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Transcranial static magnetic field stimulation over human middle temporal complex reduces spatial accuracy of continuous visuomotor performance

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The continuous visuomotor (CVM) performance of ball-sport athletes like table tennis players relies heavily on visual motion discriminability in a visual field-dependent manner. This discriminability reflects the cortical excitability of the motion-sensitive human middle temporal complex (hMT+). Therefore, hMT+ excitability may play a critical role in determining CVM performance, but direct evidence supporting this relationship remains limited. In this study, we examined whether applying transcranial static magnetic field stimulation (tSMS), which reduces cortical excitability, over hMT+ impairs CVM performance in table tennis players. Twenty table tennis players performed a CVM task requiring them to modulate their prehensile force on a force sensor to control a cursor to hit balls moving continuously from right to left on a screen. The task was performed both before (Pre-test) and during (During-test) tSMS application over the left hMT+. Since participants captured the moving target information in the right visual hemifield and processed it in the left hMT+, we hypothesized that reducing hMT+ excitability would impair performance. Results showed a significant deterioration in the spatial accuracy of the cursor movements during the During-test compared to the Pre-test. These findings suggest that hMT+ excitability is crucial for maintaining the spatial accuracy of CVM performance.

In ball sports such as table tennis, players must continuously adjust the position of their rackets in response to a rapidly moving ball, relying heavily on visual information. This ability is referred to as continuous visuomotor (CVM) performance, and it is critically dependent on the efficiency of visual information processing. In particular, the capacity to discriminate visual motion signals such as the speed and direction of movement (i.e., visual motion discriminability) is essential for achieving high levels of accuracy in the CVM task. In our previous work, we combined a motion direction discrimination task using a random dot kinematogram with a CVM task, and found that perceptual motion direction discrimination performance correlated with CVM performance[1]. These findings suggest that visual motion processing plays a key role in supporting accurate visuomotor behavior.

Perceptual motion direction discrimination performance reflects the function of the human middle temporal complex (hMT+; the putative homolog of macaque MT)[2–4], a motion-sensitive region located in the V5/MT+ area of the visual cortex. In addition to its role in visual perception, hMT+ has also been implicated in visuomotor performance. For instance, microstimulation to monkey medial superior temporal area (MST), the anterior portion of hMT+ homologue, during arm-reaching movements toward a moving target has been shown to impair the spatial accuracy of those pointing performance[5], suggesting that disruptions in visual motion processing within MST can negatively affect visually guided movements aimed at moving objects. Similarly, applying repetitive transcranial magnetic stimulation (rTMS) over hMT+ in humans during tasks involving moving targets, such as a visual trajectory perception task[6] and a manual interception task[7], led to significant declines in task performance.

Together, these findings suggest that hMT+ plays a critical role in both perceptual and perceptual-motor performances involving moving stimuli. Further support comes from an EEG study, in which reaction time from visual motion onset to the button press in ball-sports was found to correlate with the latency of the N2

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component of motion-evoked potential recorded over hMT +[8,9]. This relationship implies that visual responses in hMT + contribute to the rapid motor reactions required in visuomotor tasks. Therefore, hMT + will likely play a key role in supporting CVM performance.

We recently demonstrated that applying transcranial static magnetic field stimulation (tSMS) over hMT + leads to a reduction in perceptual motion direction discrimination performance[10]. tSMS is a novel, noninvasive brain stimulation technique that uses a high-intensity (100–200 mT) cylindrical magnet of neodymium, iron, and boron (NdFeB) to locally suppress cortical excitability in a safe and targeted manner. These findings indicate that the hMT + excitability is closely linked to visual motion discriminability. However, it remains unclear whether and to what extent, hMT + excitability contributes to CVM performance.

Based on the findings outlined above, we hypothesized that activity in hMT + contributes not only to perceptual performance but also to CVM performance in response to moving targets. Given that applying tSMS over hMT + effectively suppresses visual motion discriminability[10], we investigated whether tSMS-induced inhibition of hMT + excitability would also impair CVM performance.

Results

Target acquisition rate in the right and left visual hemifields from the appearance of the target to the rapid cursor approach (RCA) onset time

In each condition, we analyzed the target acquisition rate in the right and left visual hemifields from the target appearance to the onset of the RCA. As shown in Table 1, the target was mainly on the right visual hemifield. For all conditions, the difference between the left and right sides was statistically significant (Wilcoxon signed rank test, $p < 0.001$) (Table 1). Thus, the target motion information essential for the success of the CVM task was obtained from the right visual hemifield, and participants processed visual motion information in left hMT +.

