The Real Time EEG Phase Locked Feedback Control for Alpha Amplitude and Frequency Regulation: An OpenBCI Implementation

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ABSTRACT

The neural oscillation in electroencephalogram (EEG) signals is highly related to people's psychological cognitive ability. In this work, an OpenBCI version of phase-locked feedback control system has been implemented for real time alpha wave regulation. As compared with the distributed system architecture on Brainamp, PC and Arduino in the previous work, the new proposed system has integrated all the modules for signal acquisition, phase estimation and applying stimulation on one chip. Hence, the delay for signal transmission can be effectively eliminated, which leads to a better accuracy for phase estimation in phase-locked feedback control. The results show the effective of the proposed system to alpha wave regulation.

CCS CONCEPTS

• **Human-centered computing** → HCI design and evaluation methods.

KEYWORDS

EEG, Phase locked feedback control, Alpha wave, Amplitude and frequency regulation, OpenBCI

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1 INTRODUCTION

The neural oscillation in electroencephalogram (EEG) signals is closely related to people's psychological cognitive ability [1], [2]. Typically, being relevant to the cognitive processes and short-term memories, the 8-12Hz alpha band oscillation has been used to reveal pathological changes in spontaneous EEG associated with different brain pathologies [3], [4]. Based on these, neurofeedback technique is developed to regulate people's brain wave to desired patterns voluntarily for the treatment of several types of brain diseases and disorders [5], [6], such as attention-deficit/hyperactivity disorder (ADHD) [7], epilepsy [8], stroke [9], [10], autistic spectrum disorder (ASD) [11], and emotional disorders [12]. However, a considerable number of people are not able to regulate their own brain activity, which greatly limits the effect of neural feedback [13].

In the previous work [14], we proposed a new externally-regulated neurofeedback (ER-NF) protocol to regulate the alpha wave using phase locked feedback control technique with external sensory stimulation. The experiment evidence shows that visual stimulation delivered at different phases of alpha wave would evoke different EEG response [15], [16], [17]. In detail, the latency and amplitude of the evoked potentials depends on the phase of the alpha wave at the stimulation time. Therefore, we think of alpha oscillations as a simple pendulum model without damping. As shown in Figure 1 a, without external stimulus, the system will execute a simple harmonic motion with certain frequency and amplitude. A continuous external stimulus at a specific phase would make the amplitude of the single pendulum increase or decrease, which depends on the phase of pendulum when the stimulus is exerted (Figure 1 b and Figure 1 c). In the experiment with 20 subjects, the new ER-NF protocol could regulate the alpha wave for all subjects.

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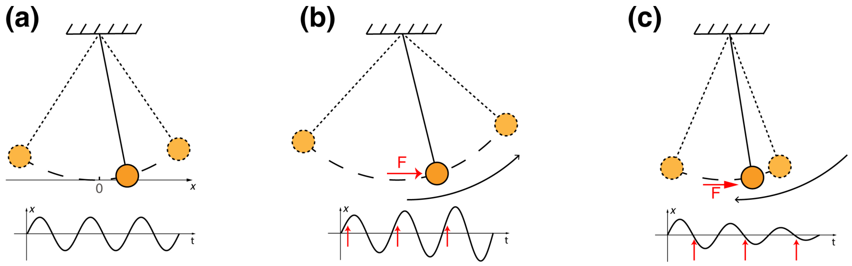

Figure 1: The principle of the proposed phase locked feedback control (Figure 1 in Ref. [14]). (a) The alpha oscillation is simplified as the motion trajectory of a simple pendulum without damping. The motion trajectory of the simple pendulum is a sinusoidal function with fixed frequency and amplitude. The amplitude indicates horizontal displacement of the ball. (b) If a force (the red arrow F in the figure) is exerted at a phase where the pendulum moves in the same direction as the force, the amplitude of the pendulum would be increased. (c) On the contrary, if the force is exerted at the phase where the pendulum moves in the reverse direction as the force, the amplitude of the pendulum would be decreased

By delivering visual stimuli at the specific phase of the ongoing alpha wave, the new ER-NF protocol can either enhance or abate the frequency and amplitude of alpha wave, which depends on the stimuli phase of the alpha wave.

