# Wheelchair Control Based on Multimodal Brain-Computer Interfaces

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**Abstract.** Electroencephalogram (EEG) based brain-computer interfaces (BCIs) for wheelchair control have great value for those with devastating neuromuscular disorders. Although there have been many attempts to implement EEG-based wheelchair control systems by P300, steady state visual evoked potential (SSVEP), and motor imagery (MI) related event-related desynchronization/synchronization (ERD/ERS), the number of simultaneous control commands in those BCI systems is strictly limited, and those BCI control do not work for a non-negligible portion of users due to the problem of BCI Illiteracy. In this paper, we develop a multimodal BCI based wheelchair control system, the user could employ subject-optimized mental strategies to produce multiple commands to control the wheelchair, which include ERD/ERS, SSVEP, and simultaneous ERD/ERS and SSVEP. It could not only help address "BCI illiteracy", but also provide simultaneous control commands for complex control. Experiment results demonstrate the proposed system is effective and flexible in practical application.

**Keywords:** BCI, wheelchair control, multimodal, BCI Illiteracy.

## 1 Introduction

Electroencephalogram (EEG) based brain-computer interfaces (BCIs) provide a potentially powerful new communication channel for people to mentally control machines through translating brain electrical activities into machine codes or commands[1]. EEG based BCIs for wheelchair control have great value for those with devastating neuromuscular disorders, such as the amyotrophic lateral sclerosis (ALS), brainstem stroke, cerebral palsy, and spinal cord injury.

There have been many attempts to implement EEG-based wheelchair control systems relying on one of following typical EEG activity for control: steady state visual evoked potential (SSVEP), event-related desynchronization /synchronization (ERD/ERS) and P300 evoked potential. For examples, an asynchronous BCI based on MI task helped the subject to control a wheelchair to go or stop by

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imagination of feet movements in virtual reality (VR)[2]. A 2-class MI based BCI for robotic wheelchair control was shown by Tsui et al.[3], and a real wheelchair was steered by three different kinds of MI tasks, i.e. left, right and feet motor imageries corresponded to turn left, turn right, and go forward respectively[4]. Wheelchair was designed to run on predefined paths to the target location by detecting P300 potentials[5,6], and also demonstrated in SSVEP-based BCI system equipped with a safety layer and navigation software[7]. However, in generally, it is still challenging to design an effective and flexible BCI system for real wheelchair control in practical application since the number of control commands, especially for simultaneous commands, in those BCI systems is strictly limited. Furthermore, recently, many BCI groups reported the forementioned BCI control could not work for a non-negligible portion of users (estimated 15% to 30%) due to the problem of "BCI illiteracy"[8,9]. This problem exists across different BCI approaches, although some possible solution, such as improved signal processing, training, have been explored, it is still not solved since some of the users can not produce detectable patterns of brain activity necessary to a particular BCI approach[10,11].

Therefore, we develop a multimodal BCI based wheelchair control system, the user could employ subject-optimized mental strategies to produce multiple commands to control wheelchair, which could be ERD/ERS, SSVEP, or simultaneous ERD and SSVEP. It can not only help address "BCI illiteracy", but also provide more and simultaneous control commands for complex control. Experiment results demonstrate the proposed system is effective and flexible in practical application.

The remainder of this paper is organized as follows. The Methods, including experiment Setup, system paradigm, subject-optimized control algorithm are described in Section 2. Section 3 presents experiments and results, and section 4 finally concludes the paper.

