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Effect of Duty Cycle in Different Frequency Domains on SSVEP Based BCI: A Preliminary Study

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Abstract— **Compared with the well learned amplitude-frequency characteristic of Steady State Visual Evoked Potential (SSVEP), the effect of duty cycle is still unclear. In this work, the influence of duty cycle on SSVEP response is investigated in differnt frequency domains. The amplitude surface with the change of both frequencies and duty cycles is plotted. To get a stable response, the experiment arranged in 3 days, and each result is an average of 12 repetitions. It is interesting that the results from power spectral density (PSD) and canonical correlation analysis (CCA) method are not consistent. In addition, the relation between the fundamental component and its second harmonic component with the change of duty cycle is quite different at frequency of 7Hz, 10Hz and 13Hz. Based on the amplitude surface, we try to configure the subject-specific SSVEP based BCI. The frequencies and duty cycles of the stimulus are selected corresponding to the higher SSVEP response in the amplitude surface. Cross validation results show a significant improvement in the performance for the adjustment of duty cycle.**

I. INTRODUCTION

In recent years, the fast developed Brain Computer Interface (BCI) technology brings human being a direct way to communicate with computer programs or technical devices by intention alone. This new communication way may help the patients with severe motor impairments like late-stage amyotrophic lateral sclerosis, severe cerebral palsy, head trauma, and spinal injuries in the life. The neuromechanism used in noninvasive BCI mainly includes motor imagery, P300 and SSVEP etc.. Encouraged by the advantages of less training time, shorter response time and higher information transfer rates [4], [8], [11], [3], SSVEP based BCIs are more suitable to be developed in real time control. In recent years, SSVEP based BCIs used in cursor control [15], prosthetic control [10] and Functional Electrical Stimulation (FES) [5] have been reported.

SSVEP is a brain response evoked by repetitive visual stimuli, which is an oscillatory component at the same frequency and its harmonics of the stimulus. It is prominent in the occipital cortex. The amplitude of SSVEP is not the same for different frequency or different subjects [13], which also depends on the type, color and shape of the stimulus [12], [9], [14]. In Ref.[18], the authors compared the stimulation methods used in 58 literatures. All the facts as mentioned above are discussed. However, there is little literature noting and discussing the selection of duty cycle.

In the SSVEP based BCI systems, the duty cycle of 0.5 is usually used to get the maximum contrast [10], [3]. Some researchers also choose some other duty cycles empirically to get a better performance of the system [16], [1], or set a lower duty cycle to meet the needs of the experiment [6]. In Ref.[7], emphasizing on the use of comfort, the authors select a higher duty cycle as 0.895. Ref.[17], [7] stress the importance of the duty cycle on the SSVEP. In Ref.[17], the authors studied the influence of the duty cycle on SSVEP with frequency of 10Hz. As a result, it is found that the amplitude depends on the duty cycle in an inverted-U fashion, with the highest value around 0.5. The influence on the amplitude of the fundamental components and the its higher harmonic components by duty cycle is similar. A repetitive stimulus at 13.16 Hz is used in Ref.[7]. In result, the amplitude of the fundamental components increases significantly with the increase of duty cycle. Meanwhile the amplitude of the second harmonic components shows a decreasing trend. It is inconsistent with the reuslt reported in Ref.[17] at the the frequency of 10Hz. Hence, we speculate the changes of the amplitude with the duty cycle may not be the same in different frequency domains.

To verify the speculation, an experiment is designed in this work to investigate the effect of duty cycle on SSVEP response in a continuous frequency space. Both power spectral density (PSD) and canonical correlation analysis (CCA) method are used for amplitude estimation. The relation between fundamental components and its higher harmonic components is considered with different frequencies. Considering the stimulus with frequencies higher than 31 Hz typically produce poor SSVEP response and weaker SNR, we limit the frequency in less than 30Hz and use duty cycle increasing from 0.1 to 0.9 with step 0.1. In fact, due to high variation of the SSVEP response, it is a hard work to get a stable result in a large number of combinations between different frequencies and duty cycles. Several repetitions should be done for each combination of frequency and duty cycles. Furthermore, we compare the performance of SSVEP based BCI system with different duty cycles. The frequencies used in the system depend on the response in the former experiment.

II. MATERIALS AND METHODS

A. EEG Recording

EEG signals were recorded using a SynAmps system (Neuroscan, USA). Signals from channel CP1, CPz, CP2,

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P1, Pz, P2, PO3, POz, PO4, O1, Oz, O2, CB1 and CB2 were recorded for analysis (Fs=1000 samples/s, 0.05-200Hz). The grounding electrode was mounted on the forehead and reference electrodes between position Cz and CPz according to the system of electrode placement described in [2]. The electrodes were placed according to the extended international 10/20-system.