The real time phase estimation of alpha wave is key important for phase locked feedback control. The precision of phase estimation is mainly determined by software and hardware factors: 1) phase shift caused by causal filter in software and 2) the delay in signal transmission in hardware. For software phase estimation, the use of online causal filter makes it impossible to get the accurate value of the current signal phase. In Ref. [18], McIntosh et. al. used machine learning methods for EEG phase estimation. Furthermore, due to the random noise in the generation of alpha wave [19], to what extent the phase of alpha wave can be predicted is still an open question. For hardware signal transmission, buffer is commonly applied for temporarily store EEG signal from input device for the stability and efficiency of real-time data transmission. But the use of buffer would inevitably cause delay, as a result, we can only get the signal from a certain time before, but not the instantaneous signal. The setting of buffer is common in several types of commercial EEG amplifiers, which may be not well documented or did not provide friendly real time API to let us reduce it.

In this work, OpenBCI is used to develop the real time EEG phase locked feedback system for ER-NF. By programming on Arduino, data analysis is performed immediately after data acquisition. The process of signal transmission can be omitted, which almost eliminates the hardware delay. In the following, Methods and experiments are arranged in Section 2. Section 3 is for the results and conclusion and discussion is in Section 4.

2 METHOD AND EXPERIMENT

2.1 System design

In the proposed system, all the functions have been implemented on OpenBCI, including signal acquisition, phase estimation and applying stimulation. As is shown in Figure 2, as compared with previous work, the integration of all functions into one board can eliminate the delay caused by signal transmission, which is 60ms for Brainamp amplifier in our test.

As illustrated in Figure 3, the whole system is made up of six modules, which are EEG acquisition module, Real-time phase decoding module, Trigger phase setting module, Visual stimulation module, Data storage module and Data sending module. Firstly, raw EEG data is recorded by the EEG acquisition module. And then the phase of the ongoing EEG signal is calculated by the Real-time phase decoding module. Based on this, Trigger phase setting module is used to determine the time for release the stimulus. Visual stimulation module is used for LED control. At the same time, the real-time raw EEG data will be stored in the SD card by the Data storage module. With the help of Data sending module, the ongoing EEG signal and the regulation result can be monitored in real-time on another PC. The details of the six modules are introduced in the following:

2.1.1 EEG Acquisition. The raw data was sampled from Oz and referenced to Tp9 at 250Hz by 8 channel OpenBCI Cyton Biosensing Board. Although it is feasible to elevate sampling rate, 250Hz is the most suitable rate to guarantee the best performance of whole system since higher sampling rate. Before experiments started, the impendence of every channel was checked to be 5kΩ below.

2.1.2 Real-time Phase Decoding. Once raw EEG data was recorded, it will be analysed by this module which was developed by C++ and uploaded by Arduino IDE. Firstly two 2nd-order Butterworth IIR causal filters were used for data pre-processing, in which a notch filter with bandwidth from 48Hz to 52Hz was applied for removing power-line interference, an 8-12Hz bandpass filter is applied for alpha wave filtering. Due to the use of causal filters a phase shift would be introduced into the system. Further, the upward zero-cross point was checked to detect the phase of $3\pi/2$ for phase estimation, which was simple and effective for online processing.

