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Harmonic Coupling of Steady-State Visual Evoked Potentials

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Abstract—**Steady-state visual evoked potentials (SSVEPs) are oscillating components of the electroencephalogram (EEG) that are detected over the occipital areas, having frequencies corresponding to visual stimulus frequencies. SSVEPs have been demonstrated to be reliable control signals for operating a brain-computer interface (BCI). This study uses offline analyses to investigate the characteristics of SSVEP harmonic amplitude and phase coupling and the impact of using this information to construct a matched filter for continuously tracking the signal.**

I. INTRODUCTION

A brain-computer interface (BCI) is a device that provides individuals with severe neuromuscular disorders with a non-muscular channel for communication and control [14]. Steady-state visual evoked potentials (SSVEPs) observed from scalp recorded electroencephalogram (EEG) have been demonstrated as a reliable control signal for BCIs [1][2][3][5][6][11][12][13]. In this approach, the user views one or more stimuli that each oscillate at a different constant frequency. When the subject focuses attention on one such stimulus, EEG activity may be detected over occipital areas at corresponding frequencies as illustrated in Figure 1. Hence, an SSVEP BCI can infer user intent by measuring EEG activity at a specific frequency or frequencies over occipital areas. While the largest spectral power is often observed at the stimulating frequency, SSVEPs also commonly exhibit power at harmonic frequencies of the stimulating frequency [7]. While the existence of SSVEP harmonics is well-known, the preferred amplitude and phase coupling information is often not utilized for continuous tracking of these signals.

This study attempts to characterize SSVEP amplitude and phase coupling, and use this knowledge to construct a matched filter for continuous tracking. Matched filters are known to be particularly effective for detection of waveforms with consistent temporal characteristics in the presence of noise, such as the EEG μ-rhythm [4]. The results are compared with conventional Fourier-based spectral techniques that do not account for precise coupling relationships.

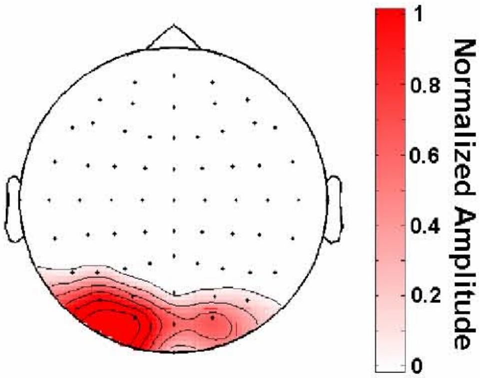

Fig. 1. Typical occipital topography of SSVEP response amplitude at the stimulation frequency.

II. METHODOLOGY

A. Subjects

Subjects were 6 able-bodied adults (3 women, 3 men; age range 18–29 years). All subjects were free of neurological or psychiatric disorders or medications known to adversely affect EEG recording. None had prior experience with EEG recording or BCIs. The study was reviewed and approved by the Georgia State University Institutional Review Board, and each user gave informed consent.

B. Data Collection

The details of the data collection and analysis are as follows: Using BCI2000 software [9], the EEG activity was collected from 64 channels at standard locations distributed over the scalp using the International 10-20 system of electrode placement [10]. All 64 channels were referenced to the right earlobe, bandpass filtered (0.1-50 Hz), amplified 20,000x using an SA Instruments biosignal amplifier, and digitized at 160 Hz. Stimuli were presented using Presentation (Neurobehavioral Systems).

C. Task

Subjects were seated in a comfortable chair about 3 ft from monitor with a 60 Hz refresh rate. The left and right sides of the monitor contained a tall rectangular black and white checkerbox (refer to Figure 2) that oscillated between two reversed images at 6 Hz and 15 Hz, respectively. These stimulation frequencies were determined to be suitable based on a prior pilot study [1].

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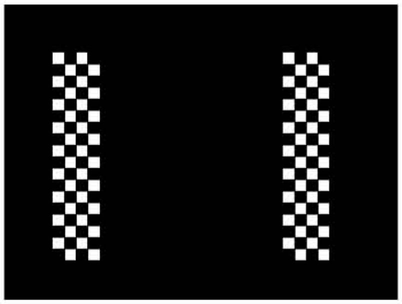

Fig. 2. The checkerbox task display. The left and right checkerbox oscillated between two reversed images at 6 Hz and 15 Hz, respectively.