Effects of tSMS/sham on hit rate

Next, we compared the effects of tSMS and sham interventions on all the parameters of the CVM task by adopting the change rate (Δ) in each parameter of the During-test relative to the Pre-test. For the Δ hit rate, there was no statistically significant difference between sham and tSMS conditions for any target speed (3000 pixels/s, $p = 0.71$; 4000 pixels/s, $p = 0.41$; 4500 pixels/s, $p = 0.85$; 5000 pixels/s, $p = 0.29$) (Fig. 1A).

Effects of tSMS/sham on RCA onset time

For the Δ RCA onset time, a positive number means a slower reaction time. There was no statistically significant difference between sham and tSMS conditions for any target speed (3000 pixels/s, $p = 0.61$; 4000 pixels/s, $p = 0.63$; 4500 pixels/s, $p = 0.44$; 5000 pixels/s, $p = 0.85$) (Fig. 1B).

Effects of tSMS/sham on RCA end-point error

The Δ RCA end-point error was significantly higher in the tSMS condition than in the sham condition at 5000 pixels/s ($p = 0.0036$, $d = 30.8$) (Fig. 1C). For other target speeds, there was no statistically significant difference (3000 pixels/s, $p = 0.91$; 4000 pixels/s, $p = 0.75$; 4500 pixels/s, $p = 0.45$).

Difference of pre-test data between tSMS and sham conditions

We confirmed no statistically significant difference in the Pre-test data between the tSMS and sham conditions for any parameters at each target speed condition (Table 2).

Supplementary analysis: effects of target speed, time, and stimulation condition on CVM performance

As a supplementary analysis, we conducted a non-parametric Friedman test on RCA endpoint error, treating target speed, time point (pre- vs. during-intervention), and stimulation condition (tSMS vs. sham) as within-subject factors. This test was selected due to violations of the assumption of normality in the data. The omnibus Friedman test revealed a statistically significant difference across the combined conditions ($\chi^2(15) = 259.78$, $p < 0.001$), indicating that rank distributions varied depending on the combination of these factors. While the Friedman test does not permit interaction analysis, it does provide an overall assessment of rank differences among all combinations of target speed, stimulation condition, and time point.

Given our primary interest in whether tSMS affected CVM performance compared to sham at each time point, the significant omnibus result suggested the possibility of condition-specific effects. We therefore conducted post-hoc pairwise comparisons. At the pre-test, no significant differences were observed between the tSMS and sham conditions at all target speeds ($p = 1.0$). Similarly, during the intervention, no significant differences were

	3000 pixels/s	4000 pixels/s	4500 pixels/s	5000 pixels/s
	Right (Left)	Right (Left)	Right (Left)	Right (Left)
Pre-sham	97.3 ± 1.5% (2.8 ± 1.5%)**	92.8 ± 2.5% (7.2 ± 2.5%)**	92.7 ± 2.2% (7.3 ± 2.2%)**	90.4 ± 3.2% (9.7 ± 3.1%)**
During-sham	97.7 ± 0.8% (2.4 ± 0.8%)**	92.3 ± 2.6% (7.7 ± 2.6%)**	91.6 ± 2.4% (8.4 ± 2.4%)**	92.0 ± 2.0% (8.0 ± 2.0%)**
Pre-tSMS	95.9 ± 1.8% (4.2 ± 1.8%)**	91..9 ± 2.8% (8.1 ± 2.8%)**	93.1 ± 1.5% (7.0 ± 1.5%)**	89.6 ± 2.4% (10.4 ± 2.4%)**
During-tSMS	96.8 ± 1.5% (3.2 ± 1.5%)**	94.9 ± 1.9% (5.2 ± 1.8%)**	93.6 ± 2.2% (6.4 ± 2.2%)**	91.3 ± 2.0% (8.7 ± 2.0%)**

Table 1. The target acquisition rate in the right and left visual hemifields from the target appearance to the RCA onset time. $^{**}p < 0.001$.