B. Experimental Paradigms

During the experiment, the subject was seated in a comfortable armchair in an electrically shielded room with the background light on (40 lux) and 1.5m between eyes and stimuli. The stimuli consist of six light-emitting diode (LED) lights made by 20 LED 5050 SMD. Each light has a maximum luminance of 5000-6000 MCD. The timing of the six LED flickers was precisely controlled by a microprocessor C8051F120.

The experiment includes two parts. In part I, we detect the SSVEP response with different frequencies and duty cycles. 261 types of stimulating style are selected with 29 different frequencies ($\omega = 2, 3, \ldots, 30$Hz) and 9 different duty cycles ($\sigma = 0.1, 0.2, \ldots, 0.9$). To get the stable responses of all the 261 combinations, the experiment is arranged in three days. In each day, the experiment is divided into 4 sections, with 9 blocks each section. There are 29 trials in a block. Each trial keeps 3 seconds. Between each block, the subject would have a rest. Each combination appears once randomly in each section. Hence, each combination is repeated 12 times in 3 days.

The part II is about subject-specific SSVEP based BCI experiment. The stimulation frequencies are selected with the highest SSVEP response in part I. The experiment has 9 sections. The duty cycle in the 9 sections increases from 0.1 to 0.9 with step 0.1. There is 10 blocks in each section. Each block contains 6 trials, and each trial lasts 10 seconds. The subject was asked to follow the sound instruction to gaze at the target. Between each block, the subject would also have a rest.

Until now, the experiment is continuing. One subject has finished the two parts of two experiments, who is male, 28 years old, healthy, right-handed and corrected to normal vision.

C. Data Analysis

Both power spectral density (PSD) and canonical correlation analysis (CCA) method are used to estimate the amplitude of the SSVEP response. Consider the signal x with its dimensions $c \times n$, c is the number of the channel and n is the time length.

By PSD method, we estimate the SSVEP response of signal x at certain frequency ω as follows

$$\Phi(\omega) = \frac{1}{n} \left| \sum_{k=1}^{n} x(k) e^{-i2\pi\omega k/Fs} \right|,$$

where Fs is the sampling rate. PSD method estimates the amplitude from each channel independently. The correlation between channels is not considered.

CCA method could use channel covariance information to improve the signal-to-noise ratio (SNR) during the estimation[8]. CCA algorithm, introduced by Harold Hotelling, is a multivariable statistical method to estimate the correlation between two sets of data. Consider signal x and the Fourier series at frequency ω and its harmonics

$$y(t) = \begin{pmatrix} \sin(2\pi\omega t) \\ \cos(2\pi\omega t) \\ \sin(4\pi\omega t) \\ \cos(4\pi\omega t) \\ \cdots \end{pmatrix}$$

where $t = k/Fs$, $k = 1, 2, \ldots, n$, CCA algorithm could find the linear combinations w_x, w_y which have maximum correlation with x and y,

$$\max_{w_x, w_y} \rho = \frac{E[w_x^T x \cdot y^T w_y]}{\sqrt{E[w_x^T x \cdot x^T w_x] E[w_y^T y \cdot y^T w_y]}}$$

The maximum of ρ is the maximum canonical correlation. Here we use it to detect the amplitude of the SSVEP response at certain frequency ω.

III. RESULT

A. SSVEP Response

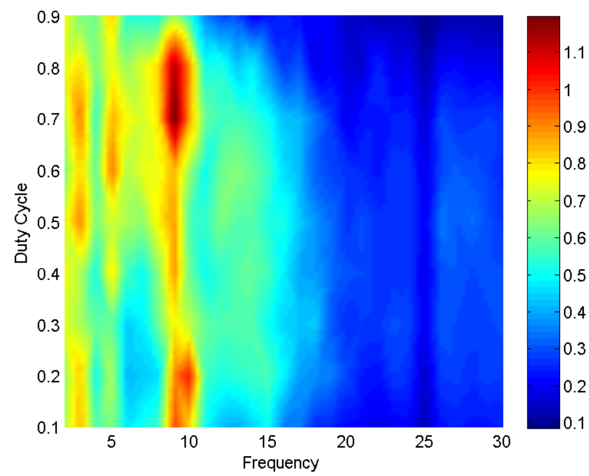

Fig. 1. The SSVEP response with different frequencies and duty cycles by PSD method.

