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Published in:
Journal of Neural Engineering

DOI (link to publication from Publisher):
10.1088/1741-2552/ab20e5

Publication date:
2019

Document Version
Accepted author manuscript, peer reviewed version

Citation for published version (APA):
Xu, R., Dosen, S., Jiang, N., Yao, L., Farooq, A., Jochumsen, M., Mrachacz-Kersting, N., Dremstrup, K., & Farina, D. (2019). Continuous 2-D control via state-machine triggered by endogenous sensory discrimination and a fast brain switch. *Journal of Neural Engineering*, *16*(5), [056001]. https://doi.org/10.1088/1741-2552/ab20e5

Journal of Neural Engineering

ACCEPTED MANUSCRIPT

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To cite this article before publication: Ren Xu *et al* 2019 *J. Neural Eng.* in press https://doi.org/10.1088/1741-2552/ab20e5

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Continuous 2-D Control via State-Machine triggered Endogenous Sensory Discrimination and a Fast Brain Switch

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Abstract

Objective. Brain computer interfacing (BCI) is a promising method to control assistive systems for patients with severe disabilities. Recently, we have presented a novel BCI approach that combines an electrotactile menu and a brain switch, which allows the user to trigger many commands robustly and efficiently. However, the commands are timed to periodic tactile cues and this may challenge online control. In the present study, therefore, we implemented and evaluated a novel approach for online closed-loop control using the proposed BCI. *Approach.* Seven healthy subjects used the novel method to move a cursor in a 2D space. To assure robust control with properly timed commands, the BCI was integrated within a state machine allowing the subject to start the cursor movement in the selected direction and asynchronously stop the cursor. The brain switch was controlled using motor execution (ME) or imagery (MI) and the menu implemented 4 (straight movements) or 8 commands (straight and diagonal movements). *Main results.* The results showed a high completion rate of a target hitting task (~97% and ~92% for ME and MI, respectively), with a small number of collisions, when 4-channel control was used. There was no significant difference in outcome measures between MI and ME, and performance was similar for 4 and 8 commands. *Significance.* These results demonstrate that the novel state-based scheme driven by a robust BCI can be successfully utilized for online control. Therefore, it can be an attractive solution for providing the user an online-control interface with many commands, which is difficult to achieve using classic BCI solutions.

Keywords

Brain-computer interface, brain switch, communication, cursor control, endogenous sensory discrimination

1. Introduction

Brain-computer interfaces (BCI) have been developed as a communication or control tool to restore lost functions in patients with motor disorders [1] [2]. Among many diverse applications in which BCI was tested (e.g., spelling, web browsing, music composing, entertainment and gaming [3]), the control of assistive technology is one of the most important. In this context, BCI detects the user's intention from brain waves (electroencephalography, EEG), and transforms it into commands to interact with external devices, such as computer cursor for writing and internet surfing [3], exoskeletons [4], assistive robotic arms to enable grasping and manipulation [5], or wheel-chairs for mobility [6]. These applications are challenging for BCI design since they require online closed-loop control of motion. For example, when steering a wheelchair, BCI should emulate a joystick allowing the user to generate directional commands. The control needs to be responsive and enable the user to react and generate timely commands based on the continuous feedback from the controlled system and environment (e.g., navigating a wheelchair through an apartment).

Several EEG signal modalities have been used for the directional control of motion. In a P300-based system [7], [8], the icons flashing on a screen represent the optional movement directions (e.g., up, down, left and right). When the user focuses on the desired icon, a P300 is detected in an oddball paradigm and the system (e.g., a wheelchair) moves in the selected direction. The P300 BCI can be implemented using other types of external stimuli, for example tactile stimuli [6]. Alternatively, the BCI control can be realized by exploiting steady-state visual evoked potentials (SSVEP) [9,10] and steady-state somatosensory evoked potentials (SSSEP) [11]. Different from the oddball paradigms used for evoking the P300, the external stimuli to elicit the evoked potentials are delivered simultaneously but at different frequencies (i.e., flash rate, vibration frequency), producing distinct frequency components in the EEG when the user is focusing on a specific stimulus (visual icon, tactile sensation) [12,13]. Alternatively, the user can actively utilize motor imagery (MI) for control. For example, the wheel-chair moves right when the user imagines right hand movement, while it moves left during MI of the left hand [14,15]. The MI generates distinguishable patterns in the EEG, such as movement related cortical potentials (MRCPs) [16], which are deflections in the EEG associated to motion preparation and execution, and sensory-motor rhythms (SMRs) [17], which appear as changes in the EEG power at specific frequency bands (event-related synchronization/desynchronization (ERS/ERD) [18]. More recently, hybrid methods combining different signal modalities (e.g., simultaneous SSVEP and MI [19]) have also been investigated [20,21].

