A Study on SSVEP-based Brain Synchronization: Road to Brain-to-Brain Communication

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***Abstract*—By applying a basic knowledge of brain-computer interfaces and brain stimulation, we introduce a novel architecture for brain-to-brain communication (B2B). Two main issues presented herein are brain synchronization and message modulation. According to our proposed B2B architecture, we assume that the higher the root mean square (RMS) of the voltage across two brains, the easier it is to recognize variations in brain potential states that can be used for communication. By using phase-synchronized alpha waves of multiple subjects via steady-state visually evoked potentials (SSVEP), we demonstrate the feasibility of our proposed B2B architecture as well as a method for maximizing the RMS of brain potentials.**

I. Introduction

By composing electrical signals from billions of neurons in the brain, brain activity can be measured non-invasively in terms of potential variation across the scalp over time. In 1924, Berger recorded the first human brain activities and coined the term electroencephalogram for recorded brain waves [1]. Nowadays, electroencephalography, or EEG, is widely used in various studies related to human brain behaviors. We present here a brief review of studies concerning brain stimulation and brain-computer interfaces (BCIs).

One of the earliest stimulation methods introduced was transcranial direct current stimulation (tDCS) [2]. The basic concept of tDCS is to inject direct current from an external source into the brain, and is minimally invasive because it requires a small amount of current over the scalp. Later, variations of tDCS such as transcranial alternating current stimulation (tACS) and transcranial random noise stimulation (tRNS) were investigated as alternative brain stimulation methods [3]. Recently, a passive technique termed transcranial extracellular impedance control (tEIC) was proposed to as a novel option for manipulating brain activity [3]. In summary of previous works, methods of brain stimulation are typically used for an improvement of brain cognitive functions.

Over the past two decades, BCIs have been developed as communication pathways between the human brain and machines (allowing patients with locked-in syndrome to operate a word processing program via brain signals, for example.) [4] By integrating background knowledge of brain stimulation and BCIs, we introduce a novel method for *brain-to-brain communication (B2B)* between two people in this research. The purpose of our experiments was to prove the feasibility of the B2B concept, so most of them were offline analysis.

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II. Proposed Brain-to-Brain Communication

Several years ago, one research group demonstrated a framework for B2B by using EEG responses from motor imagery tasks and transcranial magnetic stimulation (TMS) [5]. Here, we introduce an alternative framework for B2B by using a steady state visually evoked potential (SSVEP) response from visual stimulation, an eye-movement response from electrooculography (EOG), and brain stimulation. SSVEP is a type of brain response occurring when neurons in the brain fire at the same frequency as periodic visual stimuli (or multiples thereof) [6]. Figure 1 presents the system architecture of our proposed B2B paradigm. After first establishing an electric circuit across two brains, the two major steps for using the system are *Synchronization* and *Messaging*.

A. Synchronization

To ensure that two people are ready to communicate, they are required to synchronize their brain waves. Visual stimulations, which induce SSVEP, and a phase shift circuit are used to synchronize frequency and phase, respectively. An advantage of synchronized brain waves is that we can get a higher signal-to-noise ratio of the voltage across the inter-connection circuit than with a non-synchronized wave, so that it is easy to recognize the wave or signal by using simple electronic components. Once users' brain waves are synchronized, a communication pathway is established and is ready to send a message.

B. Messaging

In this version, we simply use an EOG signal as a message. To send the message, we modulate the EOG signal into a synchronized wave which has been established in the Synchronization step. Whenever the inter-connection circuit recognizes the EOG signal from one person, the brain stimulator will be activated and send electrical signals to stimulate the other person. Finally, the message has been transferred from one to the other. More details about modulating EOG into the synchronized wave (EEG) is provided in the next section.