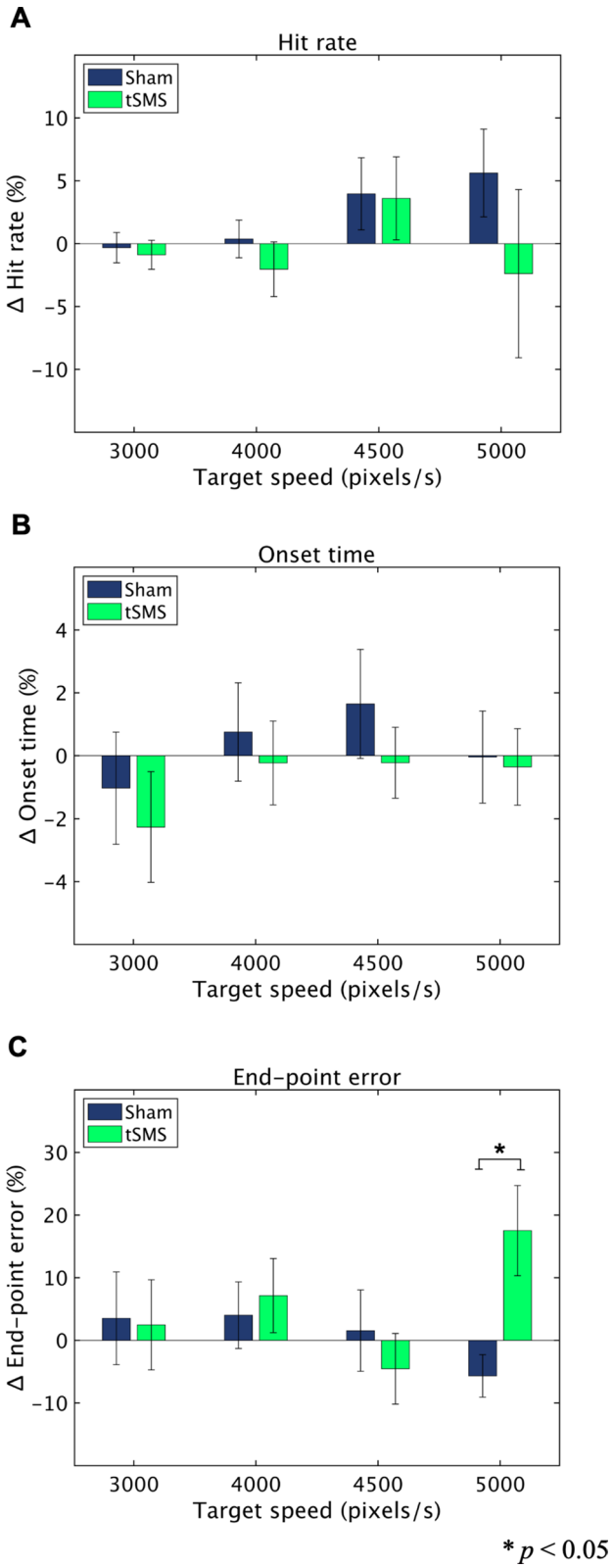

Fig. 1. Effects of tSMS on CVM task performance across target speed conditions. (**A**) Change in hit rate (Δ hit rate), (**B**) change in RCA onset time (Δ onset time), and (**C**) change in RCA end-point error (Δ end-point error) for the sham (navy) and tSMS (green) conditions across target speed levels. * $p < 0.05$.

	3000 pixels/s	4000 pixels/s	4500 pixels/s	5000 pixels/s
	tSMS (sham)	tSMS (sham)	tSMS (sham)	tSMS (sham)
Hitrate (%)	95.0 ± 1.1 (95.2 ± 0.9) $p = 0.81$	85.3 ± 1.6 (83.5 ± 1.7) $p = 0.33$	69.8 ± 3.2 (69.6 ± 2.0) $p = 0.96$	53.1 ± 3.0 (50.8 ± 3.1) $p = 0.42$
Onset time (ms)	194.3 ± 5.3 (194.9 ± 3.4) $p = 0.89$	178.6 ± 3.7 (180.8 ± 2.9) $p = 0.46$	169.1 ± 2.2 (169.6 ± 2.7) $p = 0.86$	160.4 ± 1.2 (161.6 ± 2.5) $p = 0.66$
End-point error (pixel)	38.7 ± 3.1 (41.3 ± 2.7) $p = 0.22$	61.4 ± 3.0 (66.5 ± 3.5) $p = 0.15$	106.3 ± 9.3 (103.0 ± 5.5) $p = 0.65$	141.8 ± 10.4 (155.3 ± 8.6) $p = 0.10$

Table 2. The raw data of Pre-test data between sham and tSMS conditions and p-value.

found between the two stimulation conditions at all target speeds ($p = 1.0$). These findings suggest that although the overall analysis revealed significant rank differences across conditions, the specific comparisons of interest—tSMS versus sham at each target speed and time point—did not reach statistical significance, indicating that any potential condition-specific effects were not robust enough to reach significance when analyzed collectively.

