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Simultaneous Brain-Computer Interfacing and Motor Control: Expanding the Reach of Non-Invasive BCIs

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Abstract— **Brain-computer interfaces (BCIs) have traditionally been developed for paralyzed and locked-in individuals with no motor control. However, there is a much larger population of patients with some residual motor function as well as the general population of able-bodied individuals, both of whom could benefit significantly from BCIs. An important question that has yet to be systematically studied is: can subjects use BCIs simultaneously with overt motor activity? We present results from a preliminary study aimed at exploring this question. Three subjects used hand motor imagery in an electroencephalographic (EEG) BCI while simultaneously using a joystick to control a cursor. Particular attention was paid to preventing potential muscle artifacts from influencing imagery-based control. All three subjects were able to use the hybrid "imagery+joystick" mode of control over two days, demonstrating the ability to learn and significantly improve performance. These results suggest that subjects can potentially augment their normal human sensorimotor capability by exercising direct brain control over devices concurrently with overt motor control.**

I. INTRODUCTION

There has been considerable interest in brain-computer interfaces (BCIs) in recent years. BCIs allow direct control of devices using brain signals without any overt motor activity. Much of BCI research has focused on developing assistive devices for patients with severe neuromuscular disorders, such as amyotrophic lateral sclerosis (ALS), brainstem stroke, and spinal cord injury, which result in loss of motor control [1]. Example applications include the autonomous control of a wheelchair [2] and a communication device for locked-in patients [3].

There is however a much larger population of patients and able-bodied individuals with some or all of their motor capabilities intact. Can these individuals use BCI simultaneously with other types of overt motor activity? Successful combination of BCI and manual control could push development of new user interfaces. One particularly challenging case involves using sensorimotor rhythm BCIs such as motor imagery and manual hand control, as there is significant overlap in the brain regions used. There is anecdotal evidence from BCI-based gaming studies supporting the possibility, but the question of overlap between BCI and overt motor activity has not yet been systematically studied. We take the first steps in this direction by reporting results from a preliminary study that combines motor imagery BCI with joystick control.

We use an electroencephalographic (EEG) BCI in our study. EEG non-invasively records brain signals from the scalp, and has advantages such as portability and cost effectiveness, though it suffers from a poor signal-to-noise ratio [1]. EEG is also susceptible to muscle artifacts when users produce eye movements or other types of overt movements [4]. Since our study explicitly aims to combine manual control with BCI, muscle artifacts become an important issue in contaminating EEG. We use electromyography (EMG) to ensure that muscle artifacts are not a major factor in the brain-control component of our experiments.

We report results from three subjects who learned to use right-hand motor imagery to control the vertical movement of a cursor while simultaneously using a joystick with their left hand to control the horizontal movement of the cursor. All three subjects exhibited the ability to hit one of four possible corner targets on the screen.

II. METHODS

A. Study Subjects

Three male graduate students who were right-handed and had prior experience in motor-imagery BCI volunteered to participate in our study. All subjects gave informed consent using study protocols approved by the University of Washington IRB.

B. Data Collection

Data was collected using g.USBamp (Guger Technologies) at a sampling rate of 1200Hz. A 13-electrode montage was chosen such that a Laplacian derivation could be obtained over motor areas centered at C3, Cz, and C4 electrode positions based on the international 10-20 system for EEG (distance between electrodes center was $\sim$3.5cm). One additional electrode was used for ground and reference, placed at location AFz. All electrode impedances were measured and monitored to be within an acceptable range throughout the data collection sessions. We also placed three EMG electrodes on the right hand and forearm along the wrist extensor to monitor whether any right hand movement was being performed (as measured by EMG) during right hand imagery. EEG data was notch filtered between 58-62 Hz to eliminate line noise artifacts. Online right-hand imagery control was based on EEG data from the Laplacian derived C3 channel in our experiments, though other locations could also potentially be used.