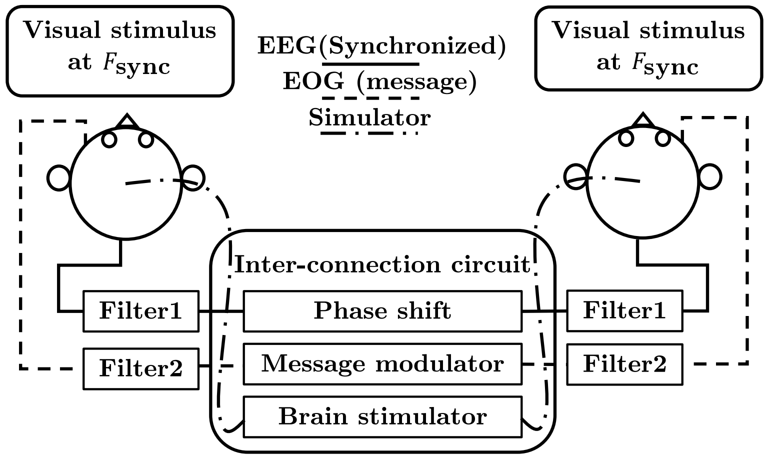

Fig. 1. System architecture of proposed B2B

According to our proposed B2B architecture, we assume that the higher the root mean square (RMS) of the voltage across two brains, the easier it is to recognize variations in brain potential states that can be used for communication. Thus, the goal of this study is to prove the feasibility of our proposed B2B architecture as by maximizing the RMS of EEG and EOG potentials.

III. Methods

In this section, we demonstrate how EEG and EOG signals recorded using a BCI serve as a proof-of-concept for eventually achieving direct B2B, and how the synchronization via SSVEP of signals from multiple subjects increases the potential information transference of an encoded message (in terms of RMS voltage). Three healthy subjects participated in this study, and this study was conducted in accordance with the Declaration of Helsinki as revised in 2000.

A. Apparatus

We recorded EEG and EOG data using an 8-bit OpenBCI brain-computer interface, at a sampling frequency of 250 Hz. Because we were interested in obtaining evidence of both SSVEP and eye saccades, we used two channels for recording. Electrodes were placed using the International 10-20 system—the reference/ground electrodes were placed on sites A_1/A_2, the channel 1 electrode on O_z, and the channel 2 electrode on Fp_2. Thus, channel 1 was used to observe SSVEP activity, and channel 2 was used to observe eye saccades in EOG.

B. Experiments

We sought to fulfill three research goals:

- *Show that SSVEP in subjects is preserved even if they make eye movements.*
- *Isolate EOG from the background EEG/noise*
- *Show that summed SSVEP signals from pairs of subjects synchronized via phase matching increases the RMS of a message modulated with EOG*

To this end, we designed a visual stimulus for subjects using Processing, a high-level Java-based programming environment for creating visual applications, to provide all necessary conditions.

The entire process hierarchy is shown in Figure 2. A single run of the program cycles through five different states: a pre-experiment state (State 0), an idle state (State 1) to allow EEG activity to stabilize for recording, the Control state (State 2), the Experimental state (State 3), and a post-experiment state (State 4). After starting the OpenBCI GUI, a Processing program for recording and saving EEG data from the BCI, the stimulus program begins in state 0, and transitions to state 1 after 15 seconds have elapsed, or until the display window initializes. Once in state 1, subjects are shown a black screen. After 15 seconds, experiment trials begin. These trials last 22.32 seconds, and consist of two states: the Control state (State 2), where the screen remains black, and the Experimental state (State 3), where a square appears in the center of the screen and flashes black and white at 8 Hz (to generate SSVEP).

In both states, a small red circle remains at the center of the screen as a fixation point. Each trial is evenly divided into four transition lasting 5.58 seconds. The first and third transition are resting, where the subject is instructed to hold their gaze on the fixation point, making as little movement as possible. The second and fourth are active transition, which cue the subject with a short beep. Upon hearing the beep, the subject is instructed to make an eye saccade down to the keyboard (to generate a large deviation in channel 2 for EOG), and then back to the fixation point, at a speed which is comfortable for them. Once the program iterates through five randomized trials for both State 2 and State 3 (ten trials total), the program enters State 4, and then terminates. To facilitate data analysis, the state, trial, and transition number were encoded as a three-digit integer (XYZ, where X is the state, Y is the trial, and Z is the transition number) and sent to each line of sampled data in the output of the OpeBCI GUI via a UDP message.

