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Effect of posterized naturalistic stimuli on SSVEP-based BCI

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Abstract—**Most visual stimuli used in steady-state visual evoked potential (SSVEP)-based brain-computer interface (BCI) are simple and elementary. Examples of such stimuli are checkerboard patterns and sinusoidal gratings. These stimuli exhibit distinct contrasts and edges that conform well to the simple cortical cells behavior first observed by Hubel and Weisel. Hence, they are effective in eliciting VEP. On the other hand, the use of naturalistic stimuli is known to advance our understanding of early visual system. However, naturalistic stimuli are spectrally and spatially complex. They may not elicit the optimal VEP and the results obtained may not easily correlate to the stimulus parameters. Hence, we proposed to posterize natural images to generate naturalistic stimuli suitable for SSVEP-BCI. The posterization process considers both the edge and contrast information of the input image. This study elucidates the effect of posterized naturalistic stimuli on SSVEP amplitudes and phases by exploring the relationship between the number of tones of posterized visual stimuli and their effect on the power spectra and phase synchrony of attended stimuli. Results show that posterized visual stimuli at four tone display a significant effect on the dominant frequency response. Our findings suggest the effectiveness of posterized naturalistic stimuli and should advance the use of naturalistic stimuli in SSVEP-BCI.**

I. Introduction

Since the work of Hubel and Wiesel [1]–[3], evidence have suggested that neurons in the primary visual cortex of cats and monkeys are highly tuned for orientation selectivity. Further electrophysiological investigations showed that human visual system exhibits similar tuning properties. The cells in our primary visual cortex are sensitive to bars and edges of a given orientation. By measuring the evoked responses, other properties such as spatiotemporal frequency, luminance contrast, and chromaticity have also demonstrated modulating effects on the visual neuron responses [4]–[6]. Therefore, it is not surprising that psychophysical and neurophysiological studies of the human visual system often employed simple and parameterized stimuli such as sinusoidal gratings, regular checkerboard patterns, spots of lights, bars and edges.

Likewise, in steady-state visual evoked potential (SSVEP)-based brain computer interface (BCI), it is common to employ visual stimuli such as flashing LEDs (light-emitting diodes), checkerboard reversal patterns, and luminance gratings as interface targets to denote available choices for users. These visual stimuli are suitable for most BCI studies as they are effective in generating optimal visual evoked potentials (VEPs). By tagging different temporal frequencies to the stimuli, we are able to present different options to the SSVEP-BCI user. When the user fixates at one of the targets, we can establish the choice made based on the detection of signal differences between attended (target) and unattended (distractor) stimuli, i.e. the signal to noise ratio (SNR) of the dominant frequency response.

While these visual stimuli are simple to implement and effective, they are not representative of the actual objects. That is, there are no contextual meaning in these plain simple stimuli that allow a user to relate what they intended to represent. For example, without employing semantic annotations, users would not be able to differentiate between two checkerboard stimuli flashing at two different frequencies that are meant to denote the choice between selecting an apple or a glass of water. Hence, there is motivation to enhance the stimuli in SSVEP-BCI towards a more naturalistic form.

Given that our understanding of visual neurons is primarily based on their responses to simple stimuli, there are no proven models that can generalize to account for the neuronal behavior during naturalistic stimulation [7]–[9]. Thus, we begin our investigation by taking the natural images through posterization process. The process converts a continuous gradation of tone to several regions of fewer tones. It takes into account the prior edge and contrast information of the input image. The resultant image is a visual stimulus that displays the essential structures of the original image with suprathreshold contrast along the contours of the object. Table. I depicts the posterized stimuli used in the experiment together with the typical checkerboard type stimulus.