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C. Subject Training and System Configuration

Prior to the actual experiment, subjects underwent a training phase to verify that they were capable of performing motor imagery and to configure the BCI system's parameters. The training phase used a visual cue-based paradigm with no feedback. For each subject, data was collected for 20 trials of right-hand motor imagery (herein referred to as imagery or MI) and 20 trials of rest (i.e., no MI). Subjects were instructed to sit comfortably and to refrain from overt movement. For imagery trials, subjects were instructed to imagine moving their right hand, with imagery of fist clenching given as an example. For rest trials, subjects were instructed to relax and pay special care to refrain from blinking or making jaw/body movements.

This data was analyzed using the BCI2000 r^2 and frequency spectrum [5] functions to select 2 or 3 candidate frequency bands that correlate the best with the imagery task. The classification feature used was estimated band power, obtained with a band-pass filter and moving average of 0.5 seconds. Using the estimated power for imagery and rest classes for each of the candidate frequency bands, we selected the frequency band with the best discriminability (based on mean and variance), and set a threshold function for classification. This relatively simple system configuration was chosen to avoid the effects of changing and re-training the classification system, and was sufficient for binary classification of imagery/rest classes for all three subjects.

In the final step of the training phase, users performed online motor imagery with feedback. A right-justified box (RJB) paradigm was used; the cursor started at the left edge, moving rightward at a constant rate over the trial length until it reached the right edge. There were two targets, a bottom (rest) target and a top (imagery) target, that completely spanned the right edge such that on any given trial the random chance level of a hit was 50%. This online feedback paradigm is similar to the two-target task in [6]. The subject controlled the up and down motion of the cursor in the following manner: every 50 ms, the binary threshold-based classifier decided whether the recorded EEG signal was in the imagery class or the rest class. The cursor moved up by a fixed amount when imagery was detected, and moved down by the same amount when the rest class was detected.

One online feedback block contained 5 imagery and 5 rest trials (randomly interleaved). Each trial consisted of the following sequence of events. First, an auditory cue (a beep) is presented to the subject along with the visual target. Two seconds later, the trial begins, giving the subject six seconds to control the up/down motion of the cursor to the designated target region. The rightward movement was set such that it took six seconds for the cursor to reach the right edge. At the end of six seconds, the trial ended, followed by a 3 second break before the next trial. Subject continued to perform online feedback blocks until they could hit 18/20 targets consecutively.

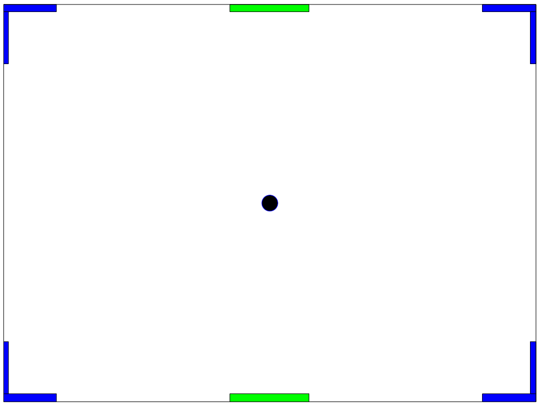

Fig. 1. **Simultaneous Brain- and Manual-Control Task.** The cursor (black ball) is shown in the center (the starting location) along with all possible targets. During BCI-only blocks, only the top and bottom (green) targets were shown. During the simultaneous BCI + manual control blocks, only the corner (blue) targets were shown. For any given trial, only one target is active. Activating motor imagery moves the cursor up, resting (no motor imagery) moves the cursor down. Left and right cursor movement is controlled using a joystick.

D. Experiments and Simultaneous BCI-Manual Task

Our experimental procedure consisted of two sessions over two days, each session lasting 1.5 hours (including electrode setup). For all experiments, the parameters from the online feedback training phase (threshold classifier and mapping to cursor movement) were maintained for each subject.

