A Collaborative Brain-Computer Interface (BCI) for ALS Patients

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This study evaluated a SSVEP-based collaborative brain-computer interface (BCI) for people with severe motor disabilities. With ten ALS (amyotrophic lateral sclerosis) patients and 10 age-matched able-bodied participants as control group, effects of collaboration and motor disability were investigated. Participants were requested to control a robot in a predefined path with their brain signals. Two collaboration modes were developed in the study: individual mode and simultaneous mode. Results revealed significantly better performance in simultaneous mode than individual mode, but no significant effect of motor disability. The study showed promising preliminary results for supporting collaborative work between BCI users with severe motor disabilities. It should provide great insights for future research and system development.

INTRODUCTION

SSVEP-based BCI is one example of non-invasive BCI systems using steady-state visual evoked potentials (SSVEPs) as a control signal. Because no initial training is required, it provides great advantages over most other BCI systems. The SSVEP based-BCI can also provide the fastest and most reliable communication as a non-invasive BCI. However, BCI research and development is still in its infancy and there are many challenges to overcome (Lebedev & Nicolelis, 2006). First, people with severe motor disabilities have not been thoroughly investigated. In its current stage, most research employs able-bodied participants, who are not true users of SSVEP-based BCIs. Second, most BCI studies are single-user focused and have not explored the integration of BCI with normal life, especially to support interactive work such as collaboration with other people. Collaborative BCIs may bring greater benefits to those with severe motor disabilities (Poli, Cinel, Matran-Fernandez, Sepulveda, & Stoica, 2013), but little emphasis has been given to the value of BCI-supported collaborative work.

Collaboration can lead to faster task completion, improved work quality, and shared insight, perspective, and expertise especially for a complex task (Heer, van Ham, Carpendale, Weaver, & Isenberg, 2008). Research has also indicated that group decisions tend to be superior to individual decisions in many different aspects (Kerr & Tindale, 2004). Collaborative brain-computer interface (C-BCI) is defined in this study as a non-invasive EEG-based BCI that supports collaboration in which, by working in a group of two, users can help each other and perform tasks jointly. Depending on the collaboration mode, users may take turns or work simultaneously to perform tasks at their own pace. Compared to individual BCIs, collaborative BCI system design and evaluation is more complex and requires multiple components to be integrated. Challenges exist in locating and recruiting multiple users with severe motor disabilities to evaluate collaborative BCIs. Most recently, researchers began to notice the advantage of collaborative BCI and argued that collaborative BCI should be investigated to better serve people with severe motor disabilities. For example, research showed that it is time to move into the collaborative BCIs, in which multiple users are connected to a BCI and help each other in carrying out a task (Poli, 2013). Initial research has also been conducted showing the possibility and potential to develop collaborative BCI. For example, research by Poli, Cinel, Sepulveda, & Stoica (2013) showed that collaborative BCIs can produce better task performance than single-user BCIs in a visual matching task. In another research, Poli, Cinel, Matran-Fernandez, Sepulveda, & Stoica (2013) investigated the collaborative BCI in space navigation task and found that collaborative BCIs produced significantly superior trajectories than single user BCI in a space navigation task.

The objective of this study was to investigate the user performance and brain activity of people with severe motor disabilities (e.g., ALS, stroke, spinal cord injury, etc.) using a SSVEP-based C-BCI, as a test bed.

METHOD

Participants

Ten ALS participants were recruited from the ALS association and local community. ALS is a severe neurodegenerative disease that leads to paralysis and eventually death within 2-5 years (Kunst, 2004). ALS patients are cognitively intact in spite of the inability to communicate by traditional means (Hanagasi, et al., 2002). Five male and five female with motor disabilities participated, with mean (M) age of 56.4 years old (Standard Deviation, SD = 9.5). The time elapsed since diagnosis of ALS varied from half a year to five years. The ALS functional rating scale varied from 2 to 45. Ten age-matched able-bodied participants were also recruited (M = 52.5; D = 6.3). Potential participants were required to complete a screening test to make sure that they are older than 18 years old and have not suffered from seizures and epilepsy. All participants were compensated by cash and provided with printed informed consent form. The study was approved by the IRB at North Carolina State University.

