A binary motor imagery tasks based brain-computer interface for two-dimensional movement control

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Abstract

Objective. Two-dimensional movement control is a popular issue in brain–computer interface (BCI) research and has many applications in the real world. In this paper, we introduce a combined control strategy to a binary class-based BCI system that allows the user to move a cursor in a two-dimensional (2D) plane. Users focus on a single moving vector to control 2D movement instead of controlling vertical and horizontal movement separately. Approach. Five participants took part in a fixed-target experiment and random-target experiment to verify the effectiveness of the combination control strategy under the fixed and random routine conditions. Both experiments were performed in a virtual 2D dimensional environment and visual feedback was provided on the screen. Main results. The five participants achieved an average hit rate of 98.9\% and 99.4\% for the fixed-target experiment and the random-target experiment, respectively. Significance. The results demonstrate that participants could move the cursor in the 2D plane effectively. The proposed control strategy is based only on a basic two-motor imagery BCI, which enables more people to use it in real-life applications.

Keywords: brain-computer interface, motor imagery, 2-dimensional movement control

(Some figures may appear in colour only in the online journal)
(2D) cursor control has been introduced which enables the user to control a considerably enhanced interface [22–24]. Generally, invasive BCIs achieve more precise movement control because of the higher signal-to-noise ratio of the brain signal acquired from action potentials or local field potentials; however, there are some substantial technical difficulties and significant clinical risks [25, 26]. By contrast, electroencephalography (EEG)-based non-invasive BCI is safer and more comfortable to apply, and could be performed by every individual with no special competence [27–29]. Wolpaw et al [30] used a non-invasive based BCI to train four participants to control a 2D cursor control with a motor imagery (MI) paradigm, and the participants achieved good performance. This pioneering study inspired more researchers to develop 2D cursor control systems using EEG-based BCI [31, 32], such as steady-state visual evoked potential (SSVEP), P300, event related desynchronization/synchronization (ERD/S) [30, 33, 34].

Recently, hybrid strategies have been used in 2D movement control to exploit different combined BCI approaches. Li et al [35] combined an motor imagery (MI) and visual attention approach to extract the ERD and P300 to control horizontal movement and vertical movement, respectively. In another study [36], the authors combined ERD and SSVEP to control 2D movement.

In previous studies, single modality and multi-modality BCIs demonstrated good performance in 2D control experiments; however, most of these BCIs applied complex control strategies with a heavy workload [17]. We developed a three-class MI-based BCI for 2D control; however, some participants failed to control a three-class MI simultaneously in these experiments [24]. Developing an easy-to-use 2D control strategy based on a single EEG modality is still a challenging issue. In this work, we use two-class MI tasks to develop a 2D movement control system. A novel combination strategy is introduced, which allows the participant to control 2D movement by controlling the combination of two-class MI tasks in a rotating coordinate system (RCS). Experimental results and further data analysis demonstrate the high performance compared with other state-of-the-art BCI-based 2D movement control systems.

2. Materials and methods

2.1. Participants

Ten healthy adults (all right-handed; four females and six males, age range 20–26 years, average age 23 years) were recruited to participate in the experiment. All participants were free of neurological or psychiatric disorders. Participant 1 and participant 2 had prior experience in MI-based BCIs, and the other participants had no prior experience. Prior to the experiment and after they received overall information about the nature of the experiment, all participants signed an informed consent form. They received 15 RMB per hour for their participation.

2.2. Data acquisition

EEG data were acquired using a Gtec Amplifier (g.tec, Graz, Austria), with a sample rate of 256 Hz and with a band-pass filter of 5–30 Hz. To fully cover the motor cortex area for all participants, 13 electrodes at the standard positions of the 10–20 international system [37] (FC3 FCz FC4 C5 C3 C1 Cz C2 C4 C6 CP3 CPz CP4) (figure 1) were used for signal acquisition. The number of electrodes can be reduced for specific participants in further studies. The ground was fixed on the AFz and a reference electrode was located at the left earlobe.

2.3. Control paradigm

In a normal two-class MI-based BCI system, the participant is required to perform one task at a time. The BCI system calculates two posterior probabilities, which represent the two MI tasks, and provides a predict label (e.g. 1 or −1) according to the higher probability. In this work, we used a left hand and right hand MI-based BCI system. Posterior probabilities ($p_1$, $p_2$) were applied to construct a 2D movement control system instead of discrete labels. For the first step, the posterior probabilities were projected into two vectors ($P_1$, $P_2$) in a 2D plane. As shown in figure 2(b), the $P_1$ was projected from probability $p_1$, and the norm was equal to $p_1$. $P_2$ was projected from $p_2$ in the same manner. $P_1$ and $P_2$ were placed on the left-hand side and right-hand side of the $y_{0}^\delta$ axis at a fixed 60° angle. In the experiment, the projected vectors that numerically translated from probabilities $P$ were produced trial by trial. In the $i$th trial, $P_1^i$ and $P_2^i$ were the projected vectors that represented the probabilities related to the left and right hand imagery, respectively.