The aim of this study, therefore, is to examine the relationship between the number of tone of the posterized naturalistic stimuli on the power spectral density (PSD) and the phase synchrony of the evoked potentials elicited by the central stimulus. We hypothesized that the naturalistic stimuli may elicit SSVEP of different amplitudes than a regular checkerboard patterns. However, as naturalistic stimuli are contextually relevant, they may draw better attention of the users. Attention is known to modulate SSVEPs [10]. Hence, when all of the concurrently displayed stimuli are of the same type (i.e. not mixing checkerboard type with naturalistic type), the SNR of the naturalistic stimuli may remain comparable to that of the checkerboard patterns.

II. Materials and Methods

A. Participants

A total of twenty healthy subjects, ten male and ten females, participated in the experiment. All were right

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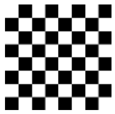
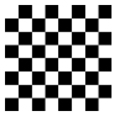
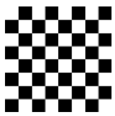
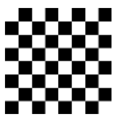
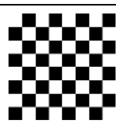
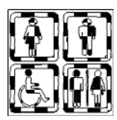
TABLE I DIFFERENT STIMULI AND THEIR TYPES USED IN THE EXPERIMENT

Stimulus Objects	Stimulus types				
	Standard checkerboard	***Shaped-checkerboard***	***Black and white***	***Four-level grey tone***	***Sixteen-level grey tone***
Apple stimuli	 apple				
Water stimuli	 water				
TV stimuli	 TV				
Medical stimuli	 medical				
Washroom stimuli	 washroom				

handed with mean age of 22.5 (standard deviation = 2.16, range = 18 - 27). All had normal or corrected-to-normal vision. None of them had any history of neurological disorder. Written informed consent was obtained from each participant prior to the beginning of the experiment. The study was approved by the Medical Research Ethics Committee of the University of Queensland.

B. EEG Acquisition

The experiment was conducted in a Faraday-caged room to reduce any electromagnetic interference from external sources. Continuous EEG was acquired using a 64-channel Biosemi ActiveTwo system. Two additional electrodes, CMS (Common Mode Sense; active electrode) and DRL (Driven Right Leg; passive electrode) were used to compose a feedback loop for amplifier reference. The electrodes used were placed according to the international 10-20 system using an appropriate EEG cap that fitted the head size of the individual subject. The EEG data were sampled at a rate of 1024 Hz to 24 bit precision.

C. Stimuli

In the study we used five different stimulus objects. Table I shows the five rows that correspond to the five different stimulus objects. The rationale of using these five stimuli was based on the choices likely encountered by a patient (e.g. a quadriplegia) who may be a BCI user. These stimuli include natural and synthetic objects such as apple and washroom sign respectively.

There are five different types of stimuli. Between each successive pair, only one property of the stimulus is changed. The first stimulus is the standard checkerboard type used in most typical visual experiments. The second is a shaped-checkerboard type similar to the first, except that the overall checkerboard takes the shape of the object it represents. Hence only the shape property has changed between them. The third stimulus differs from the second by its black and white region that goes along the contour of the object instead of the regular square-checker patterns. Thus it is a change of spatial frequency (high spatial frequency checkerboard to lower spatial frequency binary image).

The fourth stimulus is similar to the third except that it is made up of four grey tones instead of a binary black and white tones. The last stimulus type is the closest to the original object as it is made of sixteen grey tones that vary along the contours of the object. Hence, from the third to the last, only the contrast, or amount of grey shading changes (from two to four to sixteen shades of grey). This allows us to examine the effect of these properties of the stimulus, as it moves towards more naturalistic images, on the SSVEP responses.

To create the shaped-checkerboard type stimuli, we replaced the content details of the original images with the standard checkerboard patterns. To create the naturalistic stimuli, we performed a color posterization process with the help of MATLAB's image processing toolbox, in particular the rgb2ind and imapprox functions. The posterization process considered the clustering and segmentation of the original image pixels which correspond to the contour regions of the object. This allowed us to maintain the relevance of the stimuli as a representation of the original object. The chromaticity information of the posterized image was discarded. The contrast at the contours was also normalized so that the gray spectrum used the full range of absolute black and white levels. These stimuli would flicker between their ON and OFF states. The ON states are as shown in Table I. The OFF states are their inverse negative where black is the inverse of white and darker grey is the inverse of lighter grey.