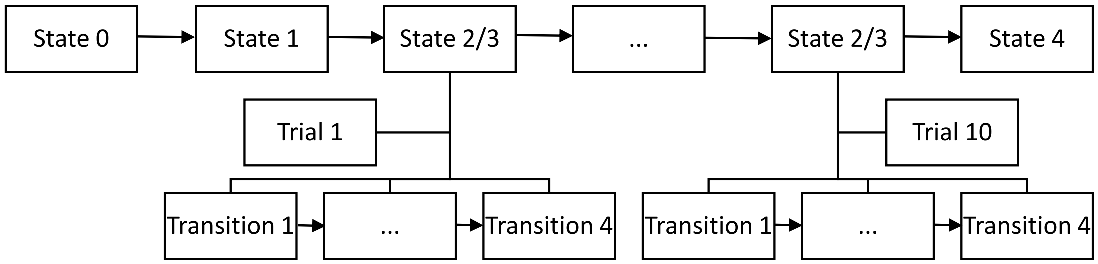

Fig. 2. The program progresses from State 0 to State 4. After State 1, either State 2 (the Control state) or State 3 (the Experimental state) are randomly chosen, a total of five trials each. Each 22.32 second trial is evenly divided into four 5.58 second transitions.

C. Data Analysis

An analysis was performed in MATLAB. We first separated all subject data by experiment states (States 2 and 3), then by trial.

- *Show that SSVEP in subjects is preserved even if they make eye movements:* To determine if SSVEP was present in channel 1 for either state, we computed the discrete time fast Fourier transform (FFT) for all trials per subject, using a transform length of 15 seconds. We then averaged the resulting amplitudes for each subject across all trials for each state.
- *EOG isolation:* EOG data were observed in channel 2. We separated each trial into its respective transition number, and then filtered the data in each even-numbered transition (those containing eye movements) using a third-order Butterworth bandpass filter from 1.5 to 10 Hz. We then calculated the RMS for the first second of each transition (enough for the subject to make an eye movement, and then return their gaze to the fixation point). These RMS values were averaged across all trials for each state, and represent the average RMS of an eye movement. Once the subjects average saccade RMS values for each condition were known, we implemented an RMS threshold to determine which data points belonged to eye saccades. We isolated each saccade by sliding a one second window across the data of each trial. If the RMS of the window was greater than 0.6 times the subjects average saccade RMS for the current condition, the last data point added to the window was classified as 1 (belonging to an eye movement); otherwise, the default classification is 0 (not an eye movement). In the case of the first window full of data, the data was assigned the classification of the first point after the windows initial ending position. We then removed blinking artifacts by iterating through the original RMS values seen by the sliding window–if these values were greater than 35 μV, the classification of the 75 data points ahead and behind the current point were changed to 0.
- *Show that summed SSVEP signals from pairs of subjects synchronized via phase matching increases the RMS of a message modulated with EOG:* We simulated the transmission of a synchronized signal in real time. As this process is contingent on the presence of SSVEP in channel 1, we only considered data from the Experimental state. Channel 1 data was first filtered using a third-order Butterworth 7–8 Hz bandpass filter. A synchronized signal is comprised of two components: channel 1 data from one subject; and channel 1 data from a second subject, whose phase is shifted to match that of the first. We organized subject data into all possible unique pairs, and iterated through all necessary components data point-by-data point to simulate the online creation and transmission of a synchronized signal. First, channel 1 data from both subjects fill buffers of size n, to be used when calculating phase-difference with FFT. Whenever the buffer is full, a new offset value for the phase shift is calculated with (1), where ϕ is the calculated phase offset and CPS is the cross-power spectrum (CPS) of the data (2). In (2), F_1 and F_2 are the Fourier transforms of channel 1 data from the first and second subjects, respectively.

$$\phi = angle(max(CPS)) \tag{1}$$

$$CPS = \frac{F_1 F_2^*}{|F_1 F_2^*|} \tag{2}$$

Then, the channel 1 signal from the second subject is shifted elementwise by the offset using a MATLAB PhaseFrequencyOffset object, and added to the channel 1 data from the first subject. High values of n increase the frequency resolution of the Fourier transforms, at the expense of updating the offset value less frequently. We used a value of $n = 30$. In addition, after the FFT buffer is initially populated, data from both subjects, as well

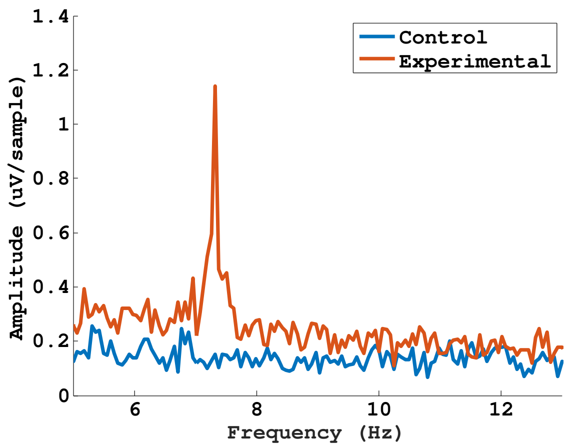

Fig. 3. Example of SSVEP. SSVEP is clearly illustrated by the peak of activity between 7 and 8 Hz in the Experimental state, but is absent in the Control state.