Despite promising results, the existing methods for directional control have limitations. The systems that rely on visual potentials (e.g., P300, SSVEP) are not applicable to users with impaired vision and they also lead to fatigue, as the user needs to continuously focus on the strong visual stimulus. In addition, the screen which displays the stimuli could be an obstacle in the visual field or it could distract the user from the surrounding environment [22]. This can have a negative impact on control. On the other hand, for a MI-based system, the accuracy decreases dramatically with the number of classes, thereby limiting the number of commands that can be sent to the system. The hybrid method may overcome some of these limitations, but at the cost of increasing mental effort. For some users, it is difficult to utilize the hybrid interface even after a long and tedious training [23]. This can be a drawback even in the single-modality BCIs (e.g., up to six weeks of training with SSVEP [24]). Some of these limitations can be overcome by using tactile stimulation (e.g., tactile P300 [6,25] and SSSEP [11]). The pros and cons of the tactile modality are usefully summarized in [11]. There are studies demonstrating that a tactile BCI is an effective approach for highly impaired subjects (case study [26], tactile modality outperformed visual BCI) as well as in elderly people (wheelchair control) [27].

The above methods estimate user intention by evoking and detecting changes in the EEG, i.e., a specific response is recognized from the EEG signal using signal processing and machine learning and then translated into a corresponding command to the system. This is a challenging task due to the nature of the EEG signals (e.g., low signal-to-noise ratio) and therefore the bandwidth of control is limited, as only few commands can be discriminated and transmitted at a low rate [28]. In order to overcome this bottleneck, we have recently proposed a novel multi-class BCI, which is based on endogenous sensory discrimination and selection [29]. In this approach, an electrotactile menu is combined with a fast brain switch [16]. Different commands are presented to the subject by cyclically activating an array of stimulation electrodes (electrotactile menu). The subject waits until a specific electrode (desired command) is activated (endogenous sensory discrimination), and then imagines the movement that is detected by a BCI (brain switch) and trigger the command selection. Therefore, the method relies on the user to discriminate between classes by recognizing the tactile stimuli, while the BCI only decodes one command (selection trigger), as a brain switch. In a previous study [24], we demonstrated the feasibility of the approach for effective (multiclass) and gaze-independent interfacing. We limited the analysis to a simple and static cue-based class selection. However, since the electrotactile stimulation is used to cue the BCI detection, the proposed method is characterized by delays in generating the commands. This can be a challenge for implementing online control. Therefore, in the present study, we integrated the BCI detection within a state-based scheme leading to a method that is suitable for online control. We then tested the performance of this novel approach during cursor control tasks. The tests investigated the feasibility and advantages of applying the novel BCI interfacing to dynamic real-life scenarios (e.g., steering a wheelchair).

2. Methods

2.1. Subjects

Eleven healthy subjects (ten male and one female, average age: 29.5±7.5 yrs) participated in the study. All the participants signed an informed consent form before starting the experiment. The experimental protocol was approved by the local ethic committee.

2.2. Apparatus and Instrumentation

2.2.1. EEG

A g.USBamp amplifier (g.tec, Austria) was used for EEG acquisition. Nine active electrodes (actiCap, Germany) were placed at the locations Cz, Fz, FC1, FC2, C3, C4, CP1, CP2, and Pz, according to the standard international 10–20 system, and connected to the first nine channels of the amplifier. The ground electrode was placed at AFz, while the reference electrode was positioned on the mastoid bony surface behind the left ear. Electrodes were mounted on the scalp by verifying the electrode-skin impedance and maintaining it below 20 kΩ, which is the recommended value by the manufacturer of the actiCap system. The sampling rate was set to 1200 Hz.

2.2.2. EMG

One channel of surface electromyography (EMG) was also recorded using the last channel of the g.USBamp amplifier. The EMG was acquired in a monopolar configuration from the tibialis anterior (TA) muscle using disposable electrodes (Neuroline 720, Ambu). The electrode was placed on the mid-belly of the right TA muscle, while the reference and ground electrodes were positioned on the bony surface of the right knee and right ankle, respectively.

The ground and reference setting was configured through a software, so that the EEG channels had a common ground and reference, while the EMG channel used a separate ground. The EMG was used to detect the movement onset during the training and online control tests based on motor execution.

2.2.3. Electrical stimulator

The electrical stimulation (ES) was delivered by an eight-channel current-controlled electrical stimulator (RehaStim, Hasomed, Germany). Four stimulation channels were used during the main experiment to evaluate a four-class BCI, and eight channels were employed during an additional session with an eight-class BCI. This is a fully programmable stimulator with independently adjustable stimulation parameters (pulse amplitude, width, and frequency) which can be set online by sending commands from the host PC via a USB port. The unit is battery powered and fully isolated from the mains supply. Standard self-adhesive, disposable stimulation electrodes were utilized (CoDe 2.0, Spes Medica, IT). The electrodes were concentric, with a circular cathode inside a ring anode, thereby generating a localized and superficial current flow to activate skin afferents and produce a localized tactile sensation. The electrodes (4 or 8) were placed around the neck, approximately equidistantly, to demonstrate that the system could be applied even to high-level paralyzed patients without sensory sensation below the neck. The stimulation intensity (<5 mA) was set individually at each location so that the subjects could clearly feel the stimulus without any discomfort. The duration of a single stimulation burst indicating an option in the electrotactile menu (see subsection 2.3.2) was set to 0.2 s, while the stimulation frequency and pulse width were fixed to 100 Hz and 200 µs, respectively. For the main protocol with 4-direction control (Subsection 2.3.2), the inter-stimulus interval was 2 s, while it was shortened to 1.5 s in the additional 8-direction control (Subsection 2.3.2).