As shown in figure 2(b), the initial velocity vector $V_0$ was combined by vector $P_1^i$ and $P_2^i$, which moved the cursor from position $S_0$ to $S_1$ in a step (trial) time (step time = 100 ms). After the first step, if $P_1$ and $P_2$ were projected in the same
direction as the initial position, the velocity vector could only move the cursor in the area between \( P_1 \) and \( P_2 \). To move the cursor toward any position in the 2D plane, we used an RCS that moved along the current velocity vector. As shown in figure 2(c), the origin of the RCS moved from \( S_0 \) to \( S_1 \) and \( YR_1 \) in the direction of \( V_0 \). Figure 2(d) demonstrates how to generate \( V_{k+1} \) from \( V_k \) (current velocity vector) and \( V^K \) (The combination of probabilities). (f) The RCS moving with the cursor’s trajectory.

\[
V_{k+1} = \varepsilon V^K + V_k
\]

where \( \varepsilon ( < 1 ) \) is an attenuation parameter, which is an empirical parameter to limit the speed of the cursor. In this paper, we chose \( \varepsilon = 0.1 \) for all participants.

To calculate the coordinates of the cursor in an absolute coordinate system, we need to determine the relationship between the RCS and absolute coordinate system. For the first step, the origin is coincident with both coordinates. The coordinates of the cursor are calculated as

\[
X_0 = V_{0x} b \\
Y_0 = V_{0y} b
\]

where \( b \) is the step length. To limit the speed of the cursor, step length \( b \) is set to 8 pixels. For the second step, the coordinates are calculated as

\[
X_k = X_{k-1} + V_{kx} b \\
= X_{k-1} + \varepsilon P_{2} \cos(\pi/3 - \alpha) + \varepsilon P_{1} \cos(\pi/3 + \alpha)]b
\]

\[
Y_k = Y_{k-1} + V_{ky} b \\
= Y_{k-1} + \varepsilon P_{2} \sin(\pi/3 - \alpha) + \varepsilon P_{1} \sin(\pi/3 + \alpha)]b
\]

Figure 2. Illustration of the combination strategy. (a) Initial position of the RCS, which is in coincident with the absolute coordinate system. \( YR_0 \) represents the vertical axis and \( X \) represents the horizontal axis. Two dotted lines indicate the projected directions and \( S_0 \) is the starting point of the cursor. \( \alpha \) is the angle between the \( YR_0 \) axis of the RCS and the positive horizontal axis of the absolute coordinate system. (b) First velocity vector \( V_0 \) is combined with \( P_{0}^{1} \) and \( P_{0}^{2} \). (c) RCS moved from \( S_0 \) to \( S_1 \) and \( YR_1 \) in the direction of \( V_0 \). (d) Demonstration of how to generate \( V_{k+1} \) from \( V_k \) (current velocity vector) and \( V^K \) (The combination of probabilities). (f) The RCS moving with the cursor’s trajectory.
where $X_{k-1}$ and $Y_{k-1}$ are the previous coordinates; $V_{kc}$ and $V_{kc}$ are the projection of $V_k$ on the horizontal and vertical axes, respectively; and $\alpha$ is the angle between the $y^R_k$ axis of the RCS and the horizontal positive axis of the absolute coordinate system (figure 3), where $\alpha$ is calculated as follows

$$\alpha = \arctan \frac{S_{(k-1)y} - S_{(k-2)y}}{S_{(k-1)x} - S_{(k-2)x}}.$$  \hspace{1cm} (6)

The control procedure is similar to our previous work [24], in which participants were instructed to control a combination of probabilities by performing one MI task or two MI tasks simultaneously; however, the main difference is the number of combinations. In [24], participants switched between three types of combination (left hand and right hand, left hand and foot, right hand and foot) according to specific target. However, participants only need to control one combination (left hand and right hand) in the proposed system, which greatly reduces the difficulty of the control task.