2.1.3 Trigger Phase Setting. By import a time lag ϕ as a phase index, we can deliver the visual stimulus at different phase of alpha wave, which is also applied in this previous work. For example, with time lag $\phi = 0$, visual stimulus at the phase of $3\pi/2$ for alpha wave. Ten different values of time lag Φ (ranging from 12.5 to 125ms with a step of 12.5ms) were examined and they correspond to 10 phases of alpha wave. With the alpha frequency ranging from 8-12Hz, the

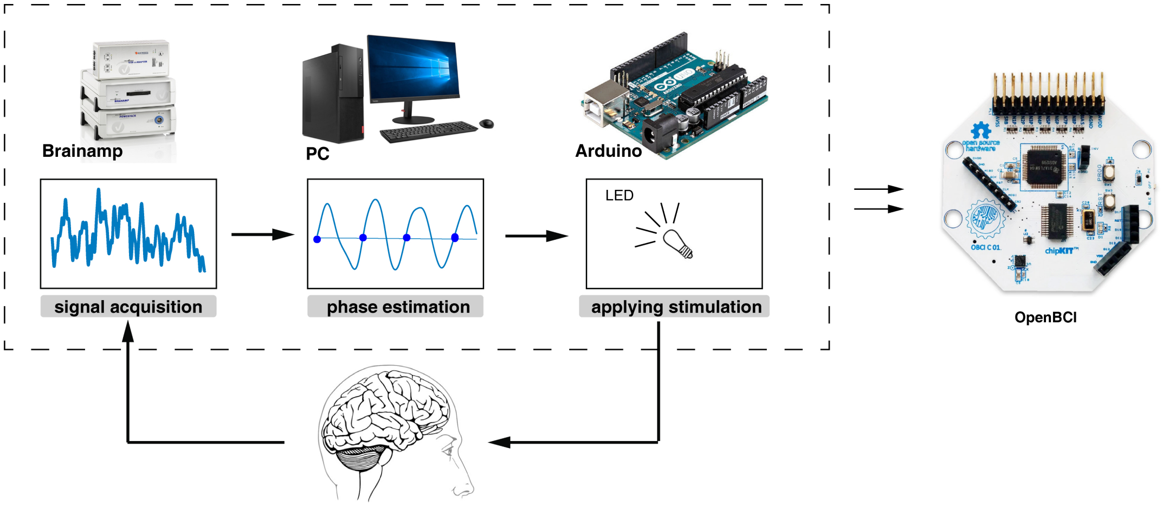

Figure 2: The system implementation of the phase locked feedback control system. As compared with previous work, the functions as signal acquisition by Brainamp, phase estimation by PC and applying stimulation by Arduino has been integrated into an OpenBCI Cyton Biosensing Board. The delay caused by signal transmission between different device could be effectivelyremoved

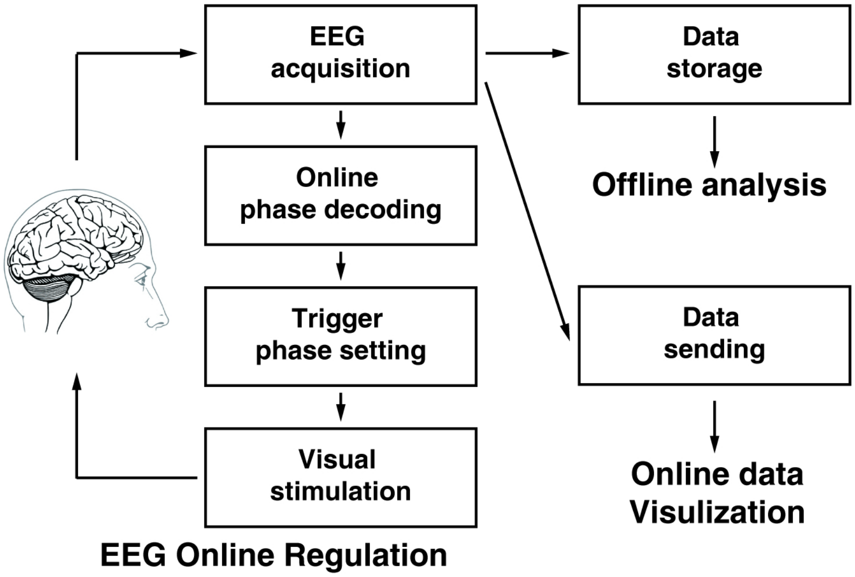

Figure 3: The system architecture of the phase locked feedback control system, which is consisted with the modules of EEG acquisition, Online phase decoding, Trigger phase setting and Visual stimulation for EEG online regulation, the modules of Data storage for offline analysis and Data sending for online data visualization