## 2 Methods

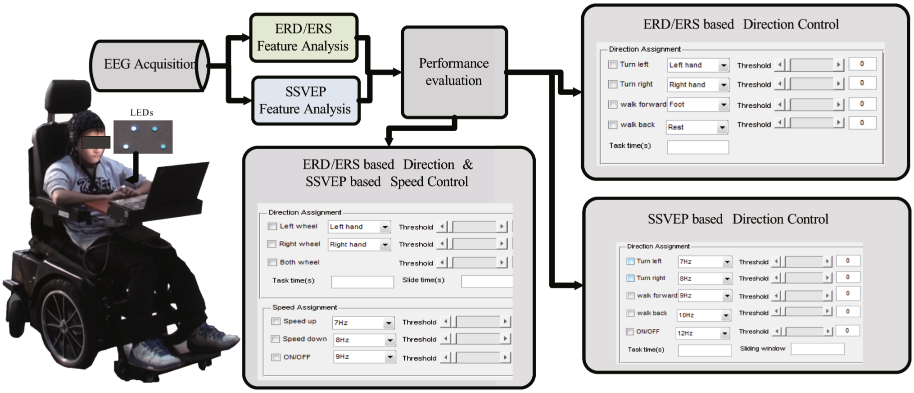
### 2.1 Experiment Setup

In order to evaluate the proposed multimodal BCI, three healthy male subjects, aged from 21 to 30, took part in the experiment. Multi-channel EEG data were acquired by Gtec Amplifier (g.tec, Graz, Austria), sampled at 256Hz and then band-pass filtered within 5-30 Hz. Channels located at standard positions of the 10-20 international system as FC3, FC4, C5, C3, C1, CZ, C2, C4, C6, CP3, CP4, POZ, O1, OZ, and O2, totally 15 channels, were used in this study. The ground and reference electrodes were respectively fixed on medial frontal cortex and the right earlobe.

In the data collection stage, each subject was seated in front of a notebook computer, keeping arms on the chair arms with hands relaxing. SSVEPs were generated by the stimuli box equipped on the desktop of the wheelchair (see left panel in Fig. 1), in which four light-emitting diodes (LEDs), separately flicking at the frequency of 7Hz, 8Hz, 9Hz, 11Hz, were used as the visual stimuli. EEG signals are acquired continuously, and then transferred to the notebook computer through an USB port. The translated control commands would be sent to the wheelchair by a wireless communication module.

## 2.2 System Paradigm

Fig. 1 presents the multimodal BCI system paradigm. First, multichannel EEG signals are collected by electrodes located in the occipital and parietal lobes; Second, MI based ERD/ERS and SSVEP features are analysed. In details, For the MI task, we used common spatial patterns (CSP)[12] algorithm to detect the spectral discriminations by calculating discriminative spatial patterns that maximized the variance of one class and at the same time minimized the variance of the other. Here, four generalized eigenvectors from both ends of the spectrum were selected as spatial patterns, and only channels in motor related parietal lobe, i.e., FC3, FC4, C5, C3, C1, CZ, C2, C4, C6, CP3, CP4 were considered. The MI features were calculated by projecting the EEG data to the CSP patterns. The features of SSVEP were obtained by canonical correlation analysis (CCA) algorithm simultaneously. CCA is a multivariable statistical method used when there are two sets of data, which may have some underlying correlation[13]. Here, multiple correlation coefficients between the the sinusoidal reference signals at stimulating frequency, and EEG signals from multiple channels located in the occipital lobes, i.e. POZ, O1, OZ, and O2, were calculated as SSVEP related features. Then in order to evaluate the performance of different mental strategies, support vector machine (SVM) classifiers with linear radial basis function (LRB) is applied to calculate the cross accuracies for each task, considering its good generalization ability in minimizing the vapnik-chervonenkis (VC) dimension and achieving a minimal structural risk[14].



ERD/ERS based Direction Control
Direction Assignment
☐ Turn left — Left hand — Threshold — 0
☐ Turn right — Right hand — Threshold — 0
☐ walk forward — Foot — Threshold — 0
☐ walk back — Rest — Threshold — 0
Task time(s)

ERD/ERS based Direction & SSVEP based Speed Control
Direction Assignment
☐ Left wheel — Left hand — Threshold
☐ Right wheel — Right hand — Threshold
☐ Both wheel — Threshold
Task time(s) — Slide time(s)
Speed Assignment
☐ Speed up — 7Hz — Threshold
☐ Speed down — 8Hz — Threshold
☐ ON/OFF — 9Hz — Threshold

SSVEP based Direction Control
Direction Assignment
☐ Turn left — 7Hz — Threshold — 0
☐ Turn right — 8Hz — Threshold — 0
☐ walk forward — 9Hz — Threshold — 0
☐ walk back — 10Hz — Threshold — 0
☐ ON/OFF — 12Hz — Threshold — 0
Task time(s) — Sliding window

**Fig. 1.** The proposed multimodal BCI system paradigm for real wheelchair control

Finally, base on the SVM classification results, the wheelchair can be controlled by subject-optimized mental strategies to produce multiple commands, which include ERD/ERS, SSVEP, and simultaneous ERD and SSVEP. For the subject who is only good at the SSVEP task, then the aforementioned SSVEP features are translated into direction control commands automatically. Similarly, the ERS/ERS features are used to set the direction if the subject has a poor performance at the MI task. Note that, the system translates the MI and SSVEP classification results into simultaneous commands to control the speed and direction at the same time if the subject could achieve good performances at both of the two mental tasks.