The checkerboxes were separated by about 7 in. Each checkerbox was about 2 in. wide by 8.5 in. tall and consisted of a 4 x 18 matrix of squares each measuring about 0.5 in. long.

All subjects participated in 12 experimental runs comprised of different SSVEP tasks. Each run was separated by a 30-60 s break. Of these 12 runs, the checkerbox task was presented on four consecutive runs where the subject was instructed to maintain focus on a single target checkerbox, with the target alternating for each run. Subjects were given no instructions regarding eye fixation. Additional details regarding the task and data collection are provided here [1].

D. Data Analysis

Data from eight occipital electrodes were analyzed (PO7, PO3, POz, PO4, PO8, O1, Oz, O2). Data from each run were segmented into 1 s epochs, with 50% overlap. The Fast Fourier Transform (FFT) was computed for each epoch using a Hanning window and zero-padding to create 1 Hz frequency bins. For each user, the single best electrode location was determined based on the correlation between the FFT amplitudes at the stimulation frequencies and the target location. These locations are provided in Table I. Although the two frequencies produced different optimal locations in some instances, the resulting correlations were not appreciably different from the location selected for presentation.

To assess the phase coupling between the fundamental at the stimulating frequency and the harmonics for each condition, the FFT phase information from each epoch was used to compute the cyclic relative phase:

$$\psi_{uv}(m) = \left(\frac{v}{u}\phi_u(m) - \phi_v(m)\right) \bmod 2\pi \text{, with } u > v \tag{1}$$

and the strength of synchronization [8]:

$$S_{uv} = \left| \frac{1}{N} \sum_{m=1}^{N} e^{j\psi_{uv}(m)} \right| \tag{2}$$

where u and v are indices denoted by the harmonically related frequencies, m is the epoch index, and N is the number of instantaneous phase observations over an interval. Ideally, if there is no phase coupling between harmonics, the relative phase should have a uniform random distribution and the strength of synchronization will approach zero.

One approach to modeling amplitude and phase coupling for continuous detection is to construct a matched-filter (MF) template based on the sum of the harmonically related sinusoidal components [4]:

$$MF(n) = \sum_{k=1}^{N} a_k \cos\left(\frac{2\pi nkf_F}{f_S} + \phi_k\right) \tag{3}$$

where n is the template sample number, f_S is the sampling frequency, f_F is the fundamental frequency of the μ-rhythm template, $N-1$ is the number of harmonics to be modeled, and a_k and ϕ_k are the amplitude and phase of the individual harmonics, respectively. These model parameters can be simply obtained from the FFT spectrum of the user's normalized characteristic waveform at each frequency as determined by a phase-aligned ensemble average [4].

A template was generated for each stimulation frequency from the corresponding runs of a single session at that frequency using the fundamental and first two harmonics ($N=3$). Each incoming data epoch was circularly convolved for one period of the template in order to evaluate the template at discrete phase shifts, essentially determining the optimal phase correlation between the data segment and the template. The square root of the maximum value of the circular convolution, corresponding to the optimal alignment, was taken to be the feature for the data segment. The result is a continuous amplitude analysis, similar to that produced by a single frequency bin of a conventional spectral analysis technique.

III. RESULTS

Table I lists, for each of the users, the strength of synchronization between the fundamental frequency and first harmonic and the fundamental frequency and second harmonic at the two stimulation frequencies (6 and 15 Hz) for each target location.

It was also observed that these phase relationships can also be dependent upon the signal amplitudes. Two-dimensional histograms of the relationship between the relative phase and the FFT amplitude are illustrated in Figure 4 for several representative cases. Note the nearly uniform phase distribution for conditions where no appreciable coupling exists. These results indicate that certain SSVEP frequencies can exhibit consistent harmonic coupling for the respective target condition. Considering this, combining harmonic bands as independent control features for a BCI is likely suboptimal in terms of detection and tracking performance.

To evaluate the performance of the parameterized SSVEP matched filter, two MF features (one at each stimulation frequency) and six FFT features (fundamental and first 2 harmonics at each stimulation frequency) were extracted from training data from a single session using the protocol described earlier. Ordinary least squares linear regression was used to determine the optimal regression weights for the two MF and six FFT features as separate models.