period of alpha wave would be less than 125ms. Hence, the setting the range of ϕ (12.5-125ms) would cover at least one cycle of the alpha wave.

2.1.4 Visual Stimulation. Visual stimulation is provided by a LED powered and controlled by OpenBCI Cyton Board, and the light intensity is constant to eliminate the influence of various light intensity. In addition, the LED was placed 50cm away from experimenter in every experiment. In order to ensure that the other functions of the whole system are still working stably when the lights are on, it is the interrupt mechanism of MCU controlling all the lights on and off.

2.1.5 Data Storage. By using the original foundation of C++ SD library of OpenBCI Cyton Board, both the raw EEG data and the filtered EEG data were stored in eight-digit hexadecimal form. Trigger information were also recorded for further offline analysis.

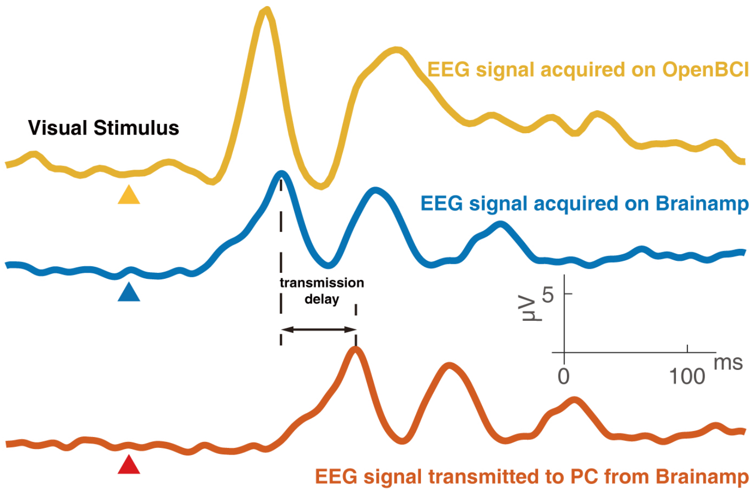

Figure 4: VEP from both Brainamp and OpenBCI recording in EXP1. To evaluate the delay for signal transmission, the trigger marked for Brainamp recording is not actually the frame the visual stimulus delivered as usual (blue triangle), but the frame that the EEG signal transmit to the PC (red triangle). For OpenBCI, the two frames are the same (yellow triangle), because there is not delay for signal transmission

2.1.6 Data Sending. This module is developed on OpenBCI C++ library, and the corresponding visualization tool on PC is developed by Python. Once the OpenBCI chip is connected to PC through the dongle board, the EEG signal can be transmitted to PC in real time. The visualization tool on PC could show the dynamic figure of real-time raw and filtered EEG signal and the frequency characteristics of the EEG signal from channel Oz was also displayed to monitor the result phase locked feedback control online. Here, welches method was applied for spectrum analysis.

2.2 Experiment

A healthy male subject participated in the study to verify the effect of the proposed system in phase locked feedback control with three experiment. The experiments were in accordance with the Declaration of Helsinki. Ethical approval of the study was sought and obtained from the Bioethics Committee, Shenzhen University Health Science Center.

