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Dual-Frequency SSVEP Stimulation Using a Stereoscopic Display

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Abstract

This study aimed to investigate the feasibility of dual-frequency Steady-State Visual Evoked Potential (SSVEP) stimulation using a 3-D display and stereoscopic glasses. Participants were exposed to a repetitive visual stimulus flashing at different frequencies in the left and right views and the SSVEP responses were observed. The results suggest that the two stimulation frequencies can still be evident in the SSVEP response. In addition, the participant ratings showed no significant differences in fatigue, annoyance, discomfort or strangeness of the stimulation compared to conventional forms of stimulation. These results pave the way for further studies using stereoscopic dual-frequency stimulation and its potential for use in virtual reality and 3-D videogames.

1 Introduction

Steady-State Visual Evoked Potentials (SSVEP) have received much attention in Brain-Computer Interface (BCI) research. However, a challenge still faced in SSVEP BCIs is the limited number of unique frequencies available for stimulation [1].

To counteract this problem, researchers have begun to investigate the use of dual-frequency stimulation, since this allows more targets to be created using a small number of frequencies. This has been done either by overlaying two targets oscillating at different frequencies [1, 2] or displaying two separate targets at different frequencies [3, 4].

In this paper, a novel method of providing dual-frequency SSVEP stimulation is investigated, which involves using a stereoscopic display, i.e. 3-D screen and stereoscopic glasses. Stereoscopic vision lends itself well for use with dual-frequency stimulation since the views to the left and right eyes can be controlled independently, which may make the concept visually more transparent to the user. Furthermore, the method is easily implementable due to the availability of low-cost equipment and easily extendable to three-dimensional videogames and virtual reality BCIs [6].

2 Method

To test the concept of stereoscopic dual-frequency SSVEP stimulation, an offline experiment was conducted.

Population: Ten participants (aged 24-33, 8 male, 2 female) participated in the experiment. All of these participants reported normal or corrected-to-normal vision. One participant was excluded from the final analysis as no SSVEP response was evident in the EEG trace.

Experimental Setup: The software used for creating and running the experiments was *OpenViBE* (http://openvibe.inria.fr/). An LCD 3-D television screen was used for displaying the SSVEP targets. Stereoscopic polarized glasses were worn by the participants for all of the stereoscopic conditions. For acquiring data the *g.Tec* USBamp was used to record data from thirteen electrodes (CPz, POz, PO7, PO8, O1, O2, Oz, Iz, Pz, PO3, PO4, O9 and O10).

Procedure: Participants were seated 1.5 m in front of the screen. They received six different forms of stimulation, as shown in Table 1. Frequencies of 6 Hz and 15 Hz were chosen as both showed high SSVEP responses in pre-testing and were possible frequencies of the refresh rate of the screen. Two normal vision and two stereoscopic vision single-frequency conditions were carried out as control conditions (Conditions C_{6N}, C_{15N}, C_{6S} and C_{15S}), in which a block on the screen was inverted from black to white at a single frequency. For the stereoscopic single-frequency conditions (C_{6S} and C_{15S}) half of the image was displayed to the right eye and the other half to the left eye through the use of the 3-D display as illustrated in Figure 1. To simulate previous work in dual-frequency stimulation, the block was divided into lines, with half flashing at 6 Hz and half at 15 Hz (C_{6_15N}). To achieve dual-frequency stimulation with stereoscopic vision, the block was again divided into lines but each eye was only exposed to half of the lines (and thus only one of the frequencies) through the use of stereoscopic glasses and the 3-D mode of the screen. This was repeated with the frequencies to the left and right eyes reversed to overcome any biasing due to ocular dominance (C_{6_15S} and C_{15_6S}).

For each condition, eight runs of stimulation were performed for eight seconds each, with three second breaks. The order of the conditions was rotated pseudo-randomly among participants to prevent a fatigue effect. Between each condition there was a rest period of approximately two minutes. The conditions were also divided into stereoscopic and normal vision blocks and rotated. Half of the participants started with a normal vision block while the other half started with a stereoscopic block. After each condition participants were asked to rate the condition using a 10-point Likert scale based on four different criteria: Fatigue, Annoyance, Discomfort and Strangeness.

Table 1: Stimulation frequencies for the different conditions of the experiment.

Condition	*Target*
C_{6N}	6 Hz normal vision
C_{15N}	15 Hz normal vision
C_{6S}	6 Hz stereoscopic vision
C_{15S}	15 Hz stereoscopic vision
C_{6_15N}	6 Hz and 15 Hz normal vision
C_{6_15S}	6 Hz (left) and 15 Hz (right) stereoscopic vision
C_{15_6S}	15 Hz (left) and 6 Hz (right) stereoscopic vision

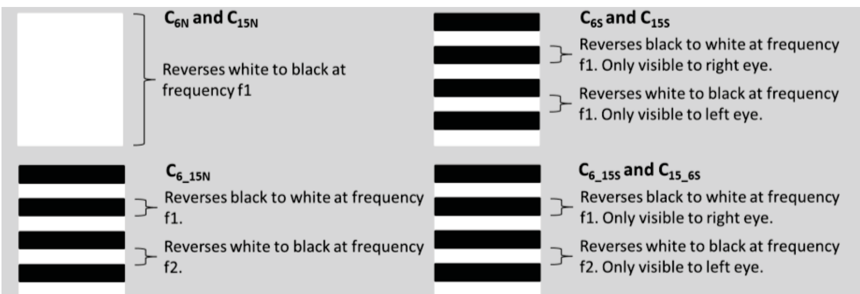

Figure 1: Illustrations of the various forms of stimulation of the experiment.