Identification of stimulus type by participants

At the end of each experimental day, we asked the participants what type of stimulus they were exposed to and confirmed that they could not identify it (tSMS or sham; $\chi^2 = 0.0$, $df = 1.0$, $p = 1.0$).

Discussion

The present study explored how applying tSMS over the hMT + region affects CVM performance. We found that while tSMS did not influence the hit rate or RCA onset time, it notably increased the error of the RCA end-point. The rate of change in the RCA end-point error for the During-test relative to the Pre-test under the tSMS condition was significantly higher than that under the sham condition at 5000 pixels/s.

Aguila et al. (2016)[11] demonstrated that tSMS to the primary visual cortex suppressed neural firing and led to a reversible impairment in visual detection, as shown through neural activity recordings in anesthetized cats and visual detection tasks in awake primates. The possible mechanisms include deforming the calcium channels and altering their activity speeds by changes in membrane phospholipids affecting ion flux[12–15], interfering with elastic and electrostatic energies involved in the channel activation-inactivation-deactivation mechanisms of biological membranes by magnetic pressure[16].

These findings suggest that tSMS can effectively and reversibly modulate cortical excitability. Therefore, in the present study, a similar mechanism may underlie the tSMS-induced suppression of hMT + neural activity, leading to impaired moving target direction discrimination and, consequently, reduced visuomotor performance.

The eye-tracking data in the CVM task (Table 1) showed that participants acquired the target motion information essential for hitting the target from the right visual hemifield and processed the visual motion information regarding the moving target in left hMT +.

Like the primary visual cortex, monkey MT neurons have receptive fields in the contralateral visual field[17]. Similar contralateral dominance has been reported in human hMT +, showing that hMT + in the left (right) hemisphere is mainly responsible for the right (left) visual field[18,19]. Therefore, in the present study, the reduction of the excitability in left hMT + by tSMS suppressed visual motion information processing ability in the right visual hemifield[10] to influence CVM performance. The application of tSMS over right hMT + probably affects CVM performance in the CVM task if the target moves from left to right and the target motion information is acquired in the left visual hemifield[1]. However, a previous study applying rTMS over hMT +[20] has reported that the receptive field of neurons in left hMT + is restricted to the right visual field, but neurons in right hMT + have receptive fields in the contralateral (left) visual field and part of the ipsilateral (right) visual field. Thus, tSMS over right hMT + may affect CVM performance in the CVM task in which the target motion information is acquired in the left and the right visual hemifields. Future research is needed to clarify this point.

In the CVM task, to hit the target with the cursor, participants had to predict the arrival point of the target correctly by the motion extrapolation of the target. Inhibiting hMT + excitability by tSMS increased the end-point error of the RCA, suggesting a decrease in the spatial accuracy of the target arrival point prediction. This effect may be due to a decrease in the accuracy of the motion extrapolation of the target based on the cortical analysis of the visual motion by hMT +. Consistently, a microstimulation over MST while monkeys reached for a moving target caused an increase in the pointing error of hand movements[5]. hMT + is known to be involved not only in visual motion analysis but also in motion estimation, and it is activated even while watching a moving ball that is temporarily occluded[21]. In addition, rTMS over hMT + during a visual trajectory perception task[6] or manual interception task[7] that requires the hand to contact a moving object at the right location decreased the accuracy of the prediction of the object arrival point. In light of the present and previous studies, hMT +/MT/MST are probably involved in motion extrapolation. In support of this conclusion, rTMS over hMT +[22,23] or damage to hMT +[24] causes an underestimation of the speed of the moving target. Consistent with this, at 5000 pixels/s in the present study, the cursor did not overtake the target in the majority of trials and instead did not reach the target (sham-Pre, 99.2 ± 0.3%; sham-During, 98.4 ± 0.3%; tSMS-Pre, 98.7 ± 0.3%; tSMS-During, 98.9 ± 0.3%). Therefore, we concluded that tSMS over hMT + increased the RCA end-point error by underestimating the target speed in the CVM task.