2.3. System setup

2.3.1. Graphical user interface (GUI)

The task for the subjects was to use the BCI system for controlling the movement of a 2D object (hereafter referred to as 'cursor') within a planar workspace, and the goal in each trial was to move the cursor from an initial position (screen center) to a target position. The cursor and the target were presented to the user via a graphical user interface (GUI) displayed on the 22" computer monitor positioned approximately 50 cm in front of the subject. As shown in Fig. 1, the size of the planar workspace was 8 × 5 arbitrary units mapped to the full screen of the computer monitor. The red circle represented the cursor, which was positioned in the middle of the workspace at the beginning of each trial. The cursor was controlled by the subject through the BCI system to reach and contact the target indicated by a green ball. There were 8 targets in total, with predefined positions, as shown in Fig. 1.

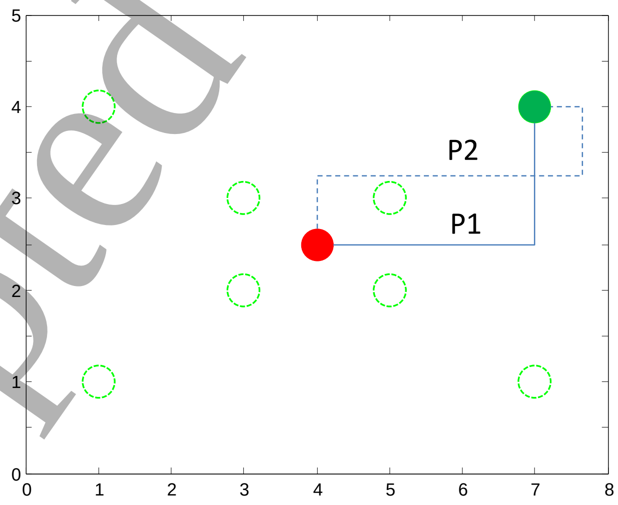


Fig. 1 Graphical user interface (GUI). The red circle is the starting point of the moving object (cursor), while the filled green circle is the current target. The 7 empty green circles represent the locations of other targets. The solid blue line P1 is the optimal path from the moving object to the target when using a 4-channel (commands) interface, while the dashed line P2 stands for a possible suboptimal path.

2.3.2. *Online control loop*

A multi-class BCI for online directional control was designed by integrating the endogenous sensory discrimination with a fast brain switch into a state machine. The aim of the state machine was to minimize the impact of delays in command generation due to electrotactile cuing as well as the amount of stimulation delivered to the user during the control trial (intrusiveness). Pilot tests were performed with different schemes (see Discussion) and the one described below has been selected as the method of choice.

The endogenous sensory discrimination and selection is a novel type of BCI presented recently in [24]. In this system, the electrical stimuli delivered through different electrodes provide the choices (classes) to the subjects, implementing thereby an electrotactile menu of commands. In the present study, the choices transmitted through the electrotactile menu corresponded to directional commands for moving the cursor. When the system required a command input from the subject (see next paragraph), the electrotactile menu was started. Each electrode was activated briefly (0.2 s) to indicate the currently active choice, and the choices were presented in a continuous loop. The subject employed his/her ability for sensory discrimination to distinguish between these electrotactile inputs. Once the subject detected that the desired command (electrode) was active (electrode stimulating), he/she triggered a fast brain switch to make the desired choice. The brain switch was implemented using real-time detection of MRCPs from scalp EEG following the methods presented in [16]. To activate the brain switch, the subjects performed (for the motor execution trials) or imagined (for the motor imaginary trials) the dorsiflexion movement of the dominant foot. Any imaginary task could be used for the brain switch. In this study, we chose the ankle dorsiflexion of the dominant foot because of our previous experience with decoding this task [16,29]. The training of the MRCP detector as well as the experimental protocol for the system assessment are explained in more detail in section 2.4.

For online control, the multi-class BCI was integrated within a control strategy named “single trigger with immediate stop”. The control was implemented as a state machine with two states, namely Waiting and Moving, and the transitions were initiated by the user activating the brain switch (Fig. 2b). At the start of the trial, the control loop was in the Waiting state. The cursor was stationary, positioned in the middle of the screen, and the electrotactile menu was activated. The user employed the tactile menu and the brain switch to select the desired direction to move the cursor, as described. Once the user triggered the command, the cursor started moving with a constant speed of 0.2 units/s in the selected direction. In the Moving state, the electrotactile menu was deactivated, and this indicated to the subject that the only command he/she could issue was the stop command. The subject stopped the cursor by another activation of the brain switch. With this, the control loop transited back into the Waiting state and the electrotactile menu was reactivated, waiting for the next subject command. Therefore, the subject moved the cursor within the workspace using a sequence of move and stop commands.

