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Brain-Computer Interface Supported Collaborative Work: Implications for Rehabilitation

C. S. Nam, J. Lee, and S. Bahn

Abstract - **Working together and collaborating in a group can provide greater benefits for people with severe motor disability. However, it is still not clear how collaboration should be supported by BCI systems. The present study explored BCI-supported collaborative work by investigating differences in performance and brain activity between when a pair of users performs a task jointly with each other and when they do alone only through means of their brain activity. We found differences in performance and brain activity between different work conditions. The results of this research should provide fundamental knowledge of BCI-supported cooperative work.**

I. INTRODUCTION

During the last decades, a new interaction technology that allows the human brain to directly communicate with the environment has emerged, called brain-computer interface (BCI). BCIs utilize a variety of invasive and noninvasive methods for acquiring brain activities including electroencephalography (EEG), magnetoencephalography (MEG), positron emission tomography (PET), functional magnetic resonance imaging (fMRI), and optical imaging [1, 2]. As a communication system that does not depend on the brain's normal output pathways of peripheral nerves and muscles [3], BCIs are known for providing alternate methods to interact with the outside world for people who cannot use their muscles but are cognitively intact. It has been known that users with and without severe motor disability can use BCI systems with accuracy levels acceptable for communication [4].

Despite these advances and a considerable amount of ongoing research, current efforts in the area of BCI research and development still have significant gaps [5, 6]. BCIs hold the promise for the restoration of communication and control ability to users with severe motor disability, but BCI research and development has not yet fully addressed the social burdens of their disabilities (i.e., interaction with other people). In effect, people with severe motor disability have had little opportunity to work jointly with other people. Doctors encourage their patients with motor disability to participate in peer groups, because active interaction with other people is important for them to reach their potential. However, few to no studies have explored integration of BCI in normal life [7, 8], especially to support interactive work such as collaboration with other people. Most existing BCIs are still single-user applications, which do not meet the needs of users with severe motor disability who want to work together. Working together and collaborating is common and natural for people in order to complete a job faster or to share expertise for a complex task [9]. It is also a way to improve the quality of work, because different team members offer different perspectives and insights. Collaboration can help to foster the sharing of knowledge, ideas, and skills, and play an important role in areas such as art, academia, business and scientific research [10, 11]. Due to the rapid advance of BCI technology and aforementioned advantages of collaborative work, we envisage that in the near future people with severe motor disability will be able to perform tasks with other people through only their brain activity. However, there has been a general lack of understanding regarding how BCIs should support collaborative work between users with severe motor disability and between users with and without severe motor disability under various task conditions; placing people in groups and assigning them a task to perform using a BCI system does not guarantee that they will engage in effective collaborative work. The main goal of this study was to explore BCI-supported collaborative work by investigating differences in performance and brain activity between when people perform a task jointly with other people and when they do alone only through means of their brain activity.

In the present study, a steady-state visual evoked potential (SSVEP)-based BCI system was used, which utilizes visually evoked potentials from the user's scalp resulting from ionic current flows within the neurons of the brain [12]. When a user looks at a source blinking at a fixed frequency, brain signals of the same frequency are produced (i.e., evoked by the visual stimulus). The brain will also produce corresponding harmonic and sub harmonic frequencies of the stimuli frequency [13]. A user of a SSVEP BCI system needs only to look at a blinking source, typically a light or other stimuli, to elicit a choice response or selection. SSVEP BCI systems are being used increasingly because of their ability to provide a high information transfer rate (ITR) while requiring little to no training [14] and to provide individuals with physical or speech disabilities the opportunity to communicate and interact [15].

The remainder of the paper is organized as follows. Section 2 explains the experimental protocol, experiment, and subjects. Section 3 presents the summary of the results obtained. Finally we conclude with some preliminary remarks on future research and implications for rehabilitation.

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II. METHOD

A. Participants

Four right-handed healthy subjects (mean age: 29.7±1.8; 3 males and 1females) participated in the study. All subjects had normal or corrected-to-normal vision with no prior experience related to SSVEP-based BCIs. Subjects were not given any financial reward for their participation.

