Effect of Stimulus Size and Shape on Steady-State Visually Evoked Potentials for Brain-Computer Interface Optimization

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Abstract: Steady-state visually evoked potentials (SSVEP) can be elicited by a large variety of stimuli. To the best of our knowledge, the size and shape effect of stimuli has never been investigated in the literature. We study the relationship between the visual parameters (size and shape) of the stimulation and the resulting brain response. A tentative physiological interpretation is proposed and the potential of the effect in a Brain-Computer Interface is outlined.

1 INTRODUCTION

A Brain-Computer Interface (BCI) allows a direct communication of an individual to a computer through direct measurements of brain electrical activity (Nicolelis et al., 2000). Since Hans Berger recorded the first electroencephalogram (EEG) from the human scalp and discovered the brain alpha waves (neural oscillations in frequency range of 8-12 Hz, Berger 1929), EEG has become a major noninvasive technique for studying brain activity. It is believed that EEG is mostly reflecting the synaptic activity that occurs in the superficial layers of the cortex.

Sensory evoked potentials are electrical responses of the brain (usually EEG) elicited by sensory stimulation. They can be recorded from the central nervous system of humans or animals while visual, somatosensory, or auditory modalities are stimulated (Dawson, 1954) ; they are distinct from spontaneous potentials (background EEG), that can be recorded without stimulation (Vialatte et al., 2010). Steady-state visual evoked potentials (SSVEP) are signals that are responses to a visual stimulation at a constant frequency. The Fourier spectrum of the EEG signal exhibits characteristic SSVEP peaks that are stable over time. SSVEP signals have a better signal-to-noise ratio than other visual evoked potentials, so that they are good candidates for applications in brain-computer interface systems (Vialatte et al., 2010). SSVEP are measured in the human visual cortex when the retina is exposed to a flickering visual stimulus that, in our experiments, is a computer-generated image that flickers at constant frequency. EEG electrodes located above the occipital lobe (where the visual cortex is located) record the brain response.

The limits and properties of SSVEP are not completely known. A better understanding of these properties would allow better designs for SSVEP-based BCI systems. In a previous investigation, we had for instance challenged the lower limits of SSVEP (Vialatte et al., 2008). In the present manuscript, we investigate the effect of the visual stimulus size and shape on the fundamental and higher harmonics of the SSVEP response. In addition, we investigate the possibility of using visual stimuli with that elicit common harmonics as SSVEP commands.

2 METHOD

2.1 Subjects

We recorded EEG signals from 13 young adults (ages 20-26, 11 males and 2 females). All subjects were healthy with normal or corrected-to-normal vision. They had no history of brain disorder or anomaly.

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2.2 Stimulus Design

The source of the stimulus was a Samsung S23A750D LED screen with 120Hz input and display refresh rate, with 250 cd/m² luminous intensity. Subjects were placed at ~1 m from the screen, sitting in a relaxed position. During the experiments, a succession of flickering images is presented to the subjects. Five different stimulus sizes and five different stimulus shapes were tested. This display was realised using Cogent Graphics developed by John Romaya at the LON at the Wellcome Department of Imaging Neuroscience, and using Hovagim Bakardjian's BCI-SSVEP-LCD toolbox.

2.3 EEG Recording

EEG was recorded using an Acticap system with 16 active channels connected to a V-Amp amplifier from Brain Products. Signals were filtered with a band-pass filter (0.5-100 Hz) and a notch filter at 50 Hz, and sampled at 500 Hz. The EEG signals were recorded from 4 channels located above the visual cortex (PO_3, PO_4, O_1, and O2 in the 10-20 international system).

2.4 Effect of Stimulus Size

We used a flickering black and white rectangle as visual stimulus to test the effect of size on SSVEP responses. Responses to stimuli of five different sizes were studied: 50-by-50 pixels (1.4-by-1.4 cm²) to 250-by-250 pixels (7 x 7 cm²) by steps of 50 pixels.

All different sizes were tested with two flickering frequencies: 15Hz and 30Hz, resulting in ten different stimulus conditions.

2.5 Effect of Stimulus Shape

The effect of the five different checkerboard shapes shown on Figure 1 was investigated. The checkerboard size was 250 x 250 pixels, divided into 2^{2n} squares, with n = 0, 1, …, 4.. As in the previous case, two flickering frequencies (15Hz and 30Hz) were investigated.

The subjects were presented with all 18 conditions in a randomized order, during one min for each condition. The total recording time was approximately 30 min.

The total duration of the experiment was about one hour, including the installation of the EEG electrodes.