Apparatus

The WolfPack BCI system developed at BCI Lab at North Carolina State University was used to acquire and process brain signals (Fig. 1). The main hardware includes the Lego® NXT® robot, an amplifier (g.tec Medical Engineering), a g.GAMMAbox (g.tec Medical Engineering), LED lights (Fig. 2), EEG caps and electrodes.

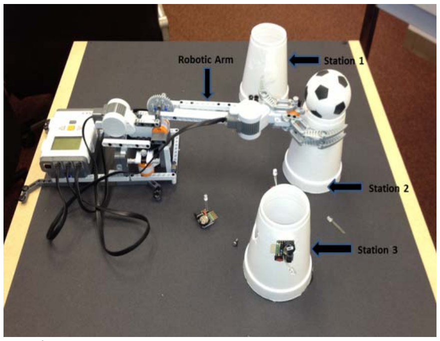

Figure 1: SSVEP-based robot control system

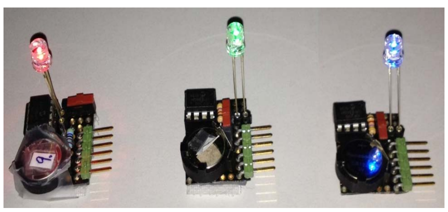

Figure 2: LED lights examples (from left to right: red, green and blue)

Independent Variables

There were two independent variables: collaboration mode and motor disability.

Collaboration Mode. There were two levels: individual mode and simultaneous mode. In the individual mode, participant performed the task alone. When an incorrect movement was made, the participant must correct it before moving next in the predetermined path. In the simultaneous mode, a pair of participants performed the task together at the same time. Each participant's brain signal was processed separately at first. If either one chose the correct command, then command was sent to the robot. If both participants made an incorrect movement, they had to correct the movement before moving on to the next step in the predetermined path.

Disability. Participants were classified into two groups, ALS group and control group based on their motor disabilities. Each group was randomly split into 5 pairs.

Dependent Variables

There were four dependent variables: accuracy, completion time, information transfer rate (ITR), and spectral power.

Accuracy (%). It was the ratio of the correct moves over the total number of successful moves. Successful moves were the moves that are successfully carried by the NXT robot. In other words, any visual stimulus which has been chosen three times in a sequence could produce a successful move. However, only the successful moves following the predefined path were considered as correct moves. For example, if the predefined path was G→St3→R and the participants had four successful moves G→St2→St3→R, then the accuracy would be 75% (3/4).

Completion Time (seconds). It measures the time duration needed to perform one trial of task.

Information Transfer Rate (ITR) (bits/min). It can be calculated by two steps. At first, the number of bits transferred per trial (B) should be calculated. Then, ITR can be obtained by dividing B by the duration of the trial. The following formula, defined by Pierce (Pierce, 1980), was used to calculate the number of bits transmitted per trial:

$$B = [\mathrm{Log}_2 N + A\,\mathrm{Log}_2 A + (1 - A)\,\mathrm{Log}_2 (\frac{1 - A}{N - 1})]$$

$$ITR = B/T$$

where N is the number of possible targets, and A is the probability that the target was accurately classified (*accuracy*).

Spectral Power (mv^2). Power was defined as:

$$P = \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{T} x(t)^2 dt$$

where x(t) is the amplitude of the EEG signal, T is the duration of one cycle.

Data Acquisition and Signal Processing

SSVEP brain waves were recorded using an EEG cap (Electro-Cap International, Inc.) embedded with 16 channels (Fz, C3, Cz, C4, CPz, P7, P3, Pz, P4, P8, PO3, POz, PO4, O1, Oz, and O2) based on the modified 10-20 system of the International Federation (Sharbrough, et al., 1991). Recordings were referenced to the left mastoid and grounded to location AFz. SSVEP brain waves were amplified with a g.USBamp amplifier (g.tec Medical Engineering).

