Time-Frequency Analysis of Duty Cycle Changing on Steady-State Visual Evoked Potential: EEG Recording

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Abstract—**The purpose of this paper is to investigate the applicability of duty cycle for steady-state visual evoked potential (SSVEP)-based application. For this, the time-frequency analysis of SSVEP during visual stimuli presentation with different duty cycles was performed. The commercial wireless EEG headset with O1 and O2 channels was utilized to record the associated brain activity. The experimental paradigm, in this experiment, we mainly focus on instantaneously changes of duty cycle of SSVEP in the four principal frequency bands, i.e., theta (3 - 7 Hz), alpha (8 - 12 Hz), beta (13 - 30 Hz), and gamma (30 - 40 Hz). Peak magnitude, peak frequency, and spectral coherence of SSVEP were measured. Results showed that coherences measured in the theta and alpha bands differed significantly with p < 0.001. Thus, the present results suggest that the duty cycle is recommended as a feature for potential multicommand SSVEP-based applications.**

I. INTRODUCTION

Steady-State Visual Evoked Potentials (SSVEPs) are neural responses to visual stimulation at specific frequencies when the retina is stimulated by a visual stimulus ranging from approximately 3.5 Hz to 75 Hz [1]. In neuroscience, SSVEP has been widely used to identify evoked responses by visual stimulations, e.g., superposition, averaging, frequency analysis, and correlation analysis [2]. SSVEPs are practical and useful in research because of its excellent signal-to-noise ratio and relative immunity to artifacts [3]. The application of using SSVEP-based system has succeeded widely in many disciplines. Especially, the SSVEP-based brain computer interface (BCI) system detects electroencephalogram (EEG) over an occipital lobe position (the anatomical region of the visual cortex; O1 or O2) when a visual stimulus flickering at a constant frequency. The driving pulses used in most of the past studies had a 50% on/off duty cycle (or D =0.5) [4][5]. Mostly, SSVEP-based BCIs use flickering frequencies lower than 20 Hz for visual flickering to retain a high signal level [6]. Although it is commonly recognized that the SSVEP response depends on the frequency of the stimulation, i.e., flickering, there are relatively few studies the duty cycle of the visual stimuli, which is usually not mentioned in investigating this relation in detail.

Recently, an SSVEP-based BCI using different duty-cycle visual flicker has been proposed. Lee et al. [7] and Shyu et al [8], they presented the different duty cycles for their SSVEP-based BCI system. The SSVEP responses depend on three main parameters: 1) The frequency in three bands: 5-12Hz, 12-25Hz and 30-50Hz, 2) the intensity of the flickering light, and 3) the structure of the repetitive visual pattern. The human SSVEP has larger amplitudes from alpha to low beta ranges and reaches its maximum amplitude at approximately 8-13 Hz [9][10]. Herrmann [14] reported that the SSVEP responses exhibited resonance phenomena around 10, 20, 40 and 80 Hz. With the duty cycle, multi-command SSVEP-based system can be realized by using only one flicker frequency. Therefore, the objective of this paper is to examine the consequence of the visual stimulation that produced SSVEP responses associated with duty cycle changing continuously in terms of time-frequency characteristics.

II. MATERIAL AND METHOD

EEG data were acquired by using a wireless Emotiv™ headset at the sampling rate of 128 Hz and 14-bit resolution, with a band-pass filter of 0.2-45Hz, digital notch filters at 50Hz. Four healthy subjects participated in this study. The average age of the subjects was 25.75(±5.44). These subjects had no report of epileptic seizure. For each trial, all the subjects were instructed to view a stimuli displaying on a center of laptop LCD screen with a resolution of 1366 × 768 pixels and a vertical refresh rate of 60Hz. A single white square field flickered at 10 Hz. For each trial, duty cycle could be defined by: $D = T_{ON} / T$ where time period, $T = T_{ON} + T_{OFF}$, in the experiment we set D to be 0.7, 0.5 and 0.3 as shown in Fig.1. The subjects observed the visual stimulus for ten trials. Then, the recorded SSVEP signal was off-line analyzed with Matlab (MathWorks) R2010b by the follow approaches:

A. *Short-Time Fourier Transform*

The short-time Fourier transform (STFT) was used to determine the spatial-temporal content, i.e., peak magnitude, peak frequency, peak time, and spectral coherence. In the sampled SSVEP, $x(m)$ at time m, the data to be transformed into sub-frames (or called window), $w(m)$, by using discrete Fourier transform as follows:

$$X(n,\omega) = \sum_{m=-\infty}^{\infty} x(m)w(m-n)e^{-j\omega m} , \quad (1)$$

The peak fundamental frequency, $F_{\max}$, of magnitude squred was then computed as follows

$$F_{\max}(\tau,\omega) = \max_{\tau \in L_w} \log\left(\left|X(\tau,\omega)\right|^2\right) . \quad (2)$$

where L_w was a window length and ω was a frequency component.