On each day, subjects ran 6 blocks of BCI-only (motor imagery/rest) and 9 blocks of simultaneous BCI + manual control (using a joystick). The task setup seen in Fig. 1 was used for both types of blocks, but different targets were shown (top/down for BCI-only, corners for simultaneous task). The sequence of events was the same as the online feedback training, except that the target could be hit before the 6-second trial duration ended. In this case, cursor movement stopped until the 6-second duration expired, and subjects were instructed to continue with imagery or rest depending on the condition.

In the BCI-only blocks, movement of the cursor was constrained to be along the vertical axis. Each block contained 5 imagery trials and 5 rest trials, resulting in 30 trials per class over one day.

For the simultaneous BCI + manual control blocks, the horizontal movement of the cursor was mapped to the left and right movement of a joystick, controlled by the subject's left hand. Horizontal movement was again by a constant amount (no acceleration). Each block contained 3 trials each of the following different cases: right motor imagery + joystick left, right motor imagery + joystick right, rest + joystick left, rest + joystick right. For data analysis, we pooled the joystick left and right such that there were two conditions: right motor imagery + joystick and rest + joystick. The 9 blocks yielded 6 trials for each condition, resulting in 60 trials per class over one day.

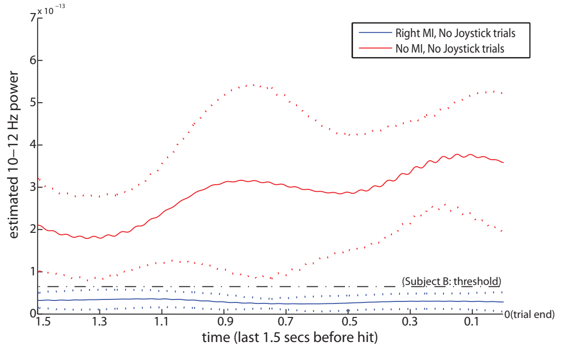

Fig. 2. **Comparison of EEG Band Power for MI versus no MI.** The red and blue solid lines indicate trial averaged power in 10-12 Hz; dotted lines indicates one standard deviation. The black dash-dot line shows the threshold chosen for classification.

III. RESULTS

The feature selected for all three subjects was the 10-12 Hz band, since all subjects showed robust and consistent difference between imagery and rest classes in this band. This feature is validated by previous BCI work from the Wadsworth group [7]. Though the band is maintained, the threshold function for each subject was different and individually determined during the initial training phase. An example of the threshold is shown for Subject B in Fig. 2.

Table I shows the performance of the three subjects in the two-day experiment. Most notable is the difference in the simultaneous motor imagery BCI (MI) + joystick condition from the first day to the second. For subjects B and C, their first day was heavily biased toward the top targets ("MI + joystick" in Table I), indicating active interference from ipsilateral motor control of the joystick. However, on the second day, subjects appear to have learned to overcome this interference from joystick control, balancing the top versus bottom target hits and exhibiting a much higher degree of purposeful control.

TABLE I

Subject Performance

Subject/Day	MI Only		MI + Joystick	
	Top Hits	Bottom Hits	Top Hits	Bottom Hits
A (day 1)	9/30 (30%)	23/30 (76%)	36/54 (67%)	21/54 (39%)
A (day 2)	12/30 (40%)	16/30 (53%)	33/54 (61%)	28/54 (51%)
B (day 1)	24/30 (80%)	18/30 (60%)	50/54 (92%)	2/54 (3%)
B (day 2)	18/40 (45%)	32/40 (80%)	37/60 (61%)	42/60 (70%)
C (day 1)	15/30 (50%)	16/30 (53%)	49/54 (90%)	1/54 (2%)
C (day 2)	17/30 (57%)	27/30 (90%)	27/54 (50%)	23/54 (42%)

It is important to note that although performance appears to be low, especially compared to the initial RJB screening task, the limited successes do demonstrate subject-specific control. Neither the up/down nor four corners task is a selection task, in which the chance outcome of a trial would follow the uniform probability distribution of 50% for up/down or 25% for corners. In our cursor movement task, a subject had a possible 140 movement steps (including along diagonals), with 62 consecutive steps from the origin necessary to hit either the up or down target. Assuming arbitrary random walk, the likelihood of hitting either the up or down target in the time allotted (6 secs) is low. To ensure consistent movement and a successful hit, a subject must maintain their signal for at least three seconds (62*50ms). Since the chance of hit in this case is less than 0.005%, any hit requires concentrated effort on the part of the subject.