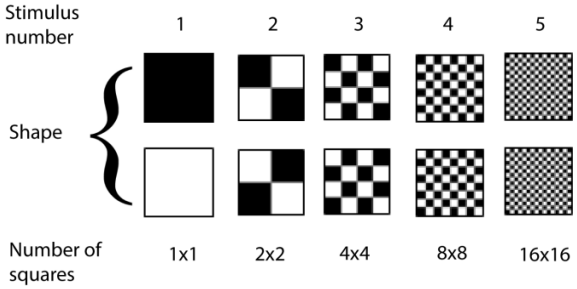

Figure 1: Illustration of the five different stimuli used to test the effect of shape.

2.6 Signal Processing

The discrete Fourier transforms of the signals were computed, and the signal-to-noise ratios (SNR) were estimated as:

$$\mathrm{SNR} = \frac{\mathrm{argmax}(\mathbf{W_1})}{\langle \mathbf{W_2} \rangle}$$

Where $\mathbf{W_1}$ is an interval of ±0.1Hz in the Fourier domain around the stimulus frequency, $\mathbf{W_2}$ is an interval of ±0.5Hz around the stimulus frequency excluding interval $\mathbf{W_1}$, and $\langle \cdot \rangle$ stands for the average. The SSVEP peaks may not appear exactly at the stimulation frequency due to hardware limits. Consequently we use the interval $\mathbf{W_1}$ to find the maximum peak nearby the stimulus frequency. SNR is actually a way to enhance SSVEP peaks (Thorey et al., 2012, Wang et al. 2006): it computes the ratio of the SSVEP peak amplitude to the average Fourier power of the background EEG.

Statistical analysis was performed using multiway analysis of variance (ANOVA). Normality of the data was controlled using a Lilliefors test.

3 RESULTS AND DISCUSSION

3.1 Effect of Stimulus Size

As expected, the response and the signal-to-noise ratio decrease significantly with stimulus size, for stimuli at 15 Hz as well as stimuli at 30 Hz. Nevertheless, SNR with a median value above 10 can still be observed for a size of 100-by-100 pixels. This size effect is illustrated in Figure 2 and Figure 3.

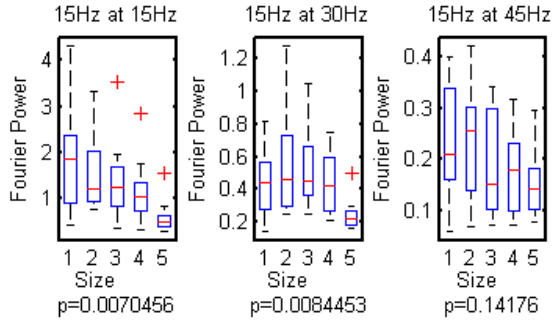

Figure 2: Boxplots of the Fourier power of the response to a 15Hz stimulus (fundamental at 15 Hz, and harmonics at 30 and 45 Hz) *vs*. stimulus size. "p" is the ANOVA p-value ($p<0.05$ indicates a significant difference between the means of the observed Fourier powers). Red crosses indicate outliers.

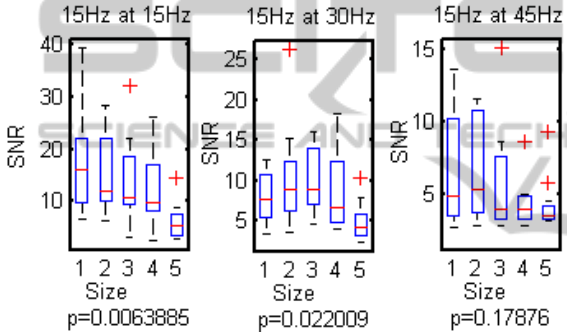

Figure 3: Boxplots of the SNR of the response to a 15Hz stimulus (fundamental at 15 Hz, and harmonics at 30 and 45 Hz) *vs*. stimulus size. "p" is the ANOVA p-value ($p<0.05$ indicates a significant difference between the means of the observed SNR values). Red crosses indicate outliers.

3.2 Effect of Stimulus Shape

Figure 4 and Figure 5 show that the response and the SNR decrease with increasing number of checkerboard squares, but that the second harmonic increases. This result may be related to the existence of two major visual pathways:

- The parvo-cellular(PC) pathway, originating in the midget retinal ganglion cells (RGCs), reacts to the high contrast, shape, color and red/blue information (e.g. Foxe et al. 2008). It is assumed to correspond to tonic cells, which generate the fundamental harmonics;
- The magno-cellular (MC) pathway, originating in the parasol RGCs. It is achromatic and reacts to low contrast stimuli, especially moving stimuli; it carries depth information. It is assumed to correspond to phasic cells, which generate the second harmonic (see for instance McKeefry et al. 1996).

