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# Goal Selection vs. Process Control in Non-invasive Brain-Computer Interface

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*Abstract*—**Today's brain-computer interfaces (BCIs) record the electrical signal from the cortex and use that signal to control an external device, such as a computer cursor, wheelchair, or neuroprosthetic. Two control strategies used by BCIs, process control and goal selection, differ in the amount of assistance the BCI system provides the user. This paper looks at non-invasive studies that directly compare goal selection to process control. In these studies, the assistance provided by a BCI using goal selection 1) increased the user's performance with the BCI and 2) resulted in an EEG signal that was more conducive to good performance.**

## I. INTRODUCTION

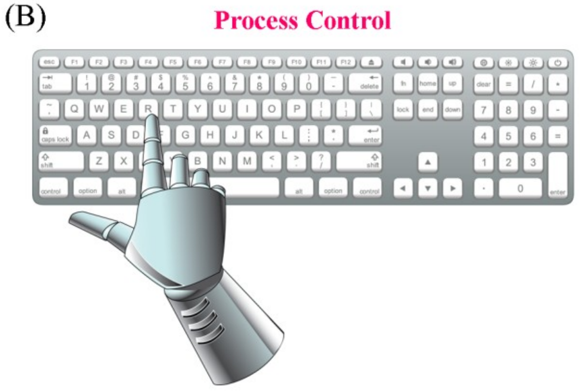
TODAY'S brain-computer interfaces (BCIs) record the electrical signal from the cortex and use that signal to control an external device, such as a computer cursor, wheelchair, or neuroprosthetic [1], [2]. The translational algorithm between the recorded signal and the device command plays a large role in determining the success of a BCI. One way translational algorithms differ is by the control strategy used to generate the device command.

Let us consider an individual with a right hand neuroprosthetic (fig. 1). While typing, a person can either touch type, leaving their hands at home row and using all 10 fingers on the keys, or "hunt and peck", using just one or two digits for the whole keyboard. While touch typing, a healthy typist thinks "N", and through experience gained via training, their fingers automatically move to the N key and push it with no additional conscious thought. If the individual with a right hand neuroprosthetic were to follow a similar procedure (fig. 1A), their motor cortex would issue the command "N", and the BCI would recognize that command. Like a healthy individual's trained fingers, the BCI system would control the prosthetic to extend the correct finger (right index finger) to the correct key (N) and push it. That is an example of the BCI using a control strategy called goal selection [3].

A second control strategy, called process control [3], would be more appropriate while "hunting and pecking". When "hunting and pecking", the typist consciously thinks about each of the different component parts of the action to type a single character. First, the typist thinks "R"; then they locate the R key on the keyboard; next they move their finger to the key, and finally they push R. The typist is consciously controlling each part of the action. If the individual with a right hand neuroprosthetic were to "hunt and peck" (fig. 1B), the BCI, using the process control strategy, would receive all action commands from the individual's cortex. The BCI would not provide any additional assistance or action commands. The individual would consciously control the BCI the entire time of the keystroke.

As the story above demonstrates, goal selection has the potential to enhance the usability of BCIs. However, current

Touch Typing



Hunting & Pecking

Fig. 1. An individual with a right hand neuroprosthetic typing. (A) The BCI uses goal selection while touch typing to automatically move the fingers to the correct key after receiving the letter as the cortical command. (B) The BCI uses process control while hunting and pecking to exactly follow the cortical commands as the typist consciously thinks: "R", find it, move to it, push it.

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BCIs predominantly use process control [3]. In an effort to increase acceptance of incorporating goal selection control strategies into current BCIs, this paper presents evidence from studies directly comparing goal selection to process control. After summarizing behavioral performance measures from two studies [4], [5], this report then extends the analysis by delving into the differences in the underlying sensorimotor rhythms as recorded by scalp EEG.

## II. METHODS

### A. Elements Common to Both Studies

The studies utilized young, healthy human subjects recruited from the community. All protocols were approved by the Institutional Review Board of the University of Minnesota. The experimental methods were previously described in [4], [5]. Brief descriptions follow. In each study, the subject sat motionless in a comfortable chair in front of a computer screen while wearing a 64 channel EEG cap configured consistent with the 10-20 international system. The signal from all electrodes was fed into a Neuroscan amplifier, sampled at 1000Hz, and processed by BCI2000 [6].

The subjects performed a one-dimensional, left-right cursor task. The standard BCI2000v2 cursor-task signal processing was used to control the movement of the cursor. In brief, the autoregressive spectral amplitudes of selected electrodes and frequencies was linearly combined into a control signal with zero mean and unit variance. The exact electrodes and frequencies used differed between the two studies and their selection is described below.