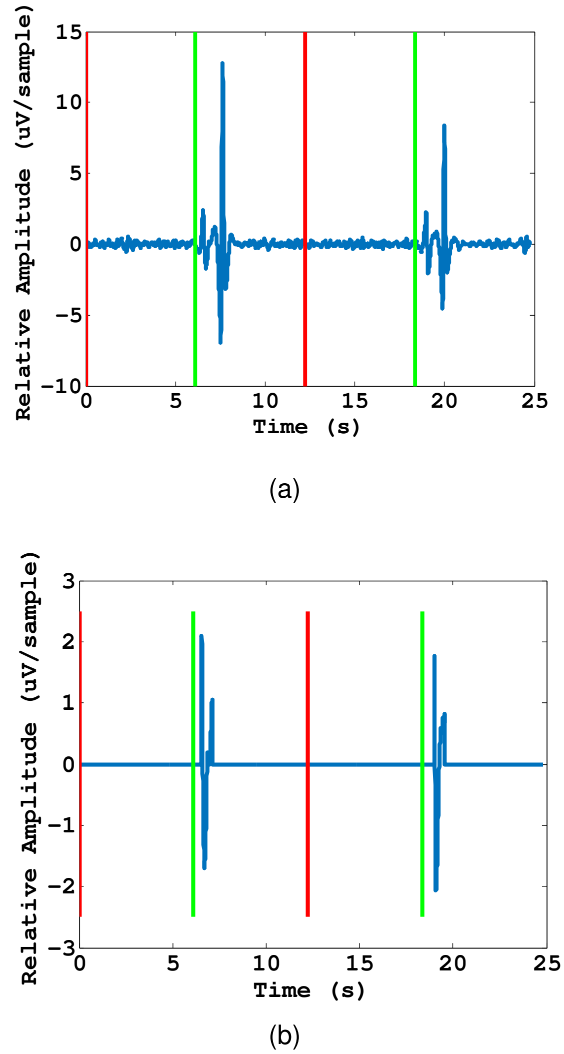

Fig. 4. Sample filtered channel 2 data (a) without any RMS thresholding, and (b) with RMS thresholding and blink artifact removal. Vertical lines represent the start of transitions; red lines are the start resting transitions, green lines are the start of active transitions with eye movements, and blue signals are eye movement responses from EOG

as the phase-shifted data, are passed into three-element buffers used to calculate the gradient of each signal. The middle point in the buffer is the current point if the gradient of the data from the first subject and the phase-shifted data from the second subject are equal in sign, their values are added in the synchronized signal. Otherwise, the signal with the largest amplitude at the current point is chosen. Concurrently, EOG from the channel 2 data of one subject were isolated using a sliding one second window, implementing RMS thresholding as above, and added to the synchronized signal using the aforementioned gradient matching method.

IV. Results

Figure 3 confirms that SSVEP activity of subjects was preserved even if they intended to send a message using EOG, as evidenced by the obvious peak in FFT magnitude within the 7–8 Hz range in the case of the Experimental state. Furthermore, there was no SSVEP activity in the case of the Control state. Thus, we concluded that messaging by EOG is a feasible method for B2B.

To recognize the EOG signal in channel 2, we implemented an isolation algorithm, as explained in the previous section. Figure 4a presents an example of EOG from one subject before isolation, and Figure 4b presents the isolated EOG. This demonstrates that the isolation algorithm was accurate enough for future use in message modulation for B2B.

After message extraction (EOG isolation) from channel 2, we modulated the isolated EOG with synchronized and non-synchronized EEG from channel 1 for comparison. Figure 5b demonstrates that a summed signal of EOG and synchronized EEG could reach higher amplitude than that in the case of the non-synchronized EEG shown in Figure 5a. Moreover, we calculated RMS voltages of summed signals from both conditions among different pairs of subjects as shown in Table I. Even though we have only three pairs of subjects in this study, preliminary analysis of RMS values for the summed signals were promising in that EOG with synchronized EEG could reach higher average RMS values than in the non-synchronized cases.