EEG raw data was sampled with a rate of 512 Hz. It was filtered by a 0.1 Hz high pass filter and a 75 Hz low pass filter, notch filtered by 60 Hz. Then, the acquired time domain EEG data was transformed into frequency domain to get SSVEP response in the power spectrum by FFT. Next, the EEG data in frequency domain was adjusted by the baseline. After normalization and averaging, the data were sent to a classifier. Finally, the frequency with the maximum average spectral power would be chosen. Any frequency chosen three times in a row would be sent to the robot.

Experiment Design

Participants performed a task consisting of six sequences either by themselves (individual mode) or together with the teammate (simultaneous mode): G→St3→R→G→St1→R. They were asked to grab (G) a rubber ball in the neutral position (St2), then move to the third position (St3) and release (R) the ball, then grab (G) the ball and move to the first position (St1), then release (R) the ball. For each movement, participant needs only focus on the corresponding visual stimulus. To determine accuracy, however, only the successful moves following the predefined path were considered as correct moves. Fig. 3 showed one example of simultaneous mode, in which two participants performed together to control the robot movement.

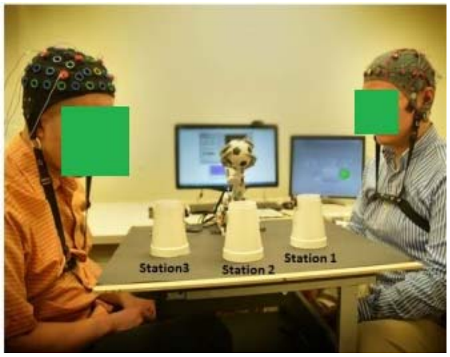

Figure 3: Experimental task (simultaneous mode)

Four user-specific stimulus configurations were used for each participant. They were randomly assigned to the four commands and were set up in front of the participant apart from each other to prevent the interference. There were 2 conditions with 2 trials in each condition. The 4 trials were completely randomized in order to reduce any trial order effect. In sum, it is a balanced 2 x 2 mixed design.

Experiment Procedure

All experiments were conducted in a quiet, dimly lit room. Participants were provided with a comfortable chair and required to avoid gross body movement. Upon coming, they were instructed about the basic procedure of the experiment and how to respond to the visual stimuli after they finish the demographic questionnaire and the informed consent form. They were instructed not to focus on accuracy or speed. The experiment took about 1 hour with a 3 minutes break between each trial. The participants were compensated by cash and debriefed with the help of the experimenters.

RESULTS

ANOVA was conducted to analyze the performance data. Table 1 summarized the significance effect for performance measures:

Table 1: Significant effect for performance measures

Dependent Variables	Effect	F-Value	p-Value
Accuracy	Collaboration Mode	51.12	< .0001
Completion Time	Collaboration Mode	77.66	< .0001
ITR	Collaboration Mode	42.59	0.0002
Spectral Power	Collaboration Mode	10.75	0.0112

Accuracy

The analysis revealed a significant main effect of collaboration mode ($F_{1,\ 8}$ = 51.12, p < 0.0001) (Fig. 4). Accuracy in the simultaneous mode (M = 0.841, SD = 0.128) was significantly higher than that in the individual mode (M = 0.644, SD = 0.112). However, no significant effect of motor disability ($F_{1,\ 8}$ = 0.03, p = 0.8680), or interaction effect ($F_{1,\ 8}$ = 0.60, p = 0.4603) was found. Average accuracy for able-bodied participants and ALS patients was 74.6% (SD = 15.5%) and 73.9% (SD = 15.9%), respectively.