Our previous study[1] reported that daily fluctuations in visual motion discriminability, which reflect the activity of hMT +, contribute to daily fluctuations in the hit rate, onset time, and end-point error of the RCA in the CVM task. Notably, there was a strong correlation between the visual motion discriminability and the end-point error of the RCA. Therefore, among the various spatiotemporal factors that constitute CVM performance, hMT + seems to play the greatest role in determining spatial accuracy. In addition, another of our previous studies

that investigated the effect on the visual motion discriminability by tSMS over hMT + reported a significantly reduced correct rate (accuracy of visual motion processing) but no effect on the reaction time (speed of visual motion processing)[10]. Our current finding that tSMS does not affect the RCA onset time regarded as reaction time supports our previous study. Therefore, the contribution of hMT + activity to the temporal aspect of CVM performance is weaker than its contribution to accuracy.

We demonstrated the significant effect of tSMS on CVM performance at only 5000 pixels/s of the four studied target speed conditions (3000 pixels/s, 4000 pixels/s, 4500 pixels/s, and 5000 pixels/s). At 5000 pixels/s, the time from the target appearance to the arrival at the same horizontal position as the cursor was 313 ms, so a target speed of 5000 pixels/s compels participants to process visual information quickly. Hence, the time available for visual information processing is possibly a bottleneck in the processes for visuomotor responses, limiting CVM performance. Consistent with this possibility, the CVM task showed that visual motion discriminability, which reflects hMT + activity[1], correlated with only CVM performance at the fastest target speed of 5000 pixels/s.

Our recent study[1] found that CVM performance correlates with motion direction discriminability, which was more potent in table tennis players than non-players. This finding suggests that the repetitive visuomotor interactions with fast-moving balls in table tennis may enhance the relationship between the two abilities. To validate this hypothesis, our previous study[10] demonstrated that inhibiting hMT + using tSMS significantly impaired table tennis players' motion direction discriminability. This evidence supports the role of hMT + in motion direction discrimination and suggests that CVM performance, which is closely linked to motion vision, may be similarly affected. The present study aims to investigate further how hMT + contributes to CVM ability. Therefore, it was necessary to maintain the same participant conditions as in Takami et al. (2024)[10], that is, the experience of table tennis, confirming the correlation between hMT + excitability and CVM ability expectedly. Although we did not apply tSMS to non-players for the reason above, future studies should investigate this to determine whether our findings can be generalized to non-athletes.

The effects of tSMS on the cerebral cortex remain controversial. Oliviero et al.[30] published the first study reporting the effects of tSMS on the human motor cortex in 2011. It demonstrated that tSMS reduced motor cortex excitability by about 25%, with effects lasting for several minutes after stimulation. Subsequent studies attempted to replicate these findings, but results were inconsistent. For example, Lorenz et al. (2020)[25] found that 10 min of tSMS did not reliably modulate motor cortex excitability, suggesting variability in its efficacy. Possible reasons include high variability in corticospinal excitability, differences in experimental procedures, the order of stimulation sessions, and individual differences[25]. While this study indicates that further research is needed to confirm reproducibility, it does not entirely rule out the effects of tSMS. Our study participants were table tennis players, and the enhanced functional connectivity between hMT + and their visuomotor processing may have played a crucial role in task performance. This possibility could explain why a significant suppression effect on task performance was observed, even if the degree of inhibition varied among individuals. However, future work is needed to determine whether the decrease in CVM performance is due to the direct reduction in hMT + excitability.

In the present study, we investigated the effect of tSMS over hMT + on visuomotor performance. Our findings revealed that tSMS significantly increased end-point error in the CVM task, but only at a specific target speed, as detected through a rate-of-change analysis. This result suggests that inhibitory modulation of hMT + selectively disrupted visual motion direction discriminability, which serves as a critical perceptual foundation for visuomotor responses under specific stimulus conditions[10]. In contrast, the omnibus non-parametric analysis using the Friedman test did not reveal any significant differences between stimulation conditions. The rate-of-change analysis quantifies within-subject differences relative to baseline performance and may offer greater sensitivity in detecting condition-specific effects[10]. These findings highlight the value of employing multiple analytical strategies when assessing neuromodulatory influences, particularly in contexts where the expected effects are subtle or context-dependent. While omnibus tests provide a useful overview, complementary approaches—such as relative change metrics—can uncover finer-grained patterns that are essential for understanding the functional consequences of tSMS.