D. Experiment Paradigm

Throughout the experiment, subjects were seated 70cm in front of the monitor. As evidence has suggested that attention modulates SSVEP signals [10], the subjects were instructed to fixate on a central crosshair and focus their attention only on the flashing stimulus that appeared in the centre; ignoring all other stimuli. The crosshair always appeared in the centre, therefore the attended stimulus was always centrally viewed.

Apart from that, the stimuli were each set to a constant size that subtended a visual angle of 2°. The display used was a LCD monitor (LG W2343T) with a response time of 5 milliseconds. The frequencies used for tagging the stimuli were 18.25, 15, 12, 10, and 8.57 Hz. An in-house presentation software was written to create and display the stimuli. The software was based on the frame-based encoding method proposed by [11]. To avoid the competing effect [12], the target stimulus was placed at the centre of the screen with four other stimuli spatially placed at 12° away at the four corners of the screen. In addition, only stimuli of the same type were displayed concurrently. There was no mixing of different stimulus type. That is, the stimuli were displayed based on the column type in table I.

For each trial, the flashing stimuli would appear for 8 s duration followed by 4 s interval with just the fixation crosshair. They were termed target and non-target epoch respectively. The subjects were asked to maintain their central fixation for 8 s during the target epoch. While VEPs can be captured in a much shorter time span, the 8 s duration provide ample resolution to avoid the time-frequency uncertainty in subsequent analysis.

To avoid any adaption effect and biasing of stimuli, we randomized the order of appearance, spatial location, and tagging frequency used for each stimulus type. The number of trials for each stimulus type is 25 (five object types with five different frequencies). The total trial time for each run is 25 mins. We repeated the run twice and the total time for the experiment was about 75 mins and the total number of trials for each stimulus type per subject was 75. Furthermore, to avoid eye fatigue, the subjects were given a break lasting 1 minute for approximately every 5 minutes of trials.

III. Analysis

All EEG signals were processed digitally offline. The data were initially filtered with a 50Hz notch filter and a 4th order Butterworth band-pass filter with cut-off frequencies at 4 and 40 Hz. The common average reference (CAR) procedure was used to re-reference all electrodes. This re-referencing procedure removes background activity [13].

We focused our analysis only on channels O1, O2, and Oz as these are the occipital regions that would experience substantial neuronal activities resulting in the SSVEP signals [14]. Furthermore, from previous studies [18–20], using only sites O1, O2, Oz is sufficient to provide the necessary information for a functional SSVEP-BCI.

Our approach to obtain the PSD and phase synchrony was based on the method described in [18]. Essentially, the PSD we used was Welch's estimate and the phase synchrony method was called component synchrony measure (CSM). The PSD indicates the energy of the signal at each frequency component while the CSM estimates the corresponding phase synchrony of the signals. The CSM is obtained by taking the one complement to the phase variance, which, according to [19] is defined as

$$\operatorname{var}\{\varphi(m)\} = 1 - \left[\frac{1}{n}\sum_{i=1}^{n}\cos\varphi_i(m)\right]^2 - \left[\frac{1}{n}\sum_{i=1}^{n}\sin\varphi_i(m)\right]^2$$

where $\varphi_i(m)$ is the phase of the mth Fourier component, and n is the number of averaged waveforms. For more detail descriptions, refer to [18].