Raw EEG was recorded by a Brainamp system (Brain Products GmbH, Germany) from Oz (referenced to TP9/TP10) with a sampling rate of 5000 Hz. For OpenBCI, the sample rate was changed to 250Hz. With the eliminating the delay in signal transmission, we firstly compared the result of Visual Evoked Potential (VEP) in Brainamp and OpenBCI. Secondly resting state EEG to check the accuracy of phase estimation. Finally, we compared effect of phase locked feedback control from Brainamp and OpenBCI to show the influence of transmission delay to the system.

2.2.1 Exp1: Evaluation of Transmission Delay. In Exp1, we recorded VEP on both Brainamp and OpenBCI devices to compare the signal quality of the two different amplifiers and the evaluate the delay in signal transmission. The 1Hz flashing visual stimuli was given to a subject via LED with constant light intensity in each session. The intensity and power of LED were set to be identical on both devices. Each recording last 60 seconds.

It should be noted that to evaluate the delay for signal transmission, there are two markers for Brainamp recording, which is the frame the visual stimulus delivered as usual (blue triangle in Figure 4), and the frame that the EEG signal transmit to the PC (red triangle in Figure 4). For OpenBCI, the two frames are the same (yellow triangle in Figure 4), because there is not delay for signal transmission.

2.2.2 Exp2: Accuracy of Phase Estimation. One-minute resting state EEG signal was recorded with eye open. In order to eliminate the difference caused by the signal quality of different amplifiers, resting state EEG was only recorded on Brainamp. The phase concentration would be compared at the zero-cross point at the two-time frames for EEG signal acquired on Brainamp (blue triangle in Figure 4) and transmitted to PC (red triangle in Figure 4). Hilbert transform was applied for phase estimation. The Mean Absolute Circular Error (MACE) is applied to calculate the phase concentration, as $\frac{1}{N}\sum_{i}^{n}|Arg(e^{i\psi_i}/e^{i\psi_p})|$, where ψ_i is the phase for each trial i, ψ_p the mean value of the phase for all trials [18].

2.2.3 Exp3: Effect of Phase Locked Feedback Control. Exp3 consists of 10 conditions, which corresponds to the 10 different time lag ϕ ranging from 12.5 to 125ms in a random order. For each condition, a continuous visual stimulus last 20 seconds for the phase-locked feedback control with a fixed value of ϕ. This experiment was done on both Brainamp and OpenBCI. The intensity and power of LED were set to be the same on both devices. Fast Fourier transform (FFT) was applied to evaluate the effect to phase locked feedback control on both Brainamp and OpenBCI.

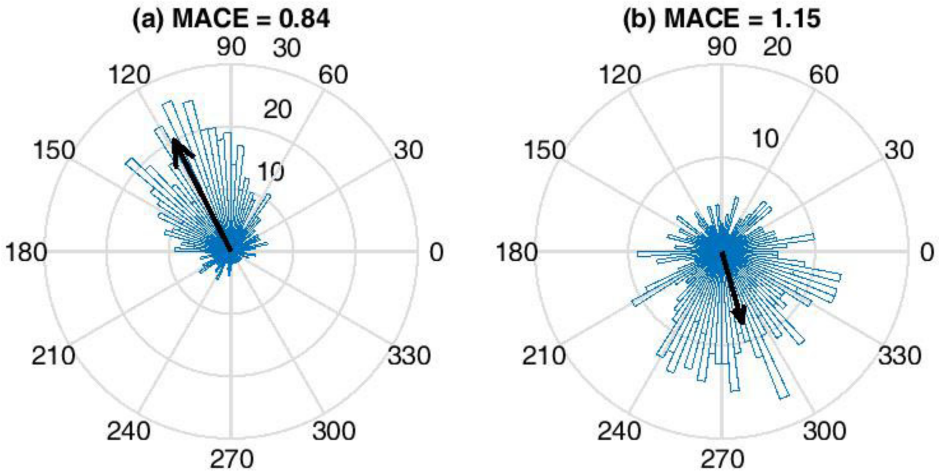

Figure 5: (a) The accuracy of phase estimation for Brainamp recording without delay in signal transmission; Figure 5: (b) The accuracy of phase estimation for Brainamp recording with delay in signal transmission