Fig.1 and Fig.2 shows the amplitude of SSVEP in the experiment part I, calculated by PSD and CCA respectively. The result is linear interpolated and averaged with 12 repetitions. For each trial, the data in the last 2.5 second are used for calculation. Here, the fundamental frequency and its second harmonic component are considered. The amplitude from PSD method is the average from all the fundamental and second harmonic component from the 14 channels. The results from the two methods are not consistent very much.

For PSD method, the amplitude of SSVEP descends from low-frequency region (2-10Hz), medium-frequency region (11-18Hz) to high-frequency region (19-30Hz). The subject

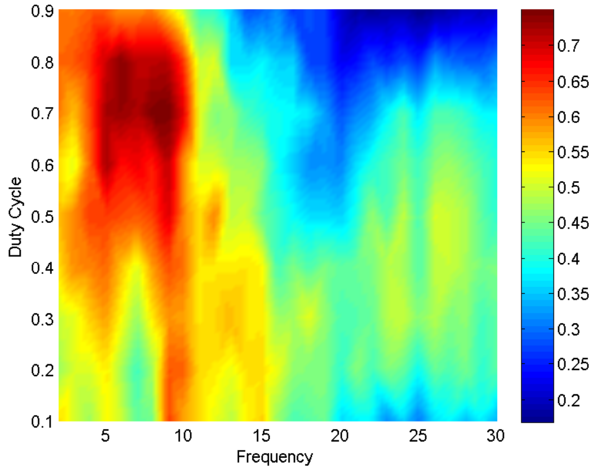

Fig. 2. The SSVEP response with different frequencies and duty cycles by CCA method.

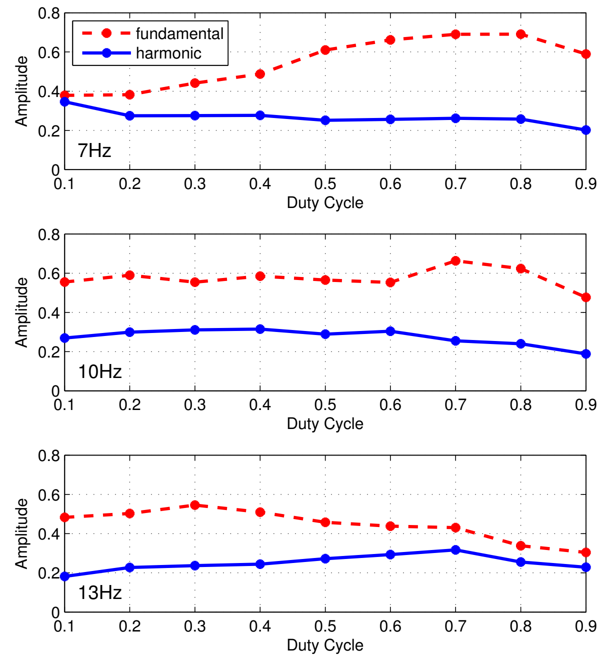

Fig. 3. The amplitude of Fundamental Component and Second Harmonic Component at frequencies of 7Hz, 10Hz and 13Hz, estimated by CCA method.

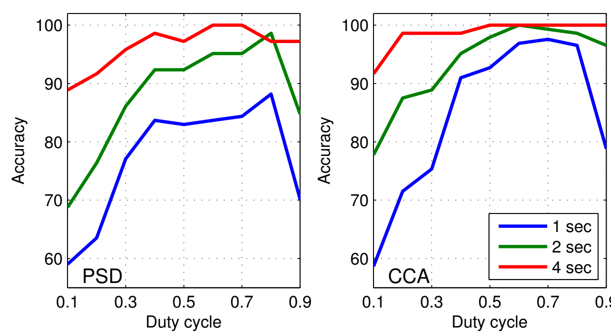

Fig. 4. The classification accuracies with the increasing of duty cycle by using PSD and CCA method. The results with time intervals 1, 2 and 4 seconds are marked with blue, green and red respectively.

has the highest response around 9Hz. It produces larger amplitude with the duty cycle around 0.2 and 0.7 than other duty cycles. The response around 5Hz is also strong due to its strong second harmonic component. And the response in medium and high-frequency region is not sensitive to duty cycle. But high duty cycle, such as 0.9, has the response weaker than others. The notch to the frequency at 50Hz makes the response map form a trough at 25Hz.