Two configurations, with 4 and 8 directional commands, as shown in Fig. 2 (a), were tested. In 4-command control, four electrodes were placed equidistantly around the subject’s neck and the directions were assigned to the electrodes in an intuitive manner: move up, down, left and right on the screen were indicated by the electrode positioned on the front, back, left and right side of the neck, respectively. For the extended eight-direction control, four additional electrodes were placed around the neck, in between the four previous electrodes, to indicate the commands for the diagonal movements of the cursor (top-left, top-right, bottom-left and bottom-right).

Fig. 1 depicts two representative trials generated using online control. Ideally, when using the 4-channel control, the target could be reached with two directional commands separated by one stop command (e.g., move left, stop, and move up for target 1). In this case, the cursor would reach the target via an optimal path, which corresponded to a simple two-line trajectory (Fig. 1, P1). To traverse the optimal path, the subject would need to perform the following sequence. The subject triggers the brain switch when he/she feels the stimulus on the electrode 2 (move right). This deactivates the electrotactile menu and the cursor starts moving to the right. When the cursor is exactly under the target, the user triggers the brain switch to issue the stop command. Then, the menu reactivates, and the subject triggers the brain switch when he/she feels the stimulation under the electrode 1 (move up). The menu stops, and the cursor starts moving up until it hits the target. With 8-channel control, the subject can be more efficient and reach the target by issuing only a single command. To this aim, he/she needs to trigger the brain switch when electrode 2 (move top—right) is activated. This would move the object diagonally, towards the top-right corner, thereby hitting the target (Fig. 1, P1). However, due to false positive activation of the brain switch or improper triggering by the user (too soon/late), the subjects would generate wrong direction commands or unintended stop commands, traversing thereby more complex trajectories while moving the cursor from the initial position to the target (Fig. 1, P2).

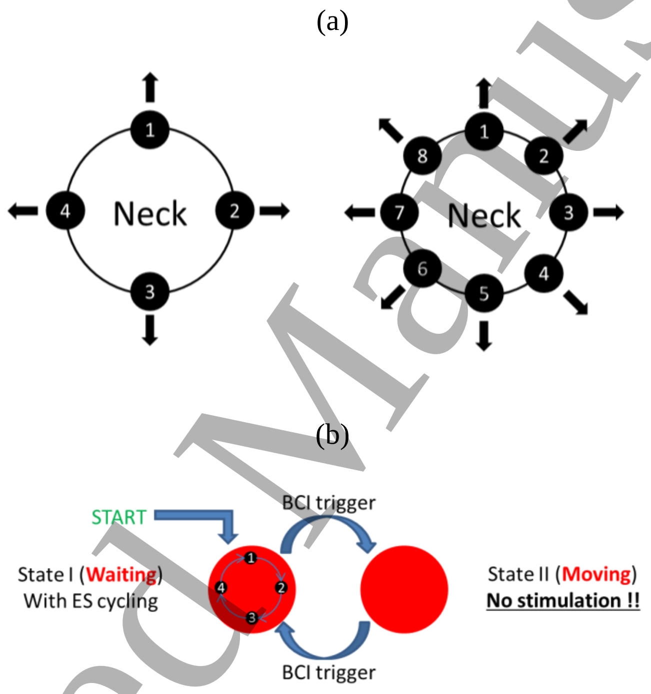


Fig. 2. The novel online control scheme based on state-machine integrating the endogenous sensory discrimination and selection BCI: (a) electrotactile menu and commands: the full black circles stand for the electrodes placed around the neck, while the arrows are the commands associated to each electrode; (b) online control strategy (state machine). The full red circles stand for two states of the online control scheme, i.e. Waiting and Moving. During State I (Waiting), the electrotactile menu is running, and the user can activate the BCI trigger to choose a direction to move. When the state machine transits to State II (Moving), the stimulation stops (inactive menu), but the user can stop the movement of the cursor by triggering the brain switch.

2.4. Experimental Procedure

The experiment consisted of a training and two testing sessions. The fast brain switch was trained in the training session, and then applied to online cursor control in the testing sessions. Between the training and testing sessions, there was a short familiarization phase for the subject to get to know the system and control strategy.

In the training session, the subjects sat in a chair with the right foot fixed in a custom-made pedal in a comfortable position. They were instructed to perform 30 trials of ballistic dorsiflexions. The EMG signal from the TA muscle was recorded to obtain the timing of the muscle activation (movement onset), while the EEG data were used for training the classifier. The EEG data were pre-processed (band-pass at 0.05-3 Hz and a Laplacian spatial filter centered at Cz) to generate the virtual Cz. The Laplacian spatial filter yields excellent performance with a few EEG channels [16], while the common spatial patterns based method performs very well with a large number of channels, as shown by Chen et al [30]. Then, EEG data of the virtual channel were segmented into “signal” (i.e. MRCP) and “noise” (the remaining part) according to the movement onset (i.e. EMG activation). Both the “signal” and “noise” segments were used to train the LPP-LDA classifier, as explained in [13], which was then used for detecting the motor intention in the testing session with online control. During the testing run, the trained classifier acts as a brain switch to classify the incoming EEG data stream into ‘signal’ or ‘noise’, resulting in a real-time detection of MRCP.