B. Data Acquisition and Processing

The EEG data was recorded by using an EEG cap (g.tec Medical Engineering) embedded with 16 electrodes covering frontal, parietal, central, and occipital areas of the brain, according to the extended International 10-20 system. Signals were amplified with a g.USBamp (g.tec Medical Engineering) amplifier. Data collection and signal processing were all conducted in LabVIEW.

The EEG signals were digitized at a sampling rate of 512 Hz, high-pass filtered at 5 Hz, low-pass filtered at 50 Hz, and notch-pass filtered at 60 Hz. Fpz and right ear lobe were used as ground and reference, respectively. A harmonic sum decision (HSD) method was employed to determine the user's SSVEP responses, using signals from two channels, O1 and O2 with the target frequencies of 6, 7, 8, 9, 11Hz. First, feature vectors have been normalized as follows:

$$f_{ijk}(N) = \frac{f'_{ijk}}{\sum_{j=1}^{5} f'_{ijk}}$$

where f'_{ijk} and $f_{ijk}(N)$ are the baseline corrected power spectrum and normalized k^{th} harmonic (k=1-3) respectively at j^{th} frequency (j=1-5) from i^{th} channel (i=1-2). Then, a class was detected by determining the maximum of the harmonic sums:

$$class = arg \max_{j}(\overline{f_1}, \overline{f_2}, \overline{f_3}, \overline{f_4}, \overline{f_5})^{\mathrm{T}}$$

where $\overline{f_j}$ is the averaged EEG at j^{th} frequency.

C. Experimental Design and Data Analysis

The type of collaborative work (co-work) was manipulated as a within-subject independent variable: (a) individual work where participants perform a task alone and (b) turn-based co-work with self-error correction where a pair of users takes turns to perform a task and any error is corrected by the person who made. This study employed several dependent measures, which can be categorized into two types of variables: (a) task performance (the number of error and task completion time) and (b) brain activity (power spectrum).

Brain signals were also analyzed using the Short-Time Fourier Transform (STFT) method to identify signals' time-varying frequency nature. The basics idea of the STFT is to compare the signal with elementary functions that are localized in time and frequency domains simultaneously, i.e.,

$$X(\tau,\omega) = \int_{-\infty}^{\infty} x(t)\omega(t-\tau)e^{-j\omega t}dt$$

where ω(t) is a window (e.g., Hamming) function, and x(t) is the signal to be transformed.

D. System overview and Procedure

We built a collaborative BCI (C-BCI) for control, *Brainbot*, which enables a pair of users, including those with severe motor disability, to jointly perform a physical control task (e.g., moving an object) with each other (see Fig. 1). *BrainBot* consists of a robot arm, three target locations, twelve LEDs and a ball. Participants were asked to grab (G, 6Hz) a ball, move and release (R, 9Hz) it to one of the three target locations (station 1, 8Hz; station 2, 11Hz; station 3, 7Hz) alone or together with their partner while focusing on corresponding LEDs to perform the desired motion.

Brainbot, communicating with the computer via the Bluetooth medium, is a robotic arm constructed using the LEGO Mindstorms NXT kit. The kit consists of a NXT brick, a programmable 32-bit microcontroller that allows the robot to operate, three Servo Motors which give the robot the ability to move, and four sensors which provide the robot with inputs from its environment. Using *Brainbot*, a pair of users can perform six basic control movements (Left/Right, Up/Down, Grab/Release) using their SSVEP responses elicited while looking at LEDs attached to the body of *Brainbot*.

Figure 1. A screenshot of the experimental set-up.

To elicit SSVEP responses from the users in a physical environment, we also developed cost effective light emitting diodes (LEDs) as a light stimulus (Fig. 1). LEDs are highly customizable and capable of adjusting to change very rapidly (e.g., LEDs can be easily replaced or changed out for different colors or frequencies via a programmable Micro Control Unit), making them more suitable and preferred for our SSVEP studies.