From an alternative perspective, the lack of a significant effect in the three-way Friedman test may be attributed to limited statistical power, considering the sample size of 20 participants. The observed statistical power, calculated using G*Power based on the current sample size and effect size, was 56.5%. In this study, recruiting a sufficient number of participants was challenging due to several constraints: (1) all participants were required to be experienced table tennis players; (2) each participant underwent up to five days of pre-training to reach a stable baseline performance on the CVM task; and (3) a minimum one-week interval was necessary between the real and sham stimulation conditions to prevent carry-over effects. Given these limitations, our findings should be interpreted with caution. The significantly greater decline in performance—reflected in the percentage change from pre- to during-intervention—in the tSMS group compared to the sham group, suggests that tSMS may exert a meaningful yet modest effect on visuomotor performance.

In conclusion, we have demonstrated that reduced hMT + excitability decreases the spatial accuracy of CVM performance. Based on our previous studies[1,10], visual motion discriminability and CVM performance fluctuations appear to stem from variations in hMT + excitability. Therefore, enhancing hMT + excitability may improve visual motion discriminability and CVM performance.

Methods

Participants and ethical approval

All candidates completed a questionnaire on their sports history and underwent a five-day familiarization session before participation. Individuals with less than six years of table tennis experience or those who failed to meet baseline performance criteria during the familiarization period were excluded. The final participant pool consisted of 20 healthy individuals with table tennis experience (mean ± SD: age = 20.6 ± 1.7 years, table tennis

experience = 9.3 ± 2.2 years; 6 females; 1 left-handed) participated in this study. Details of the familiarization session are described in a later section. The protocol was approved by the ethics committee of the Graduate School of Medicine, Osaka University (L021) and was conformed in accordance with the Declaration of Helsinki with each participant providing written informed consent.

Continuous visuomotor (CVM) task

We used the CVM task[1] (Fig. 2) for evaluating CVM performance. In this task, visual stimuli were generated using a custom-made program in Python and displayed on a liquid crystal (LC) display (Iiyama, Tokyo, Japan; resolution, 1920 × 1080 pixels; refresh rate, 100 Hz; mean background luminance, 30 cd/m^2; screen size, 60 × 34° at a viewing distance of 57 cm). Participants sat about 57 cm away from the LC display, and to restrict their head movement, their heads were fixed on a chinrest that was positioned at the center of the Y-axis and one-third of the X-axis from the left side of the LC display. Participants grasped the force sensor (USL06-H5-50N, Tec Gihan Co., Ltd., Japan; sampling rate, 1 kHz) with their thumb and index finger of the dominant hand. The participants' left eye movements during the task were recorded at 500 Hz using a USB camera (Grasshopper3, Point Gray, Japan) and an eye-tracking system [iRecHS2[26].

A Gabor patch with horizontal grating (target, diameter, 90 pixels; spatial frequency, 1.5 cycles/deg; contrast, 50%) and a white rectangle [cursor, height, 180 pixels; width, 96 pixels; RGB (1,1,1)] were presented on the LC display. The target appeared at the right edge of the LC display and moved leftward with uniform linear motion. Participants controlled the cursor to intercept the target.

When the target either collided with the cursor or reached the left edge of the display, a new target appeared at a randomly assigned height on the right edge. The cursor was positioned 240 pixels from the left edge of the display and was restricted to vertical movement along the Y-axis. Its position was modulated by the prehensile force applied to a force sensor: minimal force positioned the cursor at the top of the display, while 30% of maximum force moved it to the bottom. During the familiarization session, the baseline force (0%) was measured while pinching the force sensor, and then the maximum force was measured as 100%. Subsequently, 30% of the maximum force was calculated. Releasing the force moved the cursor upward, whereas increasing the force moved it downward. Participants were instructed to intercept the moving target using the cursor while maintaining a fixed head and hand position. No specific instructions were given regarding eye movements, allowing participants to freely direct their gaze anywhere on the display during the task.

The target speeds were 2000, 3000, 4000, 4500 and 5000 pixels/s, corresponding to visual angular speeds of 57, 86, 114, 127 and 144 deg/s, respectively. Visual angular speed was calculated by dividing the angle formed