The online control protocol was divided into a movement execution (ME) run and a motor imagery (MI) run, depending on the motor task used to trigger the brain switch. During the online control task, the subjects were looking at a monitor placed 50 cm in front of them, showing the GUI for the planar cursor control (Fig. 1). Each run consisted of 8 trials. A trial corresponded to the task of hitting one of the 8 targets, i.e. the 8 green cycles shown in Fig.1. In each trial, one target appeared on the screen and across trials the order of the targets was randomized. The task for the subject was to reach the desired position (i.e., hit the target marker) as fast as possible using the control scheme described in section 2.3.2. The trial was finished if the cursor hit the target (trial successful) or if a predefined time-out (3 min) expired (trial unsuccessful). 4-directional control was tested using ME and MI and 8-directional control was assessed using MI only. If the cursor hit the workspace boundary, it would stop immediately, and the subject needed to issue a new command for moving.

2.5. Evaluation criteria

Four criteria were used to evaluate the subject performance during online control: completion rate and time, path efficacy and the number of collisions.

The completion rate was the primary outcome measure and it was defined as a percentage of successfully completed trials w.r.t. the total number of trials. As explained above, the trial was deemed successful if the cursor reached the target before the time out period of 3 min.

The completion time was the time required for the subject to reach the target, measured from the start of the trial until the moment in which the cursor hit the target. It was computed only for successful trials.

The path efficiency was defined as the ratio between the length of the optimal path from the initial position of the cursor to the target, and the length of the path generated by the subject in the given control trial. Importantly, the optimal path was not the shortest distance on the screen (i.e., straight line between the initial and target position), but the shortest path given the possible direction commands implemented by the system (Fig. 1).

The number of collisions between the cursor and the workspace boundary was counted. Whereas the other outcome measures assessed the control effectiveness, the number of collisions evaluated the safety of the control loop.

2.6. Statistical analysis

A Friedman testwas performed to compare the system performance between ME and MI for 4-direction control. Due to the limited number of subjects who tested the 8-command control, no statistical analysis was made to compare 4-direction control with 8-direction control.

3. Results

3.1. Four-direction control

As shown in Table I, nine out of eleven subjects attained the completion rate of 100% when using ME, and seven of them still reached all the targets successfully with MI. Fig. 3. illustrates the ME and MI performance averaged over all subjects. There was no statistically significant difference (p=0.32) between the average completion rates with ME and MI (96.6±7.7% vs 92.0±14.4% respectively). Moreover, the average completion time and path efficiency were also similar for ME and MI (44.4±19.8s vs 45.3±18.5s; p=76; 30.8±11.7% vs 21.2±12.2%, p=0.13). Finally, the average number of collisions was very close for MI and ME (0.4±0.5 vs 0.5±0.5, p=0.48).

3.2. Eight-direction control

The results for the five subjects who tested the 8-direction control are shown in Fig. 4, and compared to their performance with the 4-direction control. Importantly, the completion rate, which is the primary outcome, remained at 100% in all subjects. In the secondary outcome measures, the number of collisions per trial increased with 8-direction control in four of the five subjects, while there was no clear trend for the path efficiency and completion time. Nevertheless, the average number of collisions is still overall small, less than one per trial. In summary, in one subject the performance improved with 8 directions in all the secondary outcome measures, while in two subjects it worsened, and for the remaining two the results were mixed. Some example paths traced by SUB2 utilizing 4-channel and 8-channel control are shown in Fig. 5. With 4-channel control, the subject could reach the target with 2 to 3 commands in the best trials, but occasionally, false positives would be generated leading to more complex paths. For the 8-channel interface, the subject extensively used the new commands for diagonal movements and combined them successfully with the vertical and horizontal motions.

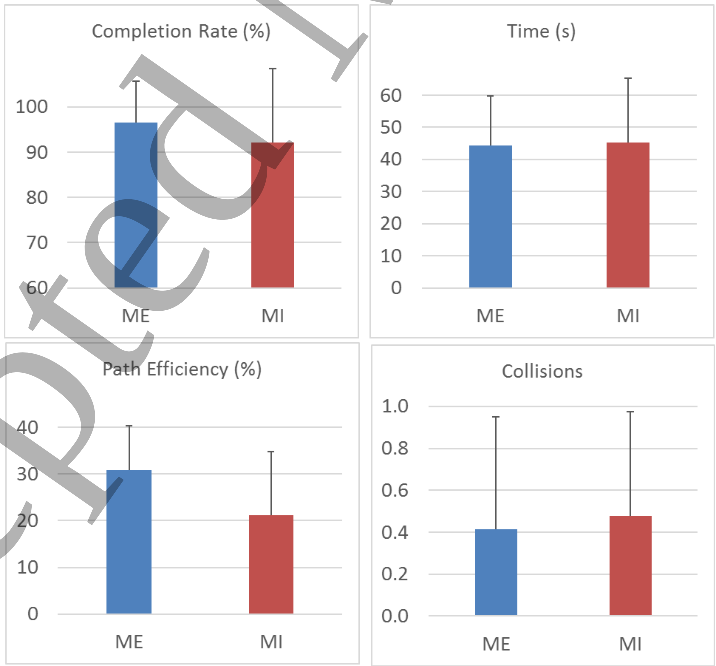


Fig. 3. Summary of performance. No statistical difference was found between motor execution (ME) and motor imagery (MI) for completion rate, time, path efficiency and number of collisions.