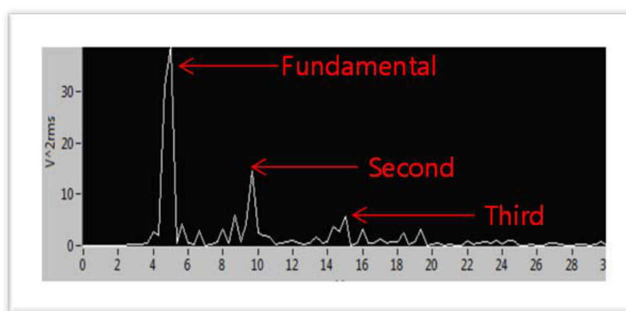

Figure 2. Harmonics of SSVEP responses

A high-intensity LED, lasting up to 36 hours with one 3-volt battery, was used in order to make the light identifiable even in brightly lit environments. Our previous study investigated users' SSVEP responses elicited by three different colors (green, red, and blue) of the LEDs flickering at low (10 Hz), medium (28 Hz), and high (42 Hz) frequencies (Pankok et al., 2013). Our results showed that the developed LEDs elicited SSVEP responses at the target stimulus frequency and its harmonic frequencies.

III. RESULTS AND DISCUSSION

A. *Task Performance: Individual vs. Co-Work*

Task Completion Time: Figure 3 shows averaged task completion time when subjects performed the tasks alone and together with their partner. When a pair of subjects were collaborating with each other, it took them longer time to finish the tasks than when the tasks were performed by subjects alone, except for the grab task.

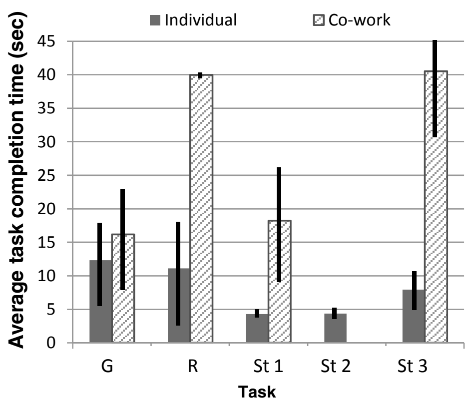

Figure 3. Averaged task completion time by individual work and collaborative work (G: Grab, R: Release, St1: Station 1, St2: Station 2, St3: Station 3)

The Number of Error: Figure 4 shows the average number of error made by subjects when performing each task. Collaborative work caused subjects to make more errors than individual work, except for the grab task.

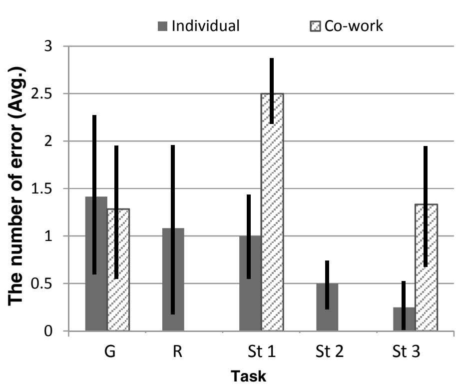

Figure 4. Averaged number of error made by individual work and collaborative work (G: Grab, R: Release, St1: Station 1, St2: Station 2, St3: Station 3)

B. *Brain Activity: Individual vs. Co-Work*

Maximum Power Spectrum: Overall, individual BCI work showed higher power spectrum values for the most of tasks than BCI supported collaborative work (Figure 5).

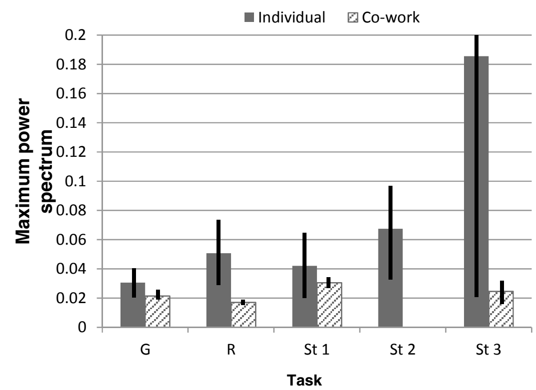

Figure 5. Maximum popwer spectrum by individual work and collaborative work (G: Grab, R: Release, St1: Station 1, St2: Station 2, St3: Station 3)

Short-Time Fourier Transform (STFT) Analysis: To investigate how the various frequency components of a brain signal evolve with time, the STFT method was used.