To build the proposed paradigm based 2D control BCI system, the common spatial pattern (CSP) [38] was applied to extract the features of two MI tasks and a linear support vector machine (SVM) classifier was trained to discriminate the different MI patterns. However, the outputs of standard SVM are discrete labels. In order to obtain the posterior probabilities, Platt proposed a method for a standard SVM [40], and this method was implemented in the LIBSVM toolbox [39]. In the LIBSVM toolbox, to output the posterior probabilities, we needed to set the $-b$ parameter in the training and testing function. We applied a grid search method to determine the best parameters, and used five-fold cross-validation.
The average time for each target in the five-fixed targets experiment. The bold type indicates that the shortest time for each target among five subjects.

| Parti | Target 1 (s) | Target 2 (s) | Target 3 (s) | Target 4 (s) | Target 5 (s) |
|-------|-------------|-------------|-------------|-------------|-------------|
| 1     | 11.9 ± 0.5  | 6.9 ± 1.4   | 9.3 ± 1.5   | 4.8 ± 1.4   | 11.3 ± 5.6  |
| 2     | 12.9 ± 1.5  | 10.0 ± 5.0  | 13.7 ± 6.0  | 5.3 ± 1.2   | 13.1 ± 2.6  |
| 3     | 12.9 ± 0.9  | 6.9 ± 2.7   | 14.1 ± 7.8  | 5.5 ± 2.5   | 11.9 ± 4.1  |
| 4     | 13.0 ± 3.2  | 10.0 ± 4.3  | 12.4 ± 4.5  | 5.3 ± 0.7   | 11.1 ± 1.8  |
| 5     | 32.4 ± 18.3 | 31.7 ± 17.1 | 32.5 ± 14.2 | 10.3 ± 6.0  | 20.9 ± 14.3 |

2.4. Experimental procedure

The experiment consisted of two conditions: the five-fixed target experiment and the five-random target experiment. Before the two experiments, the participants took part in an MI training session. In the training and 2D control experiments, all participants were instructed to imagine moving their left (right) hand to fill the left (right) side bar or move the cursor to the left (right).

2.4.1. Motor imagery training.

All participants were required to take part in two-class MI training (left versus right hand movement imagery). As shown in figure 4, the participants performed MI to fill the bar divided into subbar, where N is the step number) following the direction of the arrow. Each trial lasted 3 s, divided into 30 steps, with a step time of 0.1 s. The selection criterion was that the performance for left and right hand imagery for three consecutive runs (each run included 20 trials) was over 85%. If the participants could not achieve the selection criterion within five training sessions, they were not allowed to participate in the subsequent experiment.

2.4.2. Online 2D experimental conditions. The participants had to perform two experimental tasks. In both conditions the experimental screen size was a rectangle of 1440 × 878 pixels figure 5(a). In the lower right area of 240 × 300 pixels, a speedometer with a maximum speed of 8 pixels was depicted. A red dot indicated the cursor and blue dots represented the targets. The workspace was 1440 × 878–240 × 300 pixels. The ratio of the size of the cursor to the size of the target and workspace was 0.00048:0.0022:1.

In the five-fixed target experiment, we placed five targets in a fixed sequence figure 5(a). For each run, the objective was for the participant to hit all five targets from target 1 to target 5. At the beginning of each task, a 3 s countdown clock timer was shown at the center of the screen to indicate the start of the tasks, meanwhile the color of the current target changed to green. If the participant controlled the cursor to hit a target within 60 s, the next trial would start immediately with another 3 s countdown timer. Otherwise, the system would terminate the trial after 60 s and start the next trial. All participants were required to repeat the experiment 15 times.

The aim of the five-random target experiment was to verify that the participant could move the cursor to any position without a fixed routine. In this experiment, the initial position of the cursor was at the center of the screen. After a 3 s countdown, a green target appeared in a random position with a distance of 439 pixel from the current cursor position figure 5(b). If the participant could not complete a trial within 60 s, the system stopped the current trial and the next trial started. The next target appeared at any position within a range of 439 pixels from the current cursor position. All participants were required to repeat the experiment 15 times.

3. Results

All participants attended the training session, but only five participants (1, 2, 3, 5 and 9) met our selection criterion, that is, an average accuracy of three consecutive runs over 85%.

Four participants finished two experiments (15 runs for each condition) and one participant attended 10 runs only in both condition experiments due to a personal reason. Table 1 shows the experimental results of the five-fixed targets experiment including the hit rate and the trajectory ratio (the mean trajectory versus the shortest trajectory). Four participants achieved 100% hit rate with a small trajectory ratio. Participant 1 achieved the best trajectory ratio which is coincide with the trajectories shown in figure 6. Even the trajectory ratio of participant 9 was the biggest compared with the other participants, he also achieved a high hit rate. In table 2, the average time for each target is depicted. Participant 1 outperformed other participants in target 1, 3, 4. In addition, the performances of participant 1 in the other two remaining
targets were comparable to the best performer of the respective target. Figure 7 demonstrated that the participant was able to apply a different combination of two MI tasks to move the cursor to a specific target.