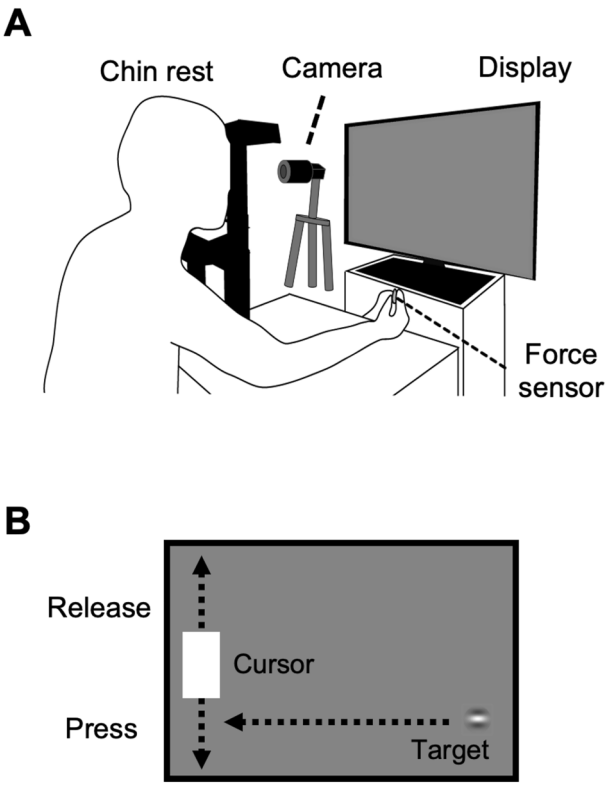

Fig. 2. The experimental setup of the CVM task. (**A**) A participant put his/her head on a chin rest and prehend the force sensor with the thumb and index finger of the dominant hand. Left eye movements during the task were recorded using a USB camera. (**B**) The target moved in a constant speed from right to left. The cursor moved in the Y-axis direction only, and its position corresponded to the magnitude of the prehensile force given to the force sensor.

by two vectors—one from the center of both eyes to the right edge of the LCD and the other to the left edge of the cursor—by the target arrival time (TAT). TAT was defined as the time from target appearance to arrival at the same horizontal position as the cursor, which was 782, 521, 391, 347, and 313 ms for each target speed condition, respectively. The task duration was fixed at 30 s across all target speed conditions to minimize the effects of fatigue on task performance. The number of trials per target speed condition was 37, 55, 73, 81, and 88, respectively.

Experimental protocol

The present study was comprised of a familiarization session and an experimental session. In this study, participants conducted the CVM task many times, so there was a need to minimize the practice effect due to repeating the same task on the impact of tSMS. Therefore, in the familiarization session, participants conducted the CVM task until the hit rate reached 100% at 2000 pixels/s and 40% at 5000 pixels/s. The time for each day of the familiarization session was one hour, and it took 2 to 5 days to achieve our criteria.

The experimental session was comprised of 2 days. For both days, participants first wore stretch net bandages on their heads. The stimulus area (i.e., locations of left hMT +) was identified at 3 cm dorsal to the inion and 5 cm leftward from there for each participant[10,27–34]. Then, the participants conducted the CVM task at four target speeds (3000, 4000, 4500, and 5000 pixels/s)[1] twice for a day (Pre-test). Afterward, the participants were exposed to a stimulus (tSMS or sham) for 30 min over left hMT + at the sitting rest state (Intervention). For tSMS, we used an NdFeB magnet (diameter = 60 mm, thickness = 30 mm, weight = 670 g, nominal magnetic strength = 120 kg; MAG60r, Neurek, Toledo, Spain), as shown in Fig. 3, and for the sham, we used a steel metal cylinder. The two stimuli looked the same. The effect of tSMS on cortical excitability does not depend on the magnetic field polarity[35]. Therefore, we adopted the south magnetic field polarity for all participants in the present study.

After the intervention, participants performed the CVM task under stimulus exposure (During-test) at the same speed conditions as in the Pre-test. An NdFeB magnet for tSMS or a steel metal cylinder for the sham condition was fixed in the same position above the left hMT +, and participants were exposed to the respective stimulus during the task. At the end of the second experimental day, they were asked to identify which stimulus they had been exposed to (tSMS or sham) to assess their awareness of the stimulus type.

The experiment followed a double-blind crossover design. Specifically, it was conducted by a researcher who was blinded to the experimental conditions. However, the overall study, including the experimental schedule and conditions (such as the crossover design), was overseen by a researcher responsible for managing the entire experiment. Sessions were scheduled at the same time of day for each participant, at least one week apart. All participants completed both sessions and refrained from alcohol and caffeine for 24 h before each experimental day.

Data analysis

The raw spatiotemporal data of eye and cursor movements were processed in MATLAB using a fourth-order Butterworth low-pass filter with a 30-Hz cut-off frequency and zero-time shift. The"Hit zone"was defined as the Y-axis range where the center-to-center distance between the target and cursor was less than the sum of the target radius and half the vertical length of the cursor, mathematically set at ≤ 135 pixels or less. However, to account for potential filtering-induced errors (~ 10 pixels) due to high-frequency noise in the force sensor signal, the Hit zone length was adjusted to 145 pixels.