TABLE I
STRENGTH OF SYNCHRONIZATION (LEFT/RIGHT TARGET)

User	**$S_{6\text{-}12}$**	**$S_{6\text{-}18}$**	**$S_{15\text{-}30}$**	**$S_{15\text{-}45}$**
A (O_2)	0.14 / 0.13	0.06 / 0.02	0.07 / 0.10	0.08 / 0.11
B (O_z)	0.03 / 0.07	0.03 / 0.02	0.10 / 0.44	0.04 / 0.19
C (O_1)	0.04 / 0.08	0.02 / 0.06	0.10 / 0.12	0.05 / 0.08
D (O_z)	0.10 / 0.11	0.06 / 0.05	0.10 / 0.43	0.01 / 0.29
E (O_z)	0.41 / 0.10	0.27 / 0.07	0.03 / 0.47	0.04 / 0.26
F (O_2)	0.38 / 0.10	0.03 / 0.08	0.06 / 0.60	0.05 / 0.18

Table I lists, for the optimal electrode for each of the 6 users, the strength of synchronization (equation 2) between the 6 and 15 Hz fundamental frequencies and the first and second harmonics for the two target conditions.

The two models were evaluated using independent test data from the subsequent session. For each model, the predictions generated by the linearly weighted features for each epoch were correlated (using r^2) with target location. The average r^2 results are summarized in Figure 3, including the r^2 generated by the 6 harmonic FFT amplitudes independently.

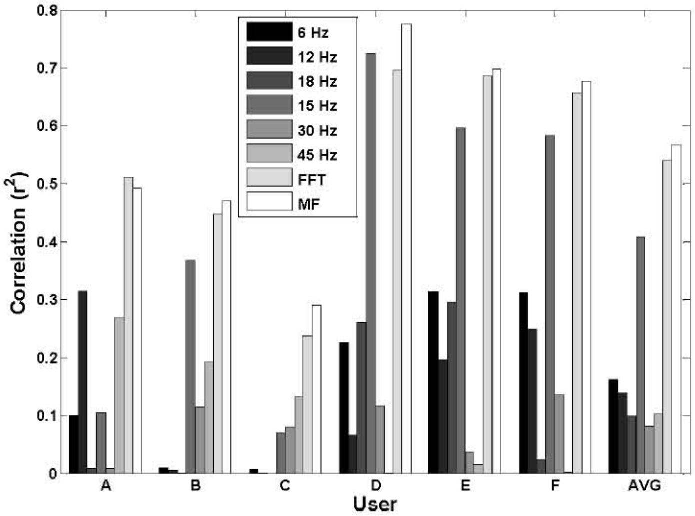

Fig. 3. Results of the offline analysis. Each bar indicates r^2 between the signal and target location for the test session. The signals include the individual FFT amplitudes at the 6 and 15 Hz stimulation frequency, the first and second harmonics of each, the 6 regressed FFT features (FFT), and the 2 regressed MF features (MF).

IV. DISCUSSION

The results indicate that incorporating harmonic coupling information can improve performance. In most cases this improvement was marginal compared to a simple regression of the FFT harmonic amplitudes. However, appreciable performance gains were realized for a few of the users. Two of the users exhibited minimal or no coupling differences for any condition, while four of the users exhibited sizable coupling differences for at least one condition.

Although Table I and Figure 4 indicate clear coupling differences between conditions, it should be noted that the coupling tends to exhibit some variability. It may be advantageous to evaluate different epoch lengths for different frequencies in attempts to minimize this variability.

Some of the users have relatively little correlated activity at one or both stimulation frequencies, compared to the harmonic frequencies. Because the MF templates were generated by phase-aligned ensemble averages at the stimulation frequencies, if minimal or no coupling exists, the templates likely will not adequately represent these harmonic frequencies and produce suboptimal results. Therefore, it may be more appropriate in these cases to generate matched-filter templates for the relevant harmonic frequencies. It is also conceivable that significant, consistent coupling could exist for both target conditions due to a response from the periphery, thus rendering the MF useless for discrimination. However, this should have little impact since the features generated by each MF template are weighted via regression.

The results of this study are primarily useful toward the development of improved SSVEP BCI systems for individual users. Since many BCI studies and reviews, like the present study, report considerable differences between users [1][2][3][4][5][7][11][12][13][14], individual performance would likely improve if critical data analysis parameters could be identified and customized accordingly. This should ideally be done via automated tools to identify the best parameters and adapt them accordingly. While the principal goal is to inspire improved BCI systems, the present results can also contribute to important theoretical issues by elucidating dynamics and interactions of neural networks responsible for vision and other functions.