Each trial began with the presentation of two targets, one grey and one yellow. After 1s, a cursor appeared in the center of the screen. Users were instructed to move the cursor to the yellow target by imagining a right hand, arm, or shoulder movement to move the cursor to the right, and imagine doing a left hand, arm, or shoulder movement to move the cursor to the left. Hitting the yellow target with the cursor counted as a hit, and hitting the grey target counted as a miss. Each hit or miss ended with 1s of feedback, and then the screen went black for three seconds of rest between trials. Runs were 4 minutes long and consisted of as many trials as the user could complete within the four minutes. Subjects were allowed to rest a user determined amount of time between runs.

Four different paradigms were used in the studies. Two were based on goal selection and two were based on process control. The paradigms were identical in their underlying signal processing, control of cursor movement, and trial timing. They differed only in what the user had to do to achieve a hit. In the process control paradigms, the user had to move the cursor all the way to the target. In the goal selection paradigms, the user received assistance from the BCI system, which moved the cursor the remaining distance to the target once the selection criteria of the paradigm had been satisfied. For data analysis, the two process control paradigms were grouped into the PCP and the two goal selection paradigms were grouped into the GSP. Both PCP and GSP consisted of one time limited paradigm and one time unlimited paradigm. For PCP, the user had either 6s or unlimited time to move the cursor to the target. If the cursor did not hit a target within the time limit, the trial counted as a miss.

The goal selection paradigms determined the user's goal in two different ways, one based on time and one based on distance. The paradigm that selected the final target based on distance had a grey circle in the center of the screen. Once the user moved the cursor outside of the circle, the BCI system automatically moved the cursor the remaining distance to the target. The user had unlimited time within the circle.

The goal selection paradigm that determined the user's goal based on time utilized three 1s intervals. At the end of the first second of cortical control, the target closest to the cursor turned blue to indicate the selection of that target. After another second of cortical control, the closest target to the cursor was again selected. If it was the same target as in the 1st interval, the target turned purple and the BCI system automatically moved the cursor the remaining distance to the target. If the closest target was not the previously selected target, both targets became blue and the third 1s interval began. At the end of the third interval, the target closest to the cursor turned purple and the BCI system automatically moved the cursor the remaining distance to the target.

### B. First Study

Eight subjects participated in the first study [4]. Three subjects were trained with 6-8 weeks of previous BCI use, and five were naive to BCI usage. Each subject participated in two separate sessions. A session consisted of three runs of each of the four paradigms performed in blocks by paradigm. The difference in spectral amplitude of C4 and C3 from 7.5 to 13.5Hz was used to control the movement of the cursor for all subjects and all sessions. The data was grouped and analyzed to determine the accuracy, number of hits per run, information transfer rate, and time to a hit for both the trained and naive subjects.

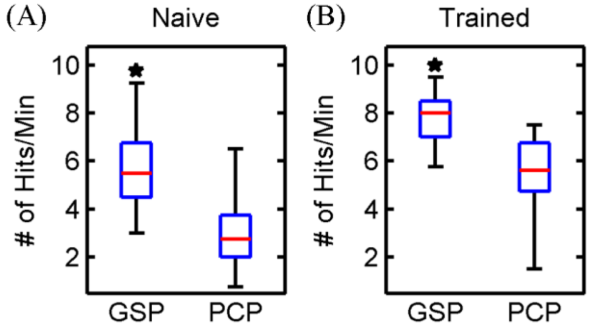

Fig. 2. GSP outperformed PCP in both naive (A) and trained (B) subjects. Asterisks indicate significantly different medians in the grouped data.

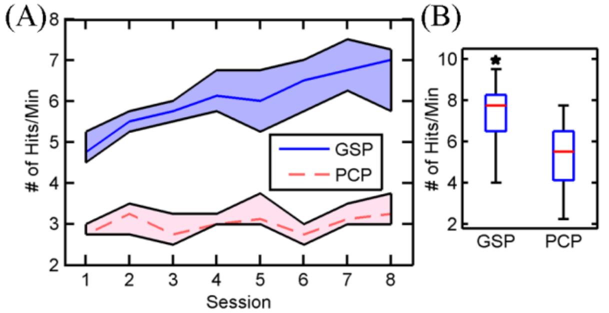

Fig. 3. GSP was easier to learn than PCP. (A) Median of the grouped data (line) and 95% confidence interval (shaded region) for the 8 single-paradigm sessions. (B) Asterisk indicates significantly different medians in the grouped data for the additional two mixed-paradigm sessions.