Table 1 Performance of the 4-direction control

SUB	**ME**				**MI**			
	CR (%)	**Time (s)**	**PE (%)**	**NC**	**CR (%)**	**Time (s)**	**PE (%)**	**NC**
1	100	33.7	29.3	0.1	100	24.2	16.3	0
2	100	72.3	28.1	1.1	100	44.3	48.6	0.6
3	100	32.3	44.3	0	100	18.7	28.7	0
4	100	38.1	35.2	0.1	100	50.7	13	0.1
5	100	24.7	41.4	0	100	34.9	16.3	0.5
6	100	90	9.1	0.1	100	54.5	35	0.1
7	87.5	31.9	31.1	0	50	72.5	7.2	1.5
8	100	26.2	37.8	0.1	87.5	51.9	14.2	1.1
9	100	53.9	39.8	0.6	87.5	78.4	13.9	0.1
10	75	52.2	7.1	1.5	87.5	22.4	9.6	0.4
11	100	33.5	36	0.9	100	45.9	30.5	0.8
Avg	**96.6±7.7**	**44.4±19.8**	**30.8±11.7**	**0.4±0.5**	**92.0±14.4**	**45.3±18.5**	**21.2±12.2**	**0.5±0.5**

*ME=motor execution; MI=motor imagery; CR=completion rate; PE=path efficiency; NC=number of collisions.