B. *Coherence analysis*

Also, we considered the coherence of two channels, i.e., SSVEP signal from the occipital lobe of left (O1) and right (O2) cerebral hemispheres, the average cross-spectrum, calculated from complex conjugate of the squared Fourier coefficients and normalized by the average residual power spectrum of the individual channel was calculated as follows

$$C_{LR}^{k} = \frac{\left|F_{LR}^{k}(\omega)\right|^2}{F_{LL}^{k}(\omega)F_{RR}^{k}(\omega)} . \quad (3)$$

where $F_{LR}^{k}(\omega)$ was the cross-spectral density between *L* and *R*, $F_{LL}^{k}(\omega)$ and $F_{RR}^{k}(\omega)$ the auto-spectral density of *L* and *R*. In (1), we computed all *k*th frequency bands. The resulting coherence statistic is highly sensitive to the consistency of the phase difference [11]. Values of (3) range from 0 to 1, where a value of 1 indicates that the two channels preserve the perfect phase synchronization, whereas a value closer to 0 indicates that the phase becomes more independent of each other.

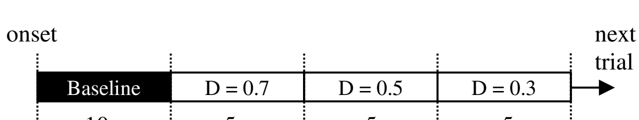

Fig. 1. Experimental paradigm for a one trial of visual presentation with different duty cycle. Resting period lasted 10 seconds, the stimulation epoch lasted 15 seconds.

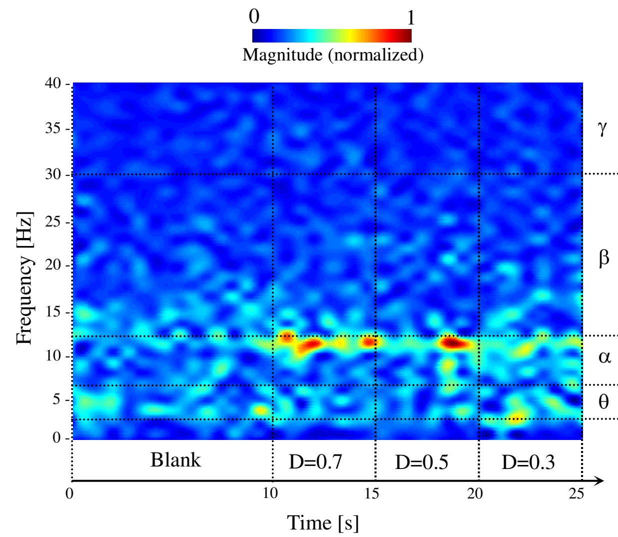

Fig. 2. The average results of time-frequency responses.

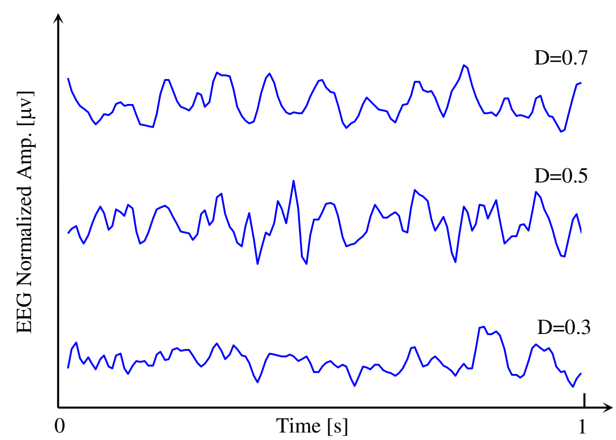

Fig. 3. Temporal waveform of average SSVEPs by different duty cycle.