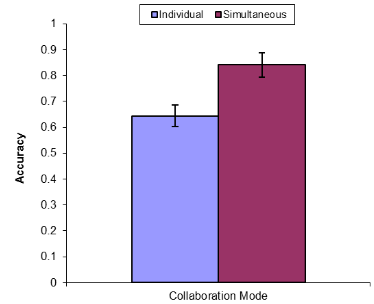

Figure 4: Main effect of collaboration mode on accuracy

Completion Time

The analysis revealed a significant main effect of collaboration mode ($F_{1,\ 8}$ = 77.66, p < 0.0001) (Fig. 5). Completion time in simultaneous mode (M = 33.7, SD = 10.3) was significantly shorter than that in individual mode (M = 53.4, SD = 11.5). However, no significant effect of motor disability ($F_{1,\ 8}$ = 2.08, p = 0.1868), or interaction effect ($F_{1,\ 8}$ = 0.84, p = 0.3856) was found.

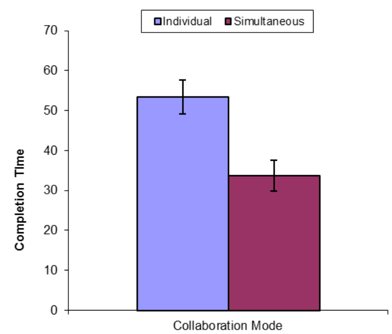

Figure 5: Main effect of collaboration mode on completion time

Information Transfer Rate (ITR)

Result revealed a significant main effect of collaboration mode ($F_{1,\ 8}$ = 42.59, p = 0.0002) (Fig. 6). ITR in simultaneous mode (M = 2.54, SD = 1.78) was significantly bigger than that in individual mode (M = 0.69, SD = 0.51). However, no significant effect of motor disability ($F_{1,\ 8}$ = 1.13, p = 0.3180), or interaction effect ($F_{1,\ 8}$ = 0.79, p = 0.3997) was found.

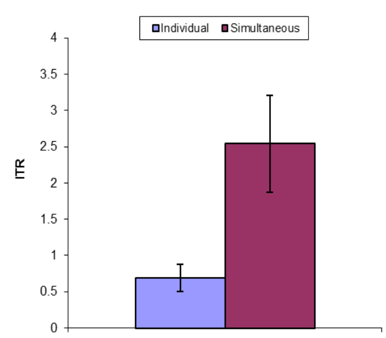

Figure 6: Main effect of collaboration mode on ITR

Spectral Power

The analysis revealed a significant main effect of collaboration mode ($F_{1,\,8}$ = 10.75, p = 0.0112) (Fig. 7). Spectral power in the simultaneous mode (*M* = 0.95, *SD* = 0.26) was significantly bigger than that in the individual mode (*M* = 0.75, *SD* = 0.261). However, no significant effect of motor disability ($F_{1,\,8}$ = 0.27, p = 0.6166), or interaction effects ($F_{1,\,8}$ = 0.70, p = 0.4273) was found.

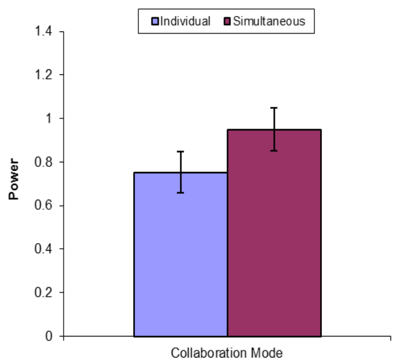

Figure 7: Main effect of collaboration mode on spectral power

DISCUSSION

Effect of Collaboration Mode

Results showed that collaboration mode had a significant effect on both task performance and brain activity. Accuracy, ITR and spectral power in simultaneous mode were significantly higher (bigger) than that in individual mode. Completion time was significantly shorter in simultaneous mode than in individual mode. In sum, participants had significantly better performance and a stronger brain activity in the simultaneous mode than the individual mode. These results are consistent with those of the previous research. Poli et al. (2013) found that collaborative BCIs produced significantly superior trajectories than single user BCIs in space navigation tasks. In another research, Poli and Cinel (2013) showed that collaborative BCIs can produce better task performance than single-user BCIs in visual matching tasks. Eckstein et al. (2012) found that collaborative BCIs took less time in decision making process. Wang & Jung (2011) found that collaborative BCIs can produce higher classification accuracy than single users in a task of movement planning.