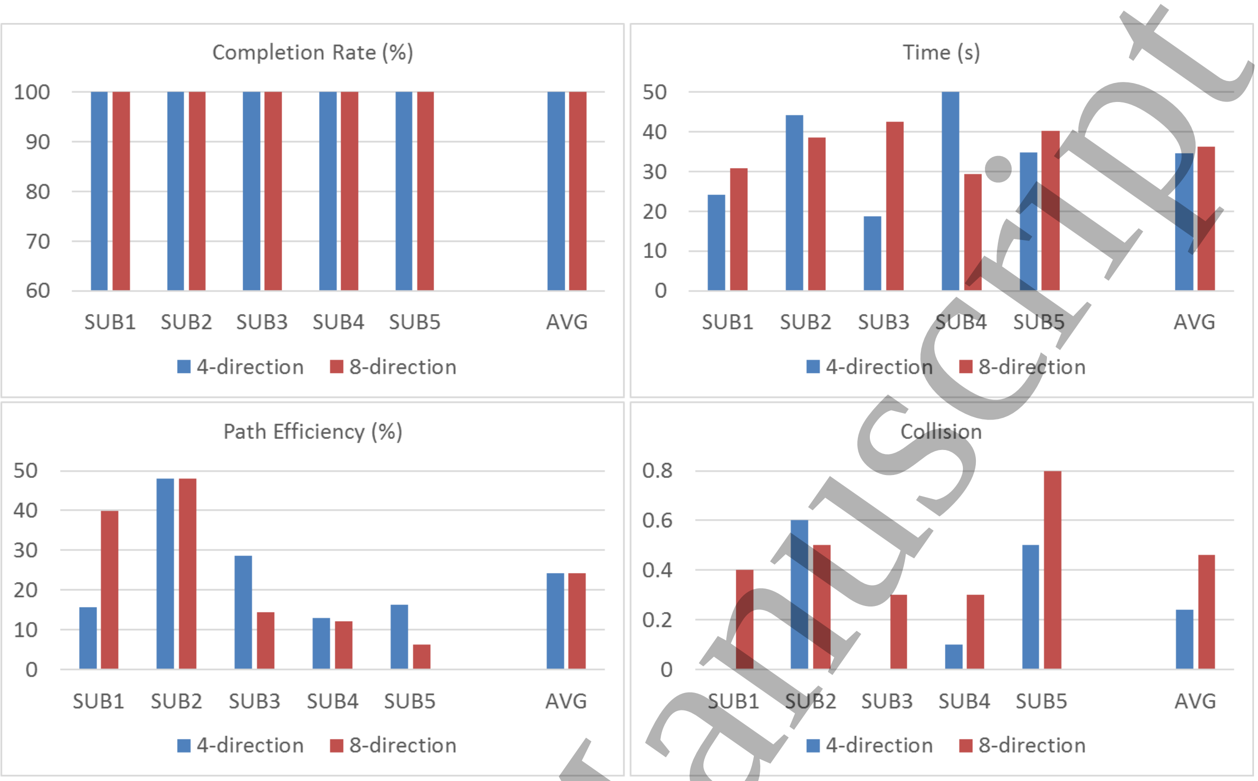


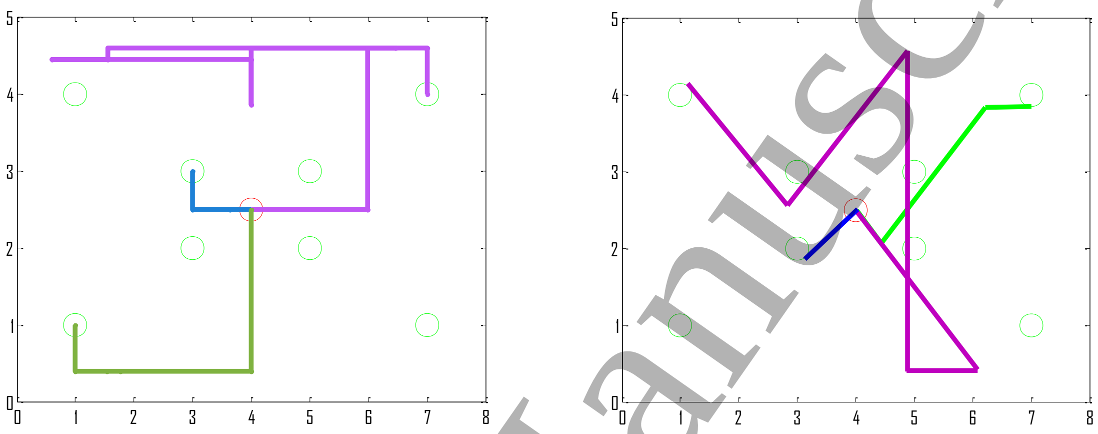
Fig. 4. Comparison of 4- and 8-direction control. The blue and red bars present the performance of 4- and 8-direction control, respectively, from SUB 1 to 5 and their average (AVG).

1. Discussion

In this study, we presented a novel control method that integrates a multi-class BCI based on endogenous sensory discrimination and selection within a simple state-machine for 2-D object control. An electrotactile menu provided 4 or 8 directions to the user who actively performed ME or MI of foot dorsiflexion to trigger the MRCP-based brain switch for the selection of the desired movement direction. The results from eleven healthy subjects showed a high completion rate (~97% and ~92% for ME and MI, respectively), with a small number of collisions in the 4-class protocol. Moreover, when the number of classes was increased to 8, the subjects still reached all the targets successfully, while the increase/decrease in performance in the secondary outcome measures was subject specific. Nevertheless, this test demonstrates that the subjects were able to utilize a larger number of commands to successfully accomplish the task. This could be very relevant for controlling complex systems using BCIs (e.g., a robotic manipulator with many degrees of freedom). .

Importantly, the performance of the online control loop remained similar when ME was replaced by MI to trigger the BCI, which demonstrates the robustness of the approach. Since the control loop requires a single mental task (imagery of right foot dorsi-flexion) to trigger all the commands, the online selection with MI was as reliable as when using a real movement. Furthermore, the imagery seemed not to be disturbed by the need to focus on the electrical stimulation and react to the cursor movement. The present study demonstrated that this novel BCI can be successfully utilized within an online control scheme. Therefore, it can be an attractive solution for dynamic tasks, especially those that require many commands, which cannot be provided using the classic MI solutions.

Continuous 2-D object control enables important applications such as moving a cursor to use a computer or steering a wheel-chair. Previous studies used different signal modalities for this purpose, including visual and tactile P300 [6,8], SSVEP [12], SSSEP [11], MI [14], and their combinations in a so-called hybrid paradigm [20,21]. However, it is difficult to directly compare their performance, since various platforms and different outcome measures have been used. Nevertheless, compared to the previous approaches, the system proposed here introduces several novel features.


(a) 4-direction control

(b) 8-direction control

Fig 5. Representative paths generated by SUB2 using (a) 4- or (b) 8-direction BCI control. The blue and green lines are examples of efficient paths to hit the center or corner targets, respectively. The purple lines are paths with poor performance.

The conventional MI BCIs for online control implement at most 3 commands (e.g., left and right rotation, and go forward), because of the limited bandwidth of BCI communication. To circumvent this limitation, mapping schemes were designed to increase the number of possible commands. One approach was to employ coding schemes, as when performing two MI tasks in a specific order across two successive cuing periods [31], and/or changing the interpretation of BCI classes depending on the state of the system [32,33]. In the latter scheme, the state transitions can be preprogramed (timed [32]), user initiated [34], or triggered using sensors (e.g., obstacle detected) [33]. For example, in [33], the same MI indicated “left turn” during normal motion and “follow left wall” if a left wall was detected by the wheelchair sensors. These strategies increase the number of commands (e.g., from 2 to 3 [32]) but also require the user to learn the mapping and monitor the system state. The method proposed in this study increases the number of commands in a simple, intuitive and effective manner. The number of commands is defined as #BCI classes × N, where N is the number of menu options. In the present study, we used a single BCI command (MRCP detection, 1 × N), but the menu could be used in combination with other BCI paradigms that allow triggering more classes (M × N, where M is the number of BCI classes). Therefore, the presented approach substantially outperforms the previous methods in the number of directional commands that can be generated. Moreover, the menu options were intuitively related to the commands as the electrodes were placed in the direction which they triggered (e.g., front electrode represented moving forward).