IV. Results and Discussion

Figure 1 plots the mean PSD, mean CSM, and ratios of attended to unattended stimuli for PSDs and CSMs. A high ratio implies that the unattended power is weaker and hence enables the attended signals to be detected at greater ease. From the figure, it can be clearly observed that as the PSD and CSM decrease from checkerboard towards the posterized naturalistic stimuli, the corresponding unattended mean PSD and CSM also decreased. The Friedman test based on attended to unattended ratios across all stimulus types returned statistically significant differences ($p < 0.05$) for both PSD and CSM. The Friedman test is a nonparametric equivalent of the repeated measures ANOVA. It does not assume that the mean classification accuracy is normally distributed. Subsequent post-hoc analysis with Wilcoxon signed-rank tests with Bonferroni correction were conducted at $p < 0.005$. There were statistically significant differences between every pair of stimulus types, with the four-tone stimulus showing the peak ratio.

According to the previous studies [24-25], human contrast sensitivity is a function of spatial frequency. A higher spatial frequency generally results in lower contrast sensitivity which in turn lowers the visual evoked potentials [7-8]. Our PSD and CSM results conformed to those studies. Furthermore, the results of correspondingly weaker responses from unattended naturalistic stimuli appeared to conform to the report of increased suppression of irrelevant information at unattended locations with enhanced information processing at attended locations [24].

V. Conclusion

Using naturalistic stimuli may be especially practical when operating BCIs in situations such as virtual environment where the contextual relevance may allow more intuitive interface. Our findings suggest that using posterized stimuli of no more than four graytone generates optimal SSVEP signals that are suitable for the detection of differences between attended and unattended stimuli. This evidence should further advance the use of naturalistic stimuli in SSVEP-BCI.

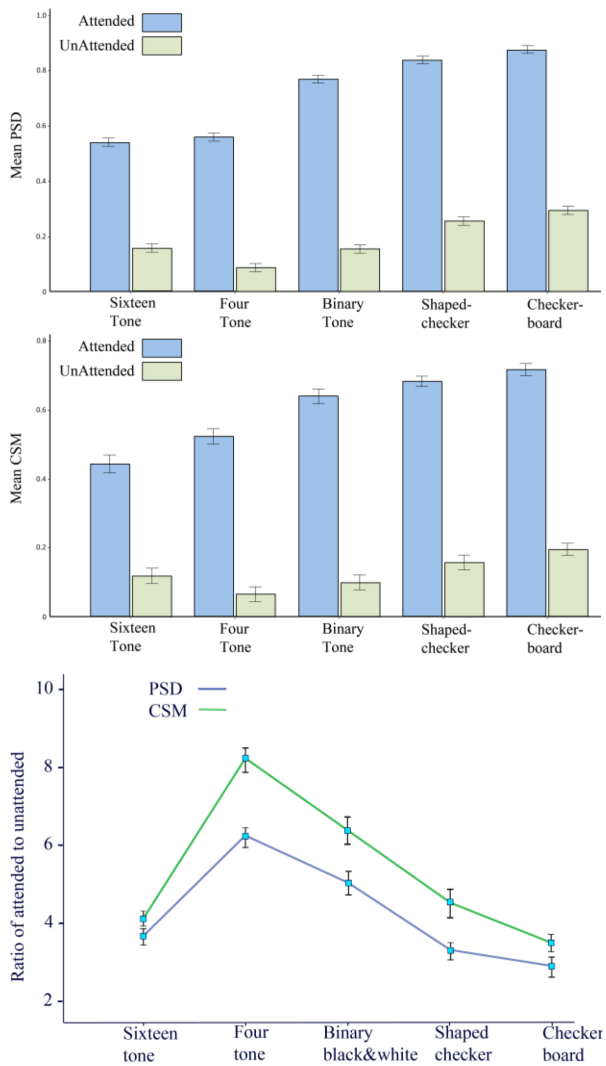


Fig. 1. The mean PSD, mean CSM, and the ratios of the mean PSD and CSM at attended frequencies to that of the corresponding unattended frequencies. The higher the ratio, the easier it is to detect that particular stimulus type in the presence of multiple same type stimuli.

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