## 2.3 Subject-Optimized Control Algorithm

Most of BCI systems for wheelchair control are based on only one typical EEG activity pattern, while the proposed multimodal BCI firstly evaluates the subject's performance in different activities, and then provides subject-optimized mental strategies to produce multiple commands to control a wheelchair. The control model is given in the following:

```
multimodal control algorithm (Output R_{l,t+1},R_{r,t+1} )
    { Assuming R_{l,t} and R_{r,t} represent the left and right
     wheels' rotation rate at the tth update respectively.
      f_{MI}, denoting the classification result for MI,is +1 for
     left hand movement and -1 for the right hand.
      f_{SSVEP} is given by the classification result for SSVEP.
     In the SSVEP mode, +1 for the LED representing "turn left"
     and -1 for "turn right".
     In the MI&SSVEP mode, +1 for the LED representing "speed up"
     and -1 for "speed down".
       TurningFactor, SpeedFactor are predefined tuning and speed
     parameters.
      }
 Switch controlmode
  Case  SSVEP mode
   R_{l,t+1}=R_{l,t} - f_{SSVEP} * TurningFactor + Given_speed;
   R_{r,t+1}=R_{r,t} + f_{SSVEP} * TurningFactor + Given_speed;
  Case  MI mode
   R_{l,t+1}=R_{l,t} - f_{MI} * TurningFactor + Given_speed;
   R_{r,t+1}=R_{r,t} + f_{MI} * TurningFactor + Given_speed;
  Case  MI&SSVEP mode
   R_{l,t+1}=R_{l,t} - f_{MI}*TurningFactor + f_{SSVEP}*SpeedFactor;
   R_{r,t+1}=R_{r,t} + f_{MI}*TurningFactor + f_{SSVEP}*SpeedFactor;
 end.
```

(A motorized wheelchair with differential drive has been retrofitted to receive the control commands by a bluetooth interface. By assigning different rotation rate for two motor wheels respectively, it can be steered in specific speed and direction.)

## 3 Experiments and Results

To evaluate the effectiveness of the proposed multimodal BCI system, and assess the capabilities of subjects' multimodal manipulation, a realtime control experiment was carried out in the real-word scenarios. Subjects were required to accomplish a complex navigation circuit in a public open space as soon as possible. Fig. 2 shows the circuit map, the subject should leave the start point and reach the stop point by passing the breakpoint and avoiding obstacles, and a possible path in an ideal situation is marked with red dotted line.

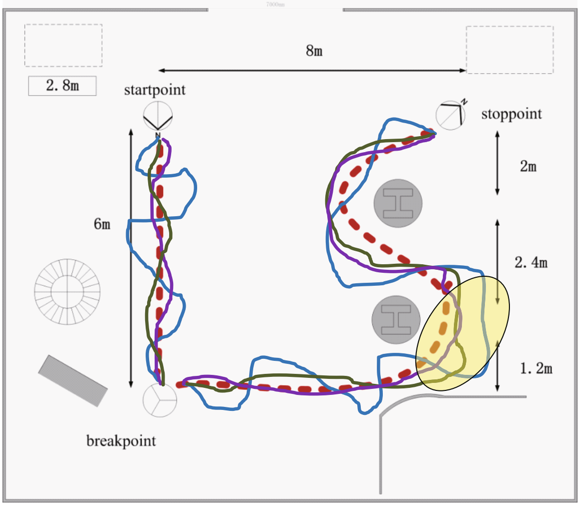


**Fig. 2.** The circuit map in the wheelchair control experiment. The subject was required to accomplish complex navigation circuit as soon as possible, the red dotted line stands for a possible path in an ideal situation. The green, purple, and blue lines denote the actual paths for Sub.1, Sub.2, Sub.3 respectively.

Before to control the real wheelchair, three subjects have been evaluated according to the proposed paradigm. They were all required to carry out the MI tasks and SSVEP tasks. The MI task consisted of three runs, each run had 10 trials for each class. In each trial, the subject was required to imagine the movements of the left or right hand for about 2s indicated by an arrow appeared on the computer screen. While in the SSVEP tasks, the subject was instructed to keep his eyes focusing on one of the LEDs according to an auditory digit cue, i.e., one of the 1, 2, 3, 4, corresponding to the serial number of LEDs, The goal of this session was to help select the mental strategy and calculate classification model in the following control experiment.