3 Results

EEG Data Results: The signals were divided into non-overlapping two-second epochs on which a 1024 point Fast Fourier Transform (FFT) was carried out. The FFTs for all the epochs were then averaged. Figure 2 shows the spectrum averaged over nine participants and averaged over electrodes O1, O2 and Oz for the dual-frequency stereoscopic conditions C_{6_15S} and C_{15_6S}. The two spectrums were averaged in order to prevent any biasing due to ocular dominance.

Power values were calculated from the FFT and then converted to relative power values, in order to cancel differences in magnitude, as follows:

$$Power_{Relative} = 3*Power(f)/(Power(f-1)+Power(f)+Power(f+1))$$

where $Power(f)$ is the average power at the relevant frequency and $Power(f-1)$ and $Power(f+1)$ are the average power at frequencies 1 Hz above and below the relevant frequency respectively.

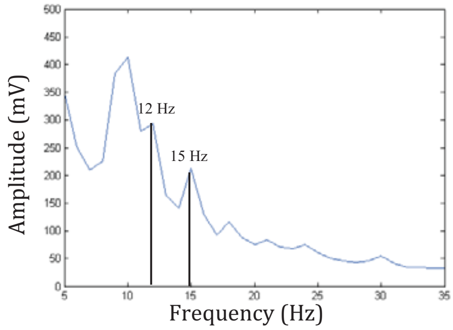

Figure 2: Averaged spectrums for the stereoscopic dual-frequency conditions (C_{6_15S} and C_{15_6S}) using 6 Hz and 15 Hz stimulation, with peaks at 12 Hz and 15 Hz indicated.

Paired t-tests were carried out between the relative power at each frequency of interest and the average relative power of the two neighbouring frequencies. The results are shown in Table 2. The single-frequency control conditions show statistically significant increases in power at the stimulation frequencies. For the dual-frequency stereoscopic stimulation (C_{6_15S} and C_{15_6S}), the 6 Hz stimulation still shows a statistically significant increase in power ($p < 0.05$) at 12 Hz (the first harmonic). For the 15 Hz stimulation, the increase in power is tending towards statistical significance ($p < 0.1$). This suggests that the two stimulation frequencies can still be identified in the dual-frequency stereoscopic case. A possible reason that not all power differences were significant is the decreased luminosity due to the use of stereoscopic glasses with tinting, or the fact that each eye was only viewing half of the lines of the image as opposed to all lines in the normal vision cases, as shown in Figure 1.

Table 2: Results of paired t-tests using relative power at relevant frequencies and neighbouring frequencies.

Condition	*Comparison*	*t value*	*Significance*
C_{6N}	12 Hz to average of 11 and 13 Hz	6.611	< 0.001*
C_{15N}	15 Hz to average of 14 and 16 Hz	5.634	0.001*
C_{6S}	12 Hz to average of 11 and 13 Hz	5.608	0.001*
C_{15S}	15 Hz to average of 14 and 16 Hz	6.844	< 0.001*
C_{6_15N}	12 Hz to average of 11 and 13 Hz	1.587	0.164
	15 Hz to average of 14 and 16 Hz	2.802	0.031*
C_{6_15S}	12 Hz to average of 11 and 13 Hz	2.954	0.025*
	15 Hz to average of 14 and 16 Hz	2.151	0.075
C_{15_6S}	12 Hz to average of 11 and 13 Hz	3.492	0.010*
	15 Hz to average of 14 and 16 Hz	2.211	0.063

Participant Questionnaires: The averaged participant ratings are shown in Figure 3, grouped according to the type of stimulation. A Friedman test revealed no significant differences in any ratings ($p > 0.05$). This suggests that the participants did not find the stereoscopic dual-frequency stimulation more fatiguing, annoying, uncomfortable or strange than the other forms of stimulation. The strangeness rating did show an increase tending towards significance ($p < 0.1$), thus the participants may have noticed a slight difference in appearance but not one that affected their other perceptions.

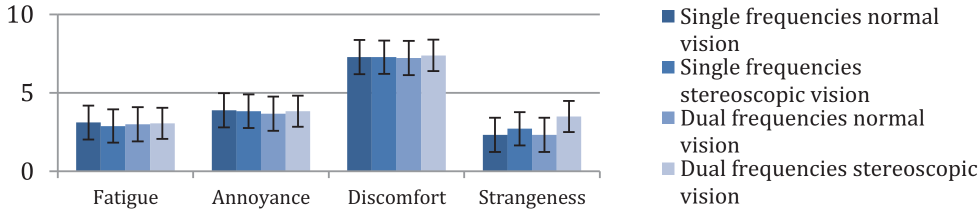

Figure 3: Participant ratings of Fatigue, Annoyance, Discomfort and Strangeness of each form of stimulation.

4 Conclusions

The aim of the experiment was to determine whether stereoscopic dual-frequency stimulation is feasible. The results indicated that the two stimulated frequencies are evident in the SSVEP response. Changes in the experimental setup may be required to achieve more significant responses, for example, by increasing the luminosity of the targets. In addition, further combinations of frequencies should be tested. The concept could then be extended to 3-D videogames and virtual reality setups. The participants did not rate the stereoscopic dual-frequency stimulation as more fatiguing, annoying, uncomfortable or strange, suggesting that this form of stimulation is also feasible from the point of view of participant preferences.

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