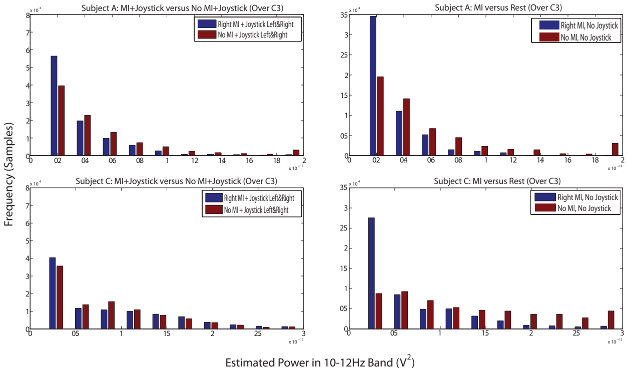

Fig. 3. **Distribution of EEG Power for Simultaneous BCI+Manual and BCI-only Tasks.** Histograms of 10-12 Hz power estimates for subjects A & C over location C3 on day 2 during the last 1.5 seconds prior to target hit or miss. Top row: Subject A, Bottom row: Subject C. Left column: Simultaneous BCI + manual control, Right column: BCI-only. Bins are the same within each subject. To help visualize the representative range of the data, outlier values (largest 2% of values) are collapsed into the last bin.

Histograms of the 10-12 Hz band power show interesting differences in alpha desynchronization activity (assessed with estimated band power from 10-12 Hz band-pass filter and moving average of 0.5 seconds, units of V^2) between the imagery and rest classes for BCI-only and simultaneous BCI + manual control. Figure 3 shows 10-12 Hz ("alpha") band power over C3 channel in the last 1.5 seconds before either a successful hit or timeout of a trial for subjects A & C (we show more in-depth histograms for subject B in Figure 4). Note that for subject C, who had the lowest performance, there is significant overlap in 10-12 Hz power between the imagery and rest classes during BCI + manual control. We postulate that this overlap may have been a factor in the low performance.

Figure 4 shows similar histograms with channels Cz and C4 included for Subject B, who had the highest target hit percentage on day 2. As expected from previous work [1], right hand MI-only resulted in a power decrease in the 10-12 Hz ("alpha") band over the contra-lateral hemisphere (C3), while central (Cz) and ipsi-lateral (C4) areas show similar band power distributions (Fig. 4, right column). Simultaneous MI + joystick resulted in more widespread alpha desynchronization (Fig 4. left column) and an overall decrease in power. However, there is still specificity in the C3 region when compared to Cz and C4. (Fig. 4, top left).

IV. CONCLUSION

Our results suggest that subjects can learn to exert direct brain control over a device while simultaneously engaging in overt motor control over another aspect of the same device.