According to the aforementioned MI and SSVEP feature extraction and classification methods, the classification accuracies were calculated as the performance evaluation for each mental task, and then the proposed system would selected

**Table 1.** The performance in the wheelchair control experiment for each subject

| | SSVEP accuracy | MI accuracy | selected strategy | time consuming |
|---|---|---|---|---|
| Sub.1 | 98.3% | 99.4% | SSVEP and MI | 274 (s) |
| Sub.2 | 57.9% | 100% | MI | 298 (s) |
| Sub.3 | 96.7% | 58.3% | SSVEP | 376 (s) |

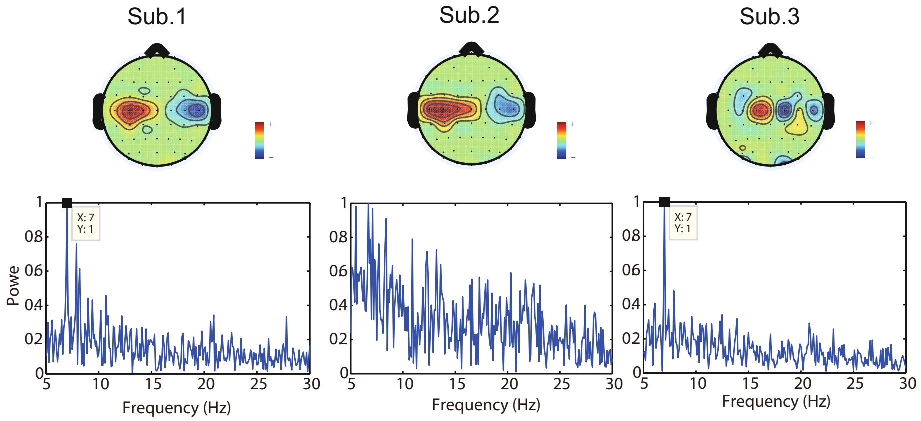


**Fig. 3.** The top line shows the power changes within 5-30Hz in the scalp map, and the bottom row shows power spectral density (PSD) of the EEG signal recorded at channel OZ for each subject when he navigated in the continuous turn-left area (marked with a yellow oval in Fig. 2). (In this experiment, for sub.2, left hand and right hand imagery were used to control wheelchair to turn left and right respectively; for sub.3, focusing on the LEDs flicking at the frequency of 7 and 9 Hz corresponded to left turn and right turn respectively. For Sub.1, left hand and right hand imagery were used to control the wheelchair to turn left and right, and at the same time, focusing on the LEDs flicking at the frequency of 7 and 9 Hz were used to control the wheelchair to speed up and speed down.)

subject-optimized mental strategy to produce multiple commands. Table 1 gives the performance and the selected strategies.

In the following wheelchair control experiment, all subjects reached the stop-point without collision, and their actual paths were showed in Fig. 2 , which are generally consistent with the predefined circuit. The time to accomplish the circuit is also listed in table 1 for each subject. It can been seen, by subject-optimized control mode, all subjects could complete the required task successfully even though Sub.2 and Sub.3 are almost illiterate in SSVEP or MI tasks. Sub.1 achieved the least time consuming since he could control the speed and direction of the wheelchair simultaneously, which would improves the control efficiency greatly. Among all subjects, Sub.3 spent the most time. Experiment path records show that he spent a lot of time to adjust the drive direction due to excessive turnings (see Fig. 2), which was probably caused by the reflection delay of SSVEP.

Fig. 3 illustrates the power changes within 5-30Hz in the scalp map, and the power spectral density (PSD) for each subject when he navigated in a continuous turn-left area (marked with a yellow oval in Fig. 2). It is obvious that the subjects applied the optimized mental activities in this multimodal BCI. Note that Sub.1 did the left hand imagery and focusing on the LEDs at 7Hz tasks to control wheelchair to accelerate and turn left at the same time. The simultaneously generated commands help this subject to reduce the consuming time effectively.

## 4 Conclusion

In this paper, a multimodal BCI based wheelchair control system is developed, and the user could employ subject-optimized mental strategies to produce multiple commands, to control wheelchair, which include ERD/ERS, SSVEP, and simultaneously ERD and SSVEP. It could not only help address "BCI illiteracy", but also provide more even simultaneous control commands for complex control. Experiment results demonstrate the proposed system is effective and flexible in practical application.

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