III. RESULTS AND DISCUSSIONS

The time-frequency results are shown in Fig. 2. For determining STFT, the 128-point FFT based Hamming window with overlapping interval of 64 points was computed consecutively. Fig. 3 shows typical temporal waveform of SSVPs related to each duty cycle. In our study, the peak magnitudes were normalized. It should be noted that these peaks were rather seen in individual subjects than in the average. The average peak times were detected from the stimulus epoch from all subjects. All peak magnitudes were found in the alpha band (8-12 Hz). The peak times of corresponding peak magnitudes were 0.43 ms, 0.51 ms, and 0.48 ms for D=0.7, D=0.5, and D=0.3, respectively. It was difficult to detect a peak time from individual subject's visual responses. However, the obtained results were statistically significant in terms of magnitude and coherence in frequency bands. The obtained results are shown in Tables I and II. In Table I, the peak magnitudes were found in alpha band for both D=0.7 and 0.5. The peak magnitudes at D=0.3 are similar in two frequency bands, i.e., alpha and beta.

TABLE I. PEAK MAGNITUDE VALUE BASED ON STFT AND STANDARD DEVIATION IN BRACKET.

Frequency Band	D(0.7)	D(0.5)	D(0.3)
theta (3-7 Hz)	0.513 (±0.180)	0.137 (±0.048)	0.529 (±0.124)
alpha (8-12 Hz)	0.662 (±0.207)	0.562 (±0.213)	0.548 (±0.172)
beta (13-30 Hz)	0.323 (±0.014)	-	-
gamma (30-40 Hz)	-	-	-

TABLE II. THE RESULTS OF MAXIMUM COHERENCE AND ITS FREQUENCY RESPONSE FOR ALL SUBJECTS.

Subject	D(0.7)	D(0.5)	D(0.3)
S1	0.82 (f = 5.3 Hz ±2.03)	0.83 (f = 12.8 Hz ±1.54)	0.81 (f = 10.5 Hz ±1.78)
S2	0.71 (f = 5.2 Hz ±1.15)	0.89 (f = 12.2 Hz ±1.06)	0.832 (f = 9.1 Hz ±1.09)
S3	0.76 (f = 5.3 Hz ±0.93)	0.88 (f = 11.7 Hz ±1.93)	0.832 (f = 11.2 Hz ±1.35)
S4	0.81 (f = 5.1 Hz ±1.76)	0.85 (f = 11.5 Hz ±1.68)	0.832 (f = 10.8 Hz ±2.01)

Our results are consistent with the other studies that the amplitude of the first harmonic depends on the duty cycle. Visual stimuli lower than the critical flicker-fusion frequency may make subjects to feel flicker jerky and cause visual discomfort [12]. The SSVEP power and the effects of attention on SSVEP power strongly depend on flicker frequencies in the delta band (2-4 Hz), and in the upper alpha band (10-11 Hz) [13].

Coherence analysis: Table II shows the maximum coherence and corresponding frequency. The results showed that the difference in coherence between duty cycles was statistically significant in the theta and alpha bands for all selected duty cycles (p < 0.001; Fig. 4). Based on these results, we recommend the optimal range of duty cycle D ≥ 0.5 as a feature for potential SSVEP-based applications. This is because the visual stimuli presented to an observer may have a direct impact on the efficiency of SSVEP response detection method. Accordingly, an SSVEP technique that achieves the high SSVEP amplitude and is comfortable to view is needed. Another important issue for SSVEP experiment through LCD is that the usual refresh rate currently limited to 60Hz. Due to the limit of the vertical refresh rate in current LCD screens, the number of frequencies for displaying flickering objects is limited [10].

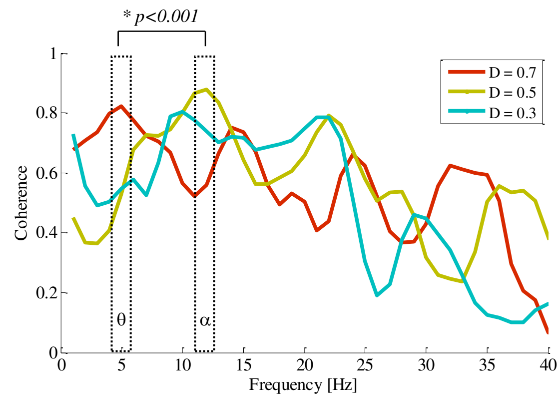

Fig. 4. The results of coherence analysis from O1 and O2 channels.

IV. CONCLUSIONS

We investigated the SSVEP with duty cycle changes 0.7, 0.5 and 0.3 from EEG recording based on time-frequency analysis including peak magnitude, peak frequency, and spectral coherence. The results showed that the difference in coherence in the theta and alpha bands was statistically significant and the duty cycle may be recommended for potential SSVEP-based applications. For the future work, we plan to apply different duty cycle for implementing multi-command SSVEP-based system.

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