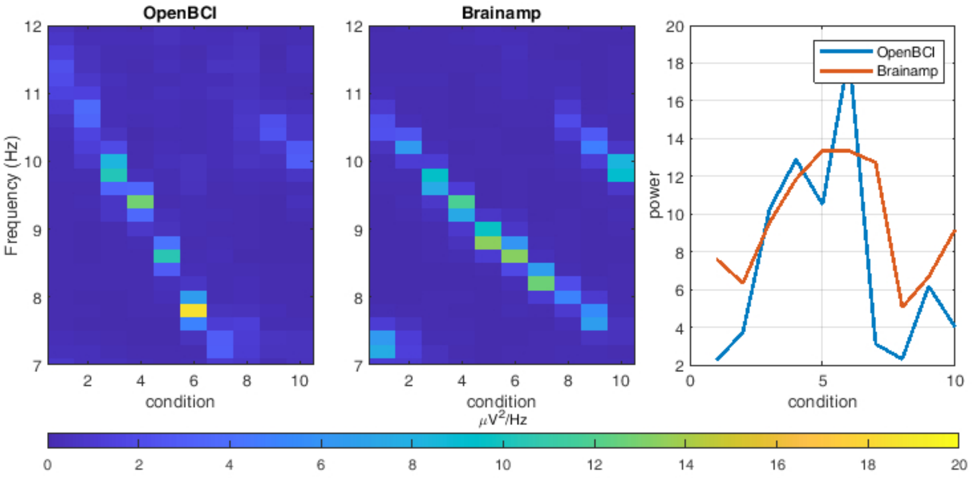

Figure 6: The comparison of the effect of phase locked feedback control between OpenBCI and Brainamp. Without the delay for signal transmission, OpenBCI could modulate the alpha wave with larger frequency and power range

3 RESULTS

3.1 Exp1: Evaluation of Transmission Delay

Figure 4 shows the results of VEP in Exp1 for both Brainamp and OpenBCI recording on the same subject. OpenBCI shows a compatible VEP result as compared with Brainamp amplifier. The latency of the first peak from OpenBCI is a little earlier (around 9ms) than Brainamp. Comparing the latency of the peak in blue curve and red curve, we can calculate the delay of signal transmission can be calculated as around 61ms for Brainamp system.

3.2 Exp2: Accuracy of Phase Estimation

For Brainamp recording, we calculated phase concentration at the frame of zero-cross point without (Figure 5 a) and with (Figure 5 b) delay in signal transmission. As is shown in Figure 5 a, due to the use of causal filter, there would be a delay of around 150ms with 2nd-order Butterworth bandpass filter from 8-12Hz, which leads to the variance for phase estimation as MACE=0.84 in Figure 5 a. With the delay in signal transmission, the variance for phase estimation would be further increased to MACE=1.15, which is not good for phase-locked feedback control.

3.3 Exp3: Effect of Phase Locked Feedback Control

The results of phase locked feedback control between OpenBCI and Brainamp are compared in Figure 6. By contrast with Brainamp, there is no signal transmission delay, which indicated higher accuracy for phase estimation. Hence, OpenBCI is capable of performing more effective for phase locked feedback control than Brainamp. In result, the neurofeedback control system based on OpenBCI shows a boarder frequency range and a wider amplitude range for alpha wave regulation.

4 CONCLUSION

In this work, an OpenBCI version of phase-locked feedback control system has been implemented for real time alpha wave regulation. Comparing to the distributed system architecture on Brainamp, PC and Arduino, the current system has integrated all the modules for signal acquisition, phase estimation and applying stimulation on one chip. Hence, the delay for signal transmission can be effectively eliminate, which leads to a better accuracy for phase estimation in phase-locked feedback control. The results show the effectiveness of the proposed system to alpha wave regulation.

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