finally, the canonical correlation analysis (CCA) method was used in filtering the best EEG signal from nine parietal and occipital channels, P1, PZ, P2, PO3, POZ, PO4, O1, Oz, and O2 [13]. After preprocessing, the fast Fourier transform (FFT) was used to carry out the spectrum analysis and calculate the sideband signal-to-noise ratio (SNR). SNR was measured to present the SSVEP performance, and it is defined as the ratio of the signal power to the sideband noise power using the following formula:

$$\mathrm{SNR}(f) = \frac{PSD(f)}{\sum_{k=2}^{n/2} PSD(f+k\Delta f) + PSD(f-k\Delta f)/(n-2)} \quad (3)$$

where f is frequency, Δf=1 Hz is the frequency step (frequency resolution), and n is the number of adjacent points.

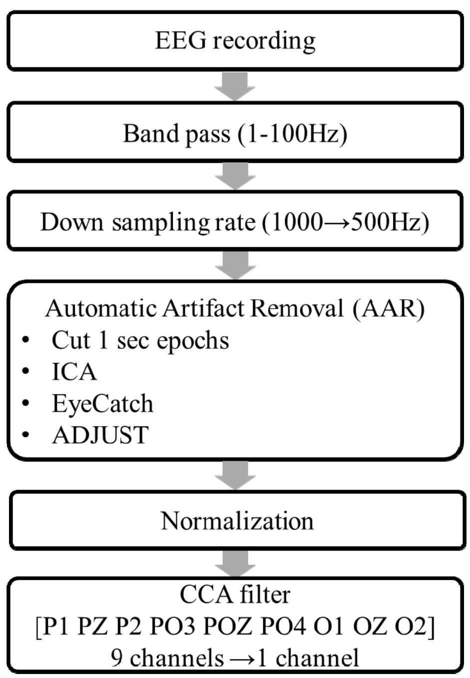


Figure 4. Block diagram of the SSVEP data analyses. ICA: independent component analysis; CCA: canonical-correlation analysis.

3. RESULTS

In the study, we set the dominant 3D factors: disparity angles and crosstalk levels, as experimental parameters explored in the participants' SSVEP response signals. Disparity angles and crosstalk levels have influences on the visual depth and the image quality of 3D stimuli respectively, which makes us infer that these two factors will also affect the user's 3D perception. The accommodation-convergence mismatch and the ghost image leakage from large disparity angle and high crosstalk level can damage the 3D perception. The experimental results of SSVEP signals with different 3D factors, and the 3D perception generated by the users are discussed in the following paragraphs.

Figure 5 shows the boxplot of SSVEP SNR responses from the visual cortex evoked by the 3D stimuli with different disparity angles and crosstalk levels. According to the results, the SNR values of different disparity angles are great than zero. It means that the stereoscopic stimulation also can elicit the SSVEP signal, so the stereoscopic stimulation is feasible to be utilized in SSVEP-based BCIs. Based on the results of statistical analyses, there is no significant difference ($p=0.055$) in different disparity angles by the analysis of variance (ANOVA). However, this study found that the averaged SSVEP SNRs of smaller disparity angles (-0.5, 0, and 0.5 degrees) are higher than those of larger disparity angles (-4, -3, 3, and 4 degrees). There is a significant difference ($p<0.05$) between -4 vs. 0, -4 vs. 0.5, -3 vs. -0.5, 4 vs. -0.5 and 4 vs. 0.5 in low crosstalk level, and -4 vs. -1, -4 vs. 0.5, -4 vs. 1.5, -3 vs. -1.5, -3 vs. -1, -3 vs. -0.5, -3 vs. 0.5 and -3 vs. 1.5 degree in high crosstalk level. Mostly, the significant difference occurred between large and small disparity angle. Thus, we speculated this phenomenon may be related to the 3D perception when participants perceive 3D images, since large disparity angle and high crosstalk level will make it more difficult to generate 3D perception. Nevertheless, there is no significant difference between different crosstalk levels ($p=0.550$).

Moreover, the 3D stimuli with smaller disparity angle and lower crosstalk level are more suitable for applications based on the results of the 3D perception and SSVEP responses. Based on the hypothesis, we chose the data from larger disparity angles (-4, -3, 3, and 4 degrees) to classify the 3D perception in three categories: successfully perceived, sometimes perceived, and unsuccessfully perceived, as shown in Figure 6. Figure 6 shows the boxplot of SSVEP SNR responses of three groups categorized by the subjective evaluation of the 3D perception score. The results validate our hypothesis that the SSVEP responses are affected by 3D perception. In addition, the ANOVA showed that there are significant differences ($p<0.001$) between the results of successful 3D perception and those of the others. On the other hand, there is no significant difference ($p=0.082$) between the two situations of ineffective 3D perception.