V. Discussions

In this section, we discuss the implications of this study for the development of future B2B techniques. Three main issues—brain synchronization, message modulation and future implementation—are addressed below.

The RMS results from the previous section (Table I) confirm that brain synchronization is crucial in developing a B2B system. To achieve a high signal-to-noise ratio communication channel, two brains must be synchronized in terms of both phase and frequency. Otherwise, brain potentials from two people can interfere destructively, making voltage levels across the inter-connection circuit drop below operating level. Here,

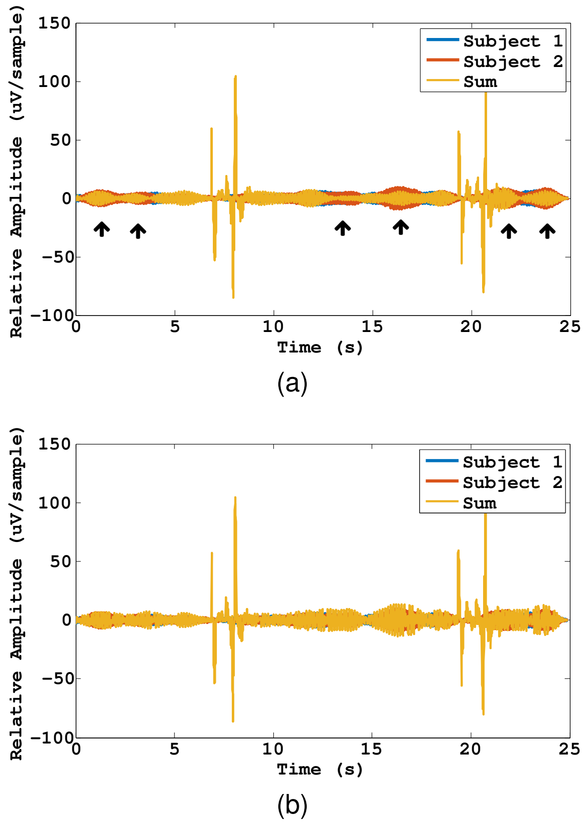

Fig. 5. (a) Sum of non-synchronized EEG from channel 1 with EOG from channel 2, and (b) sum of synchronized EEG from channel 1 with EOG from channel 2. To visualize the difference between summed signals from (a) and (b), arrows point to the positions where (b) obviously has higher amplitude than (a).

TABLE I
COMPARISON OF RMS VOLTAGES (μV) BETWEEN SYNCHRONIZED CONDITION (SYNC) AND NON-SYNCHRONIZED CONDITION (NON-SYNC) AMONG THREE PAIRS OF SUBJECTS.

Trial no.	Subject 1 & 2		Subject 1 & 3		Subject 2 & 3	
	Sync	Non-sync	Sync	Non-sync	Sync	Non-sync
1	**10.31**	9.61	**9.76**	9.63	**25.03**	25.02
2	**11.11**	10.77	**8.89**	8.84	**14.54**	14.46
3	10.97	**11.22**	**8.91**	8.82	**17.00**	16.81
4	**11.28**	9.73	**8.71**	8.69	**23.54**	23.27
5	9.56	**9.57**	**6.44**	6.09	**19.91**	19.85
Average	**10.65**	10.18	**8.54**	8.41	**20.00**	19.88

we used visual stimulus-based SSVEP to synchronize two brains. In the near future, we might investigate more options to deal with synchronization issue. Even if performing eye movements (EOG) could be one method for message modulation, we would like to investigate types of brain responses which could replace EOG. Thus, message modulation is still a challenging issue for further development. To implement our proposed B2B architecture, we still need to implement brain stimulation; tDCS will probably be first direction for our research group. In addition, we need to address electronic component design and assess safety in a real-time study.

VI. CONCLUSIONS

We propose a novel architecture for brain-to-brain communication (B2B). Here we discuss two-brain synchronization and message modulation, and the experiments conducted to demonstrate the feasibility of our proposed B2B. Finally, we discuss challenges in implementing real-time B2B that warrant further investigation. This paper can serve as a gateway to future brain-computer interface research.

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