The results proved the advantage of simultaneous mode than individual mode. Simultaneous mode in which participants cooperated together to accomplish one task was more efficient because of the error cancellation property of team work. For example, in individual mode, the individual user had to make each movement alone and correct errors alone. In simultaneous mode, however, correct movement could be made if chosen by either participant. Meanwhile, the error could be corrected by either user. This mechanism greatly improved the accuracy as well as ITR and reduced the task completion time.

It is possible that social facilitation enhanced brain activity in simultaneous mode tasks compared to individual mode tasks (Aiello & Douthitt, 2001; Zajonc, 1965; Zajonc, 1980). Likewise, social facilitation could also contribute to greater task performance in simultaneous mode compared to individual mode. The presence of a teammate could make each participant have higher arousal level and enhanced focus to the visual stimulus (Aiello and Douthitt, 2001; Zajonc, 1980), which in turn helped to produce stronger brain activity and greater task performance.

As most researchers agreed, group decisions tend to be superior to individual decisions in many different aspects (Davis, 1973; Kerr, MacCoun, & Kramer, 1996; Kerr & Tindale, 2004; Laughlin, Bonner, & Miner, 2002). Meanwhile, the presence of the teammate could also elevate the performance of the other team member (Aiello & Douthitt, 2001). The result proves that the collaborative BCI is workable and more efficient than individual mode. It indicates the feasibility of developing more collaborative applications for those with motor disabilities in order to improve their quality of life. The result also proves the possibility of interactions between two people with severe motor disabilities. More applications should be developed to provide interactive environment and improve their life qualities.

Effect of Motor Disability

The analysis didn't find any significant effects of motor disability on the task performance and brain activity, or the interaction effect between motor disability and collaboration mode. In other words, ALS participants exhibited comparable task performance to the able-bodied participants in both individual mode and simultaneous mode.

This result is different from the previous study (Li, Nam, Shadden, & Johnson, 2011; Li, Bahn, Nam, & Lee, 2014; Volosyak, Cecotti, Valbuena, & Gräser, 2009), in which able-bodied participants had significantly better performance than those with motor disabilities. Li et al. (2011) thought that participants with motor disability become easily fatigued in shorter duration of focus, which affected their performance. They also found that participants with motor disabilities were unable to avoid head or eye movement, which could produce artifacts, disturb classification and harm performance. However, the "fatigue" was not observed in this study. No ALS participants requested extra rest during the experiment, even though a break could be requested at any time. Meanwhile, the "head or eye movement" was not observed, either.

The results of this study are very promising in that ALS patients could use BCIs as efficient as the able-bodied, which proved the potential of C-BCI to support those with severe motor disabilities.

RESEARCH LIMITATIONS

It should be realized that some limitations exist in this research that warrant further study. At first, the experimental task in this study is relatively simple. With only six robotic movements to select, most tasks could be finished in less than 1 minute, which dramatically reduced the potential for fatigue. A more complex task would require more time and increase the chances of fatigue. Future research with varying degrees of task complexity may shed light on whether a complexity threshold exists for either user group.

Second, this research employed only four visual stimuli corresponding to four robot control commands. As the number of visual stimuli increases, their layout can become a concern. For the late-phase ALS users, this problem is absolutely critical as such user's field of view may drift or wander uncontrollably. Further research should be conducted with increased number of visual stimuli to determine the optimal layout.

CONCLUSIONS

This study evaluated a SSVEP-based collaborative brain-computer interface (C-BCI) for people with severe motor disabilities. With 10 ALS participants and 10 able-bodied participants, the effects of collaboration mode and motor disability were investigated. Results revealed significant effects of collaboration mode and showed promising early results for supporting collaborative work between BCI users with severe motor disabilities. More effort is needed to develop collaborative applications and improve the usability of the system.

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