Compared with PSD method, CCA method depicts a different amplitude surface in the three frequency regions. The highest response corresponds to the duty cycle 0.6-0.8 in low-frequency region (2-10Hz), 0.2-0.5 in medium-frequency region (11-18Hz) and 0.2-0.7 in high-frequency region (19-30Hz). The influence of the notch to the frequency at 50Hz is not as obvious as PSD method. Due to the strong anti-noise ability of CCA method [8], CCA method reflects the SSVEP response change with frequency and duty cycle than PSD method more realistically.

B. Fundamental Component and Second Harmonic Component

The relation between fundamental and second harmonic component on the subject is displayed in Fig.3. Here, the response of each component is estimated by CCA method. PSD method shares the similar result. At the frequency of 7Hz, the amplitude of the fundamental component increases with the duty cycle increasing from 0.1 to 0.9. At the same time, the amplitude of the second harmonic component is decreasing. At the frequency of 10Hz, the influence on the second hannonic of SSVEP by the duty cycle is similar to that on the fundamental. The situation at 13Hz is just opposite, which is also exactly opposite as it is reported in Ref.[7] with the frequency around 13.16Hz.

C. SSVEP Based BCI

Furthermore, we consider the use of duty cycle in the SSVEP based BCI systems. Due to the strong SSVEP response in the region 5-10Hz for the subject, we set the stimulation frequency as 5.6, 6.5, 7.4, 8.3, 9.2, 10.1Hz with the step 0.9Hz. In experiment part II, each section lasts 600 seconds with 60 trials, each trial 10 seconds. For each trial, the data from 2-10 second, are used for analysis and separated in to several samples with different time intervals. 480, 240 and 120 samples are obtained corresponding to the time interval 1 second, 2 seconds, and 4 seconds respectively. Both PSD and CCA method are for feature extraction, with the feature dimension 72 and 6 respectively. Three-fold cross-validation is used to get classification results.

Tab.I is the result from CCA method with the time interval 1 second. The accuracy reaches its peak at the duty cycle 0.7. Compared with the normally used duty cycle of 0.5, this

TABLE I

THE CLASSIFICATION ACCURACIES WITH DIFFERENT DUTY CYCLE. CCA METHOD ARE USED AND THE TIME INTERVAL IS 1 SECOND.

duty cycle	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
accuracy	58.68	71.53	75.35	90.97	92.71	96.88	97.57	96.53	78.82

result increases nearly 5%. Both the classification results by PSD and CCA method are illustrated in Fig.4 with the time interval 1sec, 2sec and 4sec. The trends for PSD method are similar with CCA. But CCA method attains higher recognition accuracy than PSD method.

IV. CONCLUSION AND DISCUSSION

In this paper, we consider the effect of duty cycle on SSVEP response in different frequency domains. As the result from experiment part I, the influence of duty cycle is not the same in different frequency domain. Both PSD and CCA methods are used. Due to the stronger anti-noise ability, CCA method is more reliable than PSD method. The relation between the fundamental component and its second harmonic component is also discussed at different frequencies. We compare the amplitude curves as the increasing of the duty cycle at frequencies of 7Hz, 10Hz and 13Hz, which is quite different between each other. And the result as 13Hz is also exactly the opposite, as it is reported in Ref.[7] at frequency 13.16Hz.

Unfortunately, the experiment is still continuing. Only one subject has finished both two parts of the experiment. Preliminary results on the other subjects show the variations of SSEVP response between subjects. Hence, in the SSVEP based BCI system, we are considering to set the frequencies and duty cycles subject-specifically. The classification accuracies illustrated in Tab.I and Fig.4 shows the effect of duty cycle adjustment.

However, the principle of parameter selection in the subject-specific SSVEP based BCI is still unclear. Some problems are stated as follows,

Firstly, the frequencies could not be selected too close. The frequency domain resolution for both PSD and CCA method depends on the length of the time interval. While the frequency domain with higher SSVEP response is not so wide, such as 5-10Hz in our experiment. So selecting the closer frequencies with poorer frequency domain resolution or the frequencies far from each other with lower SSVEP response still need to be considered. The final solution may be a compromise between the two sides.

Secondly, the inconsistent of the SSVEP response with certain duty cycle at different frequency domain suggests us to set different duty cycles for each frequency. But whether the separately setting of duty cycle would influences the system performance is still unknown. In the experiment, it is found that the stimulus with certain frequency and duty cycle are more shining and easier to attract the subject's attention than others.

Finally, the classification accuracies depend on the average SSVEP response of all the stimulus or the poorest one is also unclear.

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