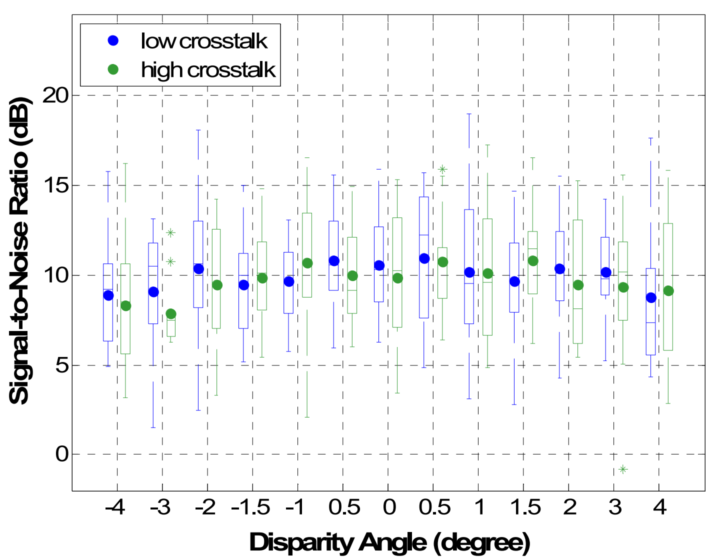


Figure 5. The SSVEP SNR responses of 3D images with different disparity angles and crosstalk levels.

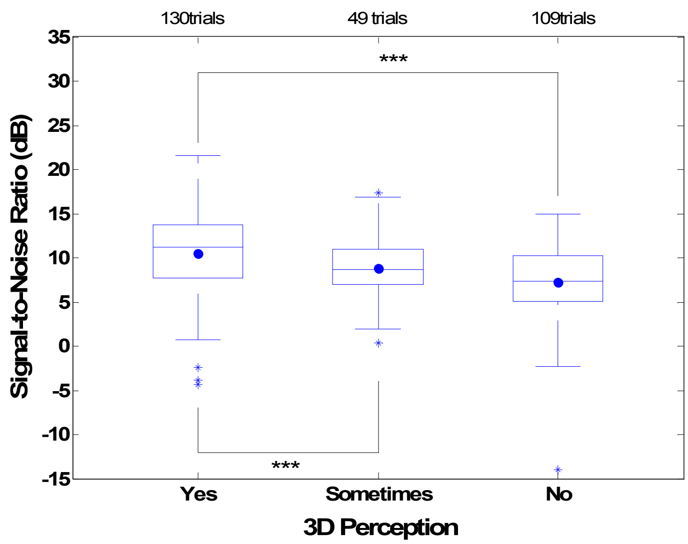


Figure 6. The SSVEP SNR responses of 3D images with large disparity angles (-4, -3, 3, and 4 degrees). The results are divided into three categories by the subjective evaluation of 3D perception.

4. CONCLUSIONS

The study showed that it is promising to develop SSVEP-based BCI systems integrated with 3D displays. Not only the 2D stimulation but also the stereoscopic stimulation can elicit the SSVEP signals. There is a significant difference of SSVEP responses between large and small disparity angles, and the SNRs of small disparity angles are higher than those of large disparity angles. Furthermore, this study investigated the SSVEP responses under different conditions of 3D perception, and there is also a significant difference between the successful 3D perception and the others. We speculated that the stereoscopic visual stimulation which can be easily perceived as 3D images is more suitable as targets in SSVEP-based BCI/BDI systems. Therefore, we can infer the 3D perception of users by SSVEP responses, and modify the proper disparity of 3D images automatically in the future. It is our vision that the full integration of the SSVEP stimuli and the display technologies will create the next-generation interactive display systems.

ACKNOWLEDGEMENTS

This work is partially supported by the grants provided by the MOST in Taiwan to the following academic research projects: NSC-102-2221-E-009-167-MY3, NSC-102-2221-E-009-168-MY3 and MOST 103-2218-E-009-012. The authors would like to express their gratitude to Dr. John K. Zao for his comments.

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