Fig. 6 illustrates the magnitude of the STFT, called the spectrogram, of a subject who successfully completed (Fig. 6a) and did not complete the task (Fig. 6b), respectively. In Fig. 6a, Red ellipses indicate valid detections of the target frequencies corresponding to the task activities. The Grab task was determined mainly by the second (12 Hz) and third harmonics (18Hz) of the assigned fundamental (i.e., 6 Hz) frequency, while other tasks were determined largely by their fundamental frequencies.

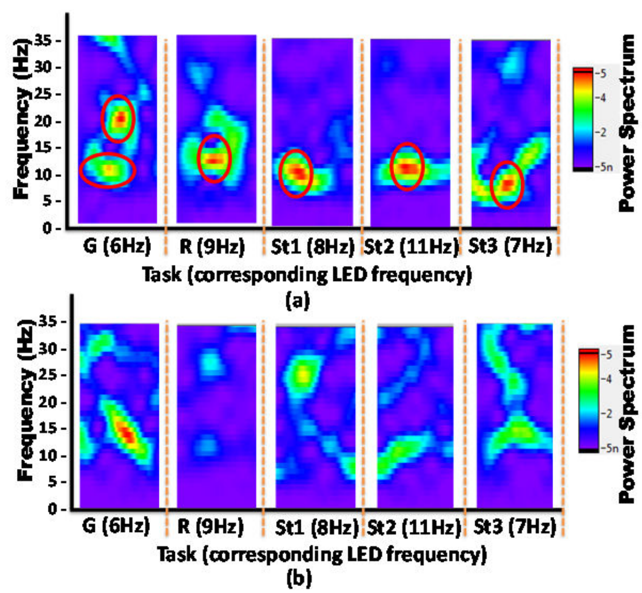

Figure 6. Spectogram of BCI-supported individual work: Short-time Fourier analysis of (a) a subject who successfully completed the whole task and (b) a subject who did not complete the task (Valid detections marked by red ellipses).

Fig. 7 demonstrates the magnitude of the STFT of teams that performed the task together, which showed different brain activity patterns between the two teams in terms of signal harmonics mainly used to determine the user's SSVEP responses

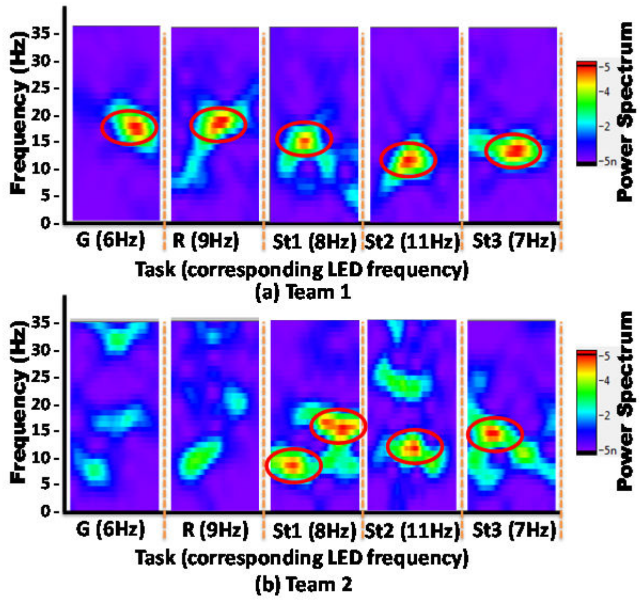

Figure 7. Spectogram of BCI-supported collaborative work: Short-time Fourier analysis of (a) team 1 and (b) team 2 that performed the task (Valid detections marked by red ellipses).

IV. CONCLUSION

To explore BCI-supported collaborative work, this study investigated differences in performance and brain activity between when people perform a task jointly with other people and when they do alone only through means of their brain activity.

Through the preliminary analysis of the data collected, we found differences in performance and brain activity between different collaborative work conditions. Working together and collaborating in a group can provide greater benefits for people with severe motor disability. However, little attention has been paid to research questions regarding BCI-supported collaborative work. This research may be of great significance due to its potential to yield fundamental knowledge of BCI-supported cooperative work, understanding of the support needed for interaction in BCI technology supported group activities, and design considerations for collaborative BCIs.

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