### *C. Second Study*

Twenty naive subjects participated in the second study [5]. Each subject was randomly assigned to one of the four paradigms so that each paradigm had five users. Subjects completed 8 sessions of 10 runs of their assigned paradigm. Sessions occurred approximately once a week for 8 weeks. The spectral amplitude of C3 from 7.5 to 13.5 Hz and 16.5 to 25.5 Hz controlled the movement of the cursor for all subjects for the first session. For sessions 2-6, the data from the previous session was used to customize the electrodes and frequencies used by each subject. The electrodes and frequencies that the user could best control were chosen using BCI2000 Offline Analysis according to the available tutorials [7], [8]. In brief, the chosen electrodes and frequencies had the highest $r^2$ to the condition left target vs. right target. At session 7, the electrodes and frequencies were limited to ones that the subject had previously used, and that combination was used for both session 7 and 8.

At the end of the eight weeks, the best user from each paradigm completed two additional sessions. These sessions consisted of three runs of each of the four paradigms in block-random order using the electrodes and frequencies that they had used in the last two sessions. The data was grouped and analyzed to determine the accuracy, number of hits per run, information transfer rate, time to a hit, and effort of a hit for both the 8 single-paradigm sessions and the two additional mixed-paradigm sessions.

### *D. Extended Analysis - EEG Data*

The EEG data from the eight single-paradigm sessions of the second study were analyzed in the same manner as done real time by the BCI with a 16th order autoregressive model calculating 3Hz bins centered on a multiple of three from 0 to 30 Hz with a window of 160ms and 50% overlap. Spectral amplitudes of all 64 electrodes were calculated.

## III. RESULTS

The results of the first study showed that, in this task, GSP outperformed PCP in terms of accuracy, number of hits per run, information transfer rate, and time to a hit. Both trained and naive users showed better performance using GSP than PCP. Fig. 2 shows that in the grouped data GSP had significantly more hits per minute than PCP, 100% more for naive users (A) and 42% more for trained users (B).

The results of the second study confirmed in a larger sample size, but in the same simple task, that GSP was more accurate and faster in use than PCP while also demonstrating the GSP was easier to learn than PCP. GSP had significantly more hits per minute than PCP for all 8 single-paradigm sessions (fig. 3A) as well as the two mixed-paradigm sessions (fig. 3B). On average, GSP had 102% more hits per

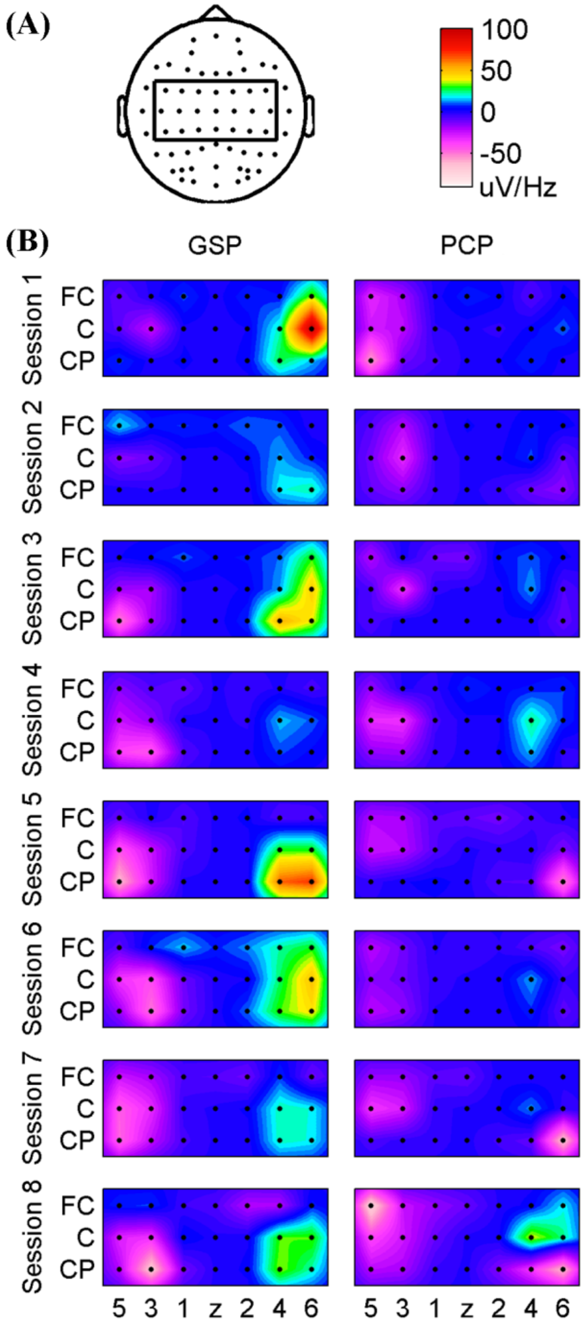

Fig. 4. GSP had greater average spectral amplitude differences between the two targets than PCP. (A) Area of the head and color scale displayed in each subpart of (B). (B) Average spectral amplitude at 12 Hz for the right target minus the left target for all 8 sessions, GSP in the left column and PCP in the right column.