By using an intuitive and task-related placement of the tactile stimuli, the user easily associated the stimulus with the corresponding command. Tactile stimulation has been used before for online control of direction through tactile P300 [6] and SSSEP [11], but these methods impose requirements on the placement of the stimulators and the stimulation parameters. In the SSSEP based BCI system, the vibrators were attached to the left hand, right hand and foot corresponding to the commands of turning left, turning right and moving forward. In addition, the stimulation frequencies had to be adjusted for each user individually to increase discriminability of SSSEPs. In the tactile P300 based BCI, the stimulators were placed on the left thigh (move left), right thigh (move right), abdomen (move forward) and neck (move backward). In both methods, therefore, the stimulators were placed far apart to assure discriminability in the EEG and the stimulation was constantly delivered to the subject, who had to focus on one of the stimulators to trigger the command. In the method presented here, the placement of the stimulators as well as the stimulation parameters are flexible, as they were not used to produce discriminable responses in EEG. The stimulators were therefore placed close together, around the neck and the stimulation could be delivered intermittently -- a short stimulus to indicate an active command -- and in the Moving state, the stimulation was deactivated. Therefore, the tactile interface is more compact and less intrusive than in the previous approaches.

The novel control scheme was designed to allow time critical control (e.g., navigating a wheelchair) despite the imposed delays in generating commands as the subject needed to wait for the proper cue (electrotactile menu). In the Waiting state, the brain switch was used to provide commands synchronized to the tactile cues, while in the Moving state, the switch operated as a truly asynchronous BCI, where the subject could issue a stop command at any time. The synchronous mode in which the subject needed to wait until the desired command was presented by the cyclic tactile menu, was used while the cursor (wheelchair) was stationary, and therefore, there was no time pressure to respond. The asynchronous mode was activated once the cursor was moving, to allow the subject to promptly react (e.g., stop the wheelchair before collision). The test results have demonstrated that the proposed control scheme was indeed effective and robust, leading to a high completion rate and low number of collisions. This level of performance was maintained even after doubling the number of commands from four to eight. The robustness and safety of the system could be further improved by implementing the proposed method within a shared control framework [28] (e.g., automatic detection and/or obstacle avoidance); however, this was outside the scope of the present study.

In addition, the proposed concept for online control is flexible and different control schemes can be devised. For example, we have performed two pilots (results not reported) with different control strategies. In the first pilot, the strategy relied on “double triggers”. In this scheme, the user needs to trigger the brain switch twice to change the status from “waiting” to “moving”. After the first trigger, an arrow was shown next to the cursor indicating the selected direction. Then the user needed to wait for another ES cycle to make a second trigger for the same direction, to confirm the previous selection and move the object. Another strategy called “silent confirmation” was tested in the second pilot. In this case, the subject confirmed the first choice by not giving any command in the subsequent ES cycle. The “double trigger” requires high true positive rate of the brain switch, while the “silent trigger” demands low false positive rate. Both control strategies were feasible and tested on a number of users before applying the final control that was chosen for reporting the results. This demonstrates the flexibility of our approach, as the control loop can be optimized according to the characteristics of the BCI method (e.g., true positive and false positive detection) selected to trigger the commands.

The interface was employed to generate horizontal, vertical and diagonal movements, but the same configuration could have been used to control rotation (as done in many studies on wheelchair control [6]). The left and right electrode can be used to start rotating the cursor to the left and right, respectively, and an additional trigger could then be employed to stop the rotation or start moving forward. Finally, a high-density electrode array around the neck or waist could be used to directly select from a range of directions, implementing thereby a proportional directional control.

A limitation of this study is that all tests were performed on healthy participants. Although the focus of this study is the feasibility validation of a state machine trigger BCI on healthy subjects, we acknowledge that the lack of patients’ tests is a substantial limitation of the study. Future work will need to focus on patients in real environments such as wheelchair control. Based on the fact that MRCPs have similar features in patients as in healthy subjects [35], and the successful application of our brain switch on patients [35,36], we are confident on the feasibility of the proposed approach in clinical applications. However, this needs further investigations in the future.

In conclusion, we have shown the feasibility of a BCI-based 2D control based endogenous sensory discrimination, where the electro-tactile menu was selected by a fast brain switch. The system allowed healthy users to control a cursor in a target hitting task in a 2D space with a high success rate and minimal training and it is therefore a promising new approach for BCI control of external systems, such as wheelchairs.

Acknowledge

This work was supported financially by the China Scholarship Council (Contract Nr. 201204910155).

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