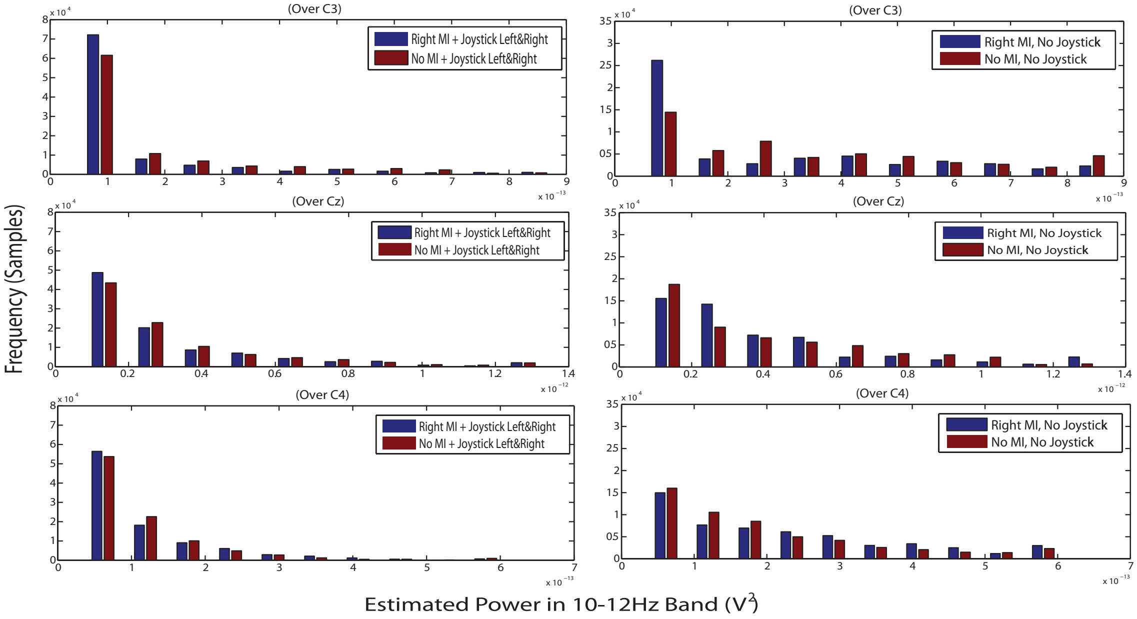

Fig. 4. **Distribution of EEG Power for Simultaneous BCI+Manual and BCI-only Tasks for a Single Subject.** Histograms of 10-12 Hz power estimates for subject B on day 2 during the last 1.5 seconds before a target was hit or end of trial (no hit). The data distribution shows that the subject was able to reduce power specifically over the control electrode location (C3) using right hand imagery, even during simultaneous BCI + manual control condition (left column), although to a lesser extent than BCI-only conditions (right column). Bins are the same within each channel (not the same across channels). To help visualize the representative range of the data, outlier values (largest 2% of values) are collapsed into the last bin.

In particular, two of the three subjects in our preliminary study showed marked improvement in performance from the first day of experiments to the second in the simultaneous BCI + manual control task.

A possible concern with the present study is whether the subjects used some form of muscle activity to control the cursor instead of imagery-based BCI control. Two types of evidence suggest otherwise. First, EMG activity recorded on the right hand does not appear to be correlated with the EEG signals used for right hand imagery-based control: the r^2 correlation of the EMG signals between imagery and rest classes were 0.04, 0.13, and 0.05 respectively for subjects A, B, and C. Second, the histograms for power estimates in Laplacian-derived C3, Cz, and C4 channels show that C3 exhibited clear differences between imagery and rest conditions, while C4 and Cz did not; this would not be expected in the event of widespread artifact contamination.

It is well-known that muscle artifacts associated with facial movements such as jaw and eyebrow movements can have significant effects on EEG signals (see, for example, [8]). However, the current study suggests that muscle movements that are distant from the scalp, such as the overt left arm movements used in the study, may not have such a strong effect on the EEG signal. Instead, activation of overlapping motor areas for imagery and movement may be a major factor affecting EEG BCI in these cases [9]. Evidence for this suggestion can be seen in the histograms in Fig. 4 for C3 and C4, where overt movement of the joystick during rest trials also caused the power distribution to shift into the lower power range, similar to imagery trials.

The study reported here is the first in a series of studies aimed at systematically investigating the extent to which BCI use can overlap with normal physical activity. Future studies will evaluate effects of long-term training, and include a larger subject pool. It is our hope that these efforts will help broaden the reach of BCIs by expanding their realm of applicability to the general population of able-bodied individuals.

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