The observed second harmonic effect might be accounted for by the fact that checkerboards with many flickering areas stimulate preferentially the MC pathway, while checkerboards with a small number of flickering areas stimulate the PC pathway. These assumptions will be substantiated by more detailed experiments in the future.

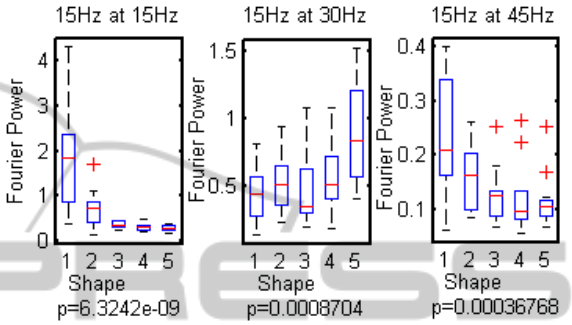

Figure 4: Boxplots of the Fourier power of the response to a 15Hz checkerboard stimulus (fundamental at 15 Hz, and harmonics at 30 and 45 Hz) with the five shapes shown on Figure 1. "p" is the ANOVA p-value ($p<0.05$ indicates a significant difference between the means of the observed Fourier powers). Red crosses indicate outliers.

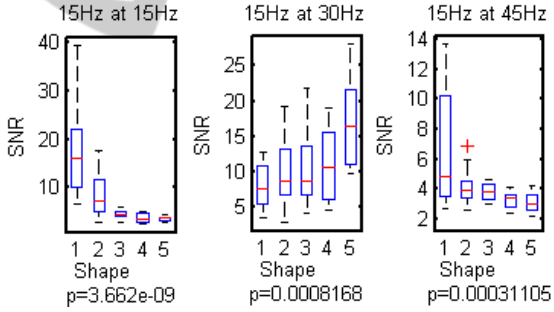

Figure 5: Boxplots of the SNR of the response to a 15Hz checkerboard stimulus (fundamental at 15 Hz, and harmonics at 30 and 45 Hz) with the five shapes shown on Figure 1. "p" represents the ANOVA p-value ($p<0.05$ indicates a significant difference between the means of the observed SNR values). Red crosses indicate outliers.

The shape effect could be useful for brain-computer interfaces, by allowing the use of stimuli having the same flickering frequency but different shapes: the stimulation by a plain rectangle can be discriminated from the stimulation by a checkerboard by the fact that the 1st harmonic of the response to the former is more powerful than its 2nd harmonic, while the reverse is true in the case of a checkerboard stimulation (Figure 6). In the design of such a BCI system, the commands would appear as the

juxtaposition of commands represented by rectangles together with commands represented by checkerboards, but flickering at the same frequency (thereby potentially doubling the number of possible commands).

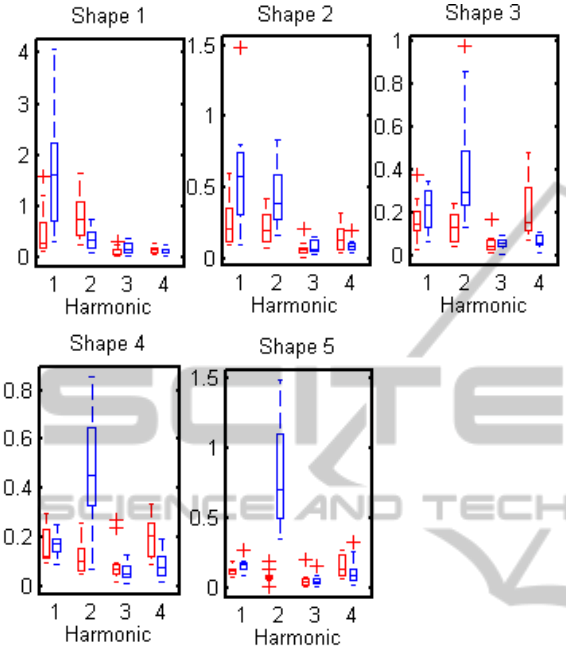

Figure 6: Fourier Power of the SSVEP responses to 30Hz and 15Hz stimuli. 1/2/3/4 denote correspondingly the frequencies 15Hz/30Hz/45Hz/60Hz (harmonics and subharmonics of 30Hz stimulation may be observed at 15, 30 and 60Hz; and for 15Hz stimulation at 15, 30, 45 and 60Hz). Red boxes denote the Fourier powers in response to a 30Hz stimulus; blue boxes denote the Fourier powers in response to a 15Hz stimulus.

4 CONCLUSIONS

In this study, we observed that different size and different type of shape of the stimuli change the properties of SSVEP responses. The main observation is the fact that a flickering checkerboard elicits responses whose 2nd harmonic contain more power than the first. This effect could be useful for increasing the number of possible commands in SSVEP brain-computer interfaces.

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