The specificity of the five-random targets experiment was that the participant could not prepare for the next target until he or she had finished the current target. Table 3 summarises the results of the five-random targets experiment including the hit rate, the average time and trajectory ratio. The performance of all participants was satisfactory.

### 4. Discussion

In this study, we present a combination strategy based 2D cursor control system which allows participant to perform the 2D cursor control by combining two different MI tasks (right hand motor imagery and left hand motor imagery). In order to demonstrate the utility of the proposed system, we set the selection criterion for the training session quite high (85%), to ensure that our paradigm could be tested without the risk that low MI performance was caused by little training practice. Five participants successfully completed the training session and participated in the five-fixed targets and five-random targets experiments. As shown above, all participants achieved high performance in both experiments. At the beginning of each trial, the initial velocity vector always points upward fixed with the initial mapping position. Afterwards, the participant needs to adjust the cursor to the direction of the target by concentrating on one MI task. When the cursor point to the target direction, the participant moves the cursor in a straight fashion to reach the target by controlling the combination of two MI tasks. As shown in figure 5(a), participant 1 controls the tasks very well and moves the cursor with a short trajectory ratio (The trajectory ratio of Participant 1 is 1.11. The more the ratio is close to 1, the more trajectory is close to a straight line). In this work, we hypothesized that participants are able to employ one MI task or simultaneous two MI tasks to control the combination of probabilities. Figure 7(b) shows how the participant controls different combinations of probabilities to move the cursor to hit different targets. Comparing the hit rates and trajectory ratios in both experiments, the participants achieved similar results. Even participant 9, whose performance in the five-fixed target experiment was the worst, performed better in the five-random target experiment. After the experiments, the participants told us that the unpredictability of the target inspired their motivation.
Wolpaw proposed three criterions to measure the performance on a point-to-point movement: movement time (i.e. the lower the better); movement precision (i.e. the target size as a percentage of workspace; the smaller the better); hit rate (percent of targets reached in the time allotted; the higher the better) [30]. Although the number of targets and the control strategy differs in our work, we all share the goal of controlling 2D point-to-point movement and was comparable in terms of success in achieving this goal. In [30], the best hit rate was 78% for healthy participants, which is less than the lowest hit rate in our work, and Wolpaw et al’s movement precision was 4.9% greater than 0.22% achieved in our present study (the movement precision the smaller the better), so their movement times were shorter (1.9s compared to the average times shown in table IV and V). In our previously study [24], a three-class MI based control strategy was employed to control 2D movement. The participants achieved high performance but they also experienced heavy workload to perform the three-class MI task. In the current work, the performance is similar but the workload is reduced because the participants need to control the combination of two MI tasks only. Compared with the hybrid BCI, Li et al [35] realized 2D cursor control by combing MI and P300 and achieved success rates of 84.5%–97.5%, which is a range that is substantially lower than the hit rate accuracy in the proposed five-fixed target experiment. Furthermore, our movement precision is smaller than their 0.3%. In another hybrid work [36] employed the MI to control the vertical position and SSVEP to control the horizontal position, the average accuracy over all participants was around 60%. These hybrid studies realized 2D control, but time was consumed to detect or trigger P300 and SSVEP compared with motor imagery. Moreover P300 and SSVEP cause visual fatigue. For single modality-based BCI, such as the SSVEP or P300, the same drawbacks occur, and the discrete commands also cause the cursor to move in a zigzag routine.

For long distance targets in both experiments (the shortest distance between two targets is 263 pixels.), five participants achieved high performance. However, with the proposed system it is difficult to move the cursor to hit a target located at a short distance. As shown in figure 2(d), the cursor only changes direction within a limited range. Therefore, the cursor does not hit the target if it is located within a short distance e.g. 20 pixels and is also outside the direction range that the cursor can reach. Figure 8 shows the cursor approaching the target 2 that is located at a short distance from the cursor and is also out of the cursors direction range, the participant can only move the cursor to turn a long curve to hit the target. However, this limitation is beneficial for some application, like wheel chair control. Using the proposed control strategy, user can control wheel chair to change the direction smoothly and avoid changing direction sharply.

5. Conclusion

We proposed a 2D control system with a combination strategy of two-class MI tasks. Participants were instructed to focus on controlling combinations of probabilities while performing one or two MI tasks simultaneously. In two types of online control experiments, the preselected participants ranked high in their performance.

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