minute than PCP across the 8 single-paradigm sessions, and 41% more during the mixed-paradigm sessions. The number of hits per minute improved 161% more for GSP than PCP across the 8 sessions, demonstrating increased learning.

Analyzing the underlying EEG signal may reveal the neural mechanisms underlying GSP's improved performance compared to PCP in these studies. Fig. 4 plots the average spectral amplitude for right trials minus the average spectral amplitude for left trials. GSP and PCP display initially dissimilar patterns of spectral amplitude differences. In the first two sessions, PCP had greater differences on the left hemisphere, whereas GSP had greater differences on the right hemisphere. Over time, both PCP and GSP developed spectral differences on both hemispheres. By the final four sessions, GSP had larger spectral differences than PCP on both hemispheres.

Additional analysis (fig. 5) looked at a single trial as a series of correct and incorrect modulations of the sensorimotor rhythms (SMRs). A correct SMR modulation moved the cursor towards the yellow target, whereas an incorrect SMR modulation moved the cursor away from the yellow target. Both GSP and PCP had similar spectral amplitudes for correct SMRs (fig. 5A), but PCP had worse spectral amplitudes for incorrect SMRs (fig. 5B). Similarly, the duration of a correct SMR was the same for both GSP and PCP, but PCP had longer incorrect SMRs (fig. 5C). When looking at the entire trial, incorrect SMRs occupied a longer percentage of the trial for PCP than for GSP (fig. 5D).

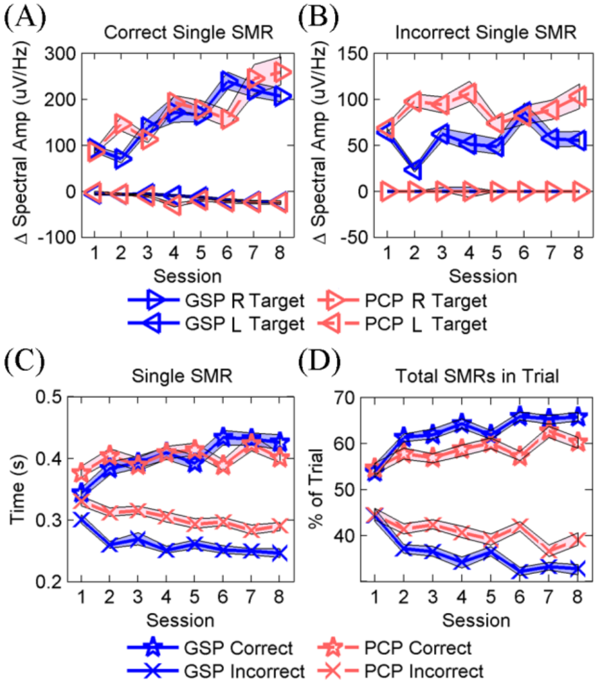

Fig. 5. GSP and PCP has similar correct modulations of sensorimotor rhythms (SMRs), but PCP had worse incorrect SMRs. A correct SMR moved the cursor towards the yellow target, whereas an incorrect SMR moved the cursor away from the yellow target. Median of the grouped data (line) and 95% confidence interval (shaded region) for the 8 single-paradigm sessions. R = right, L=Left.

## IV. DISCUSSION

The above results from cursor movement studies show that these particular implementations of goal selection and process control into the GSP and the PCP resulted in GSP being more accurate, faster in use, and easier to learn than PCP. An initial look at the underlying neural signal showed findings more favorable to GSP than PCP. Limited conclusions can be drawn from this. These studies were simple, 1-dimensional tasks with two fixed targets that used a particular implementation of goal selection into a process control BCI. Other possible implementations of goal selection into a cursor task exist, many of which may be better than what was described here. The paradigms described here were chosen for ease of comparison to the process control paradigms. Additionally, the implementation of goal selection into different tasks must be customized to the task. The direct comparison of goal selection and process control in a more complicated, real world scenario has not yet been presented. We hypothesize that ultimately, process control will continue to be useful when encountering novel situations, but goal selection will benefit users by providing assistance when possible.

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