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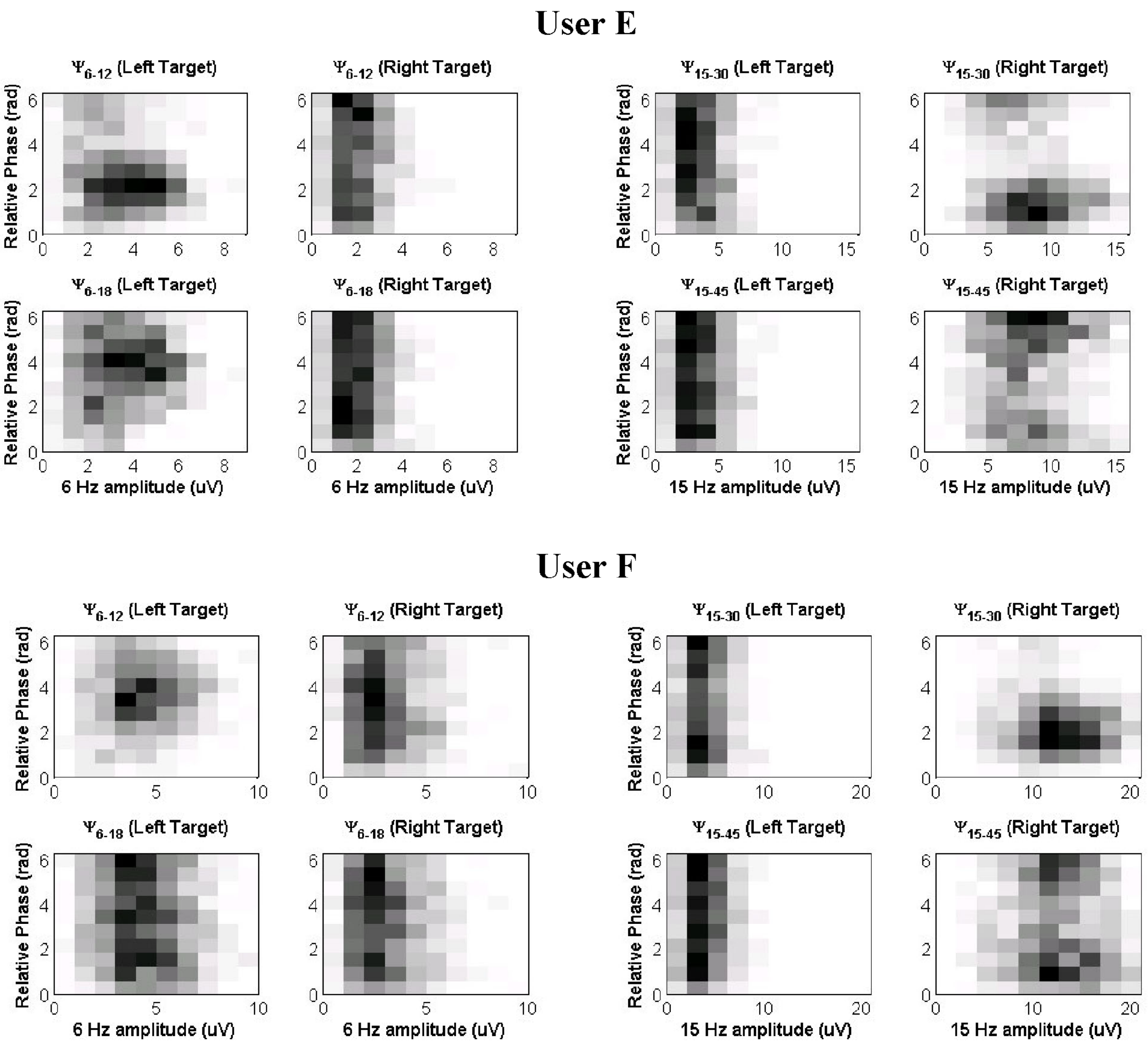

Fig. 4. Two-dimensional histograms of relative phase versus 6/15 Hz band amplitude for representative cases. Increasing density of observations is indicated by increasing darkness. The uniform distributions with respect to amplitude indicate that there is little phase coupling for that condition.