As shown in Fig. 4, participants typically moved the cursor rapidly toward the Hit zone (light yellow band) after the target appearance in an attempt to intercept it. This movement was defined as Rapid Cursor Approach

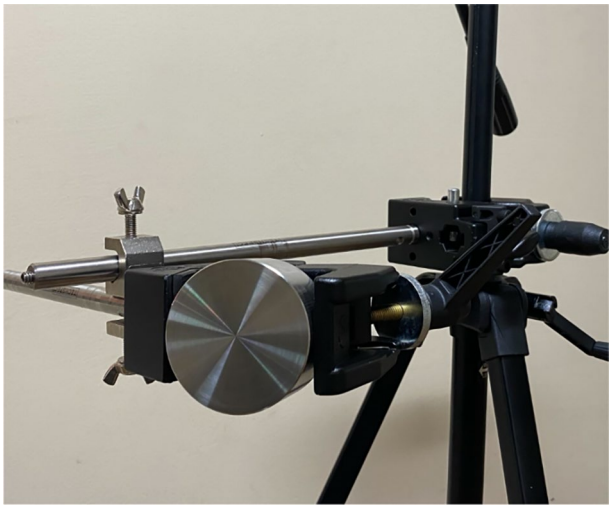

Fig. 3. Setup for transcranial static magnetic stimulation (tSMS). NdFeB magnet used for tSMS, a steel metal cylinder used for the sham.

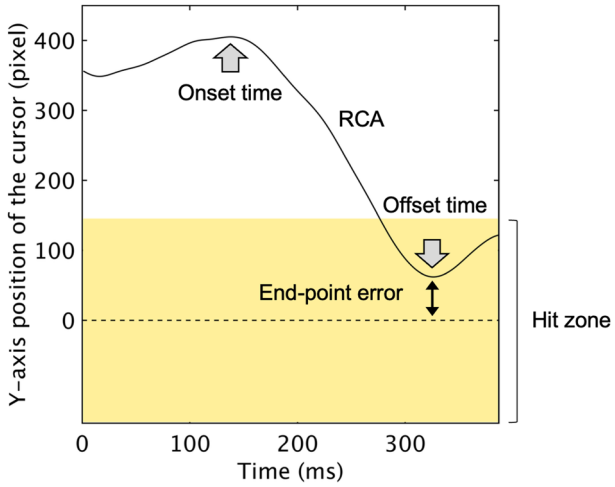

Fig. 4. A single trajectory of the cursor movement along the Y-axis and a typical example of the RCA at 4000 pixels/s. The yellow band indicates the Hit zone, and the Y-axis's zero value is the target's center. We analyzed the RCA's onset time, offset time, and end-point error for each trial.

(RCA). Trials were categorized as hit trials if participants successfully intercepted the target and as miss trials otherwise. The hit rate was calculated as the ratio of hit trials to the total number of trials.

Following our previous study[1], the RCA onset time was defined as the start time of the RCA (Fig. 4) and was used to assess its temporal characteristics by calculating the mean RCA onset time across all trials. The RCA end-point error, representing spatial accuracy, was defined as the absolute distance between the centers of the Hit zone and cursor at RCA offset (Fig. 4) and was evaluated as the mean RCA end-point error across trials.

The following trials were excluded from the analysis: (1) trials where RCA was unnecessary because the cursor was already within the Hit zone at target appearance, (2) trials with an RCA onset time of < 80 ms, as visually triggered body movements require a minimum latency of 80 ms[36], and (3) trials in which the cursor moved in the opposite direction of the target.

Following our previous study[1], hit rate, RCA onset time, and RCA end-point error were used as CVM task performance measures.

To investigate how long the target was captured in the left or right visual field, we analyzed the horizontal gaze position relative to the target from its appearance to the RCA onset time (target acquisition rate). By doing so, we could clarify whether hMT + processed the visual information regarding the moving target to hit the target in the left or right hemisphere.

We computed the effects of tSMS/sham intervention on the CVM task as the change rate (Δ) in each parameter of the During-test relative to the Pre-test.

Statistical analysis

We checked whether the raw data of the Pre-test, the rate of change of all parameters (hit rate, RCA onset time, and RCA end-point error), and the target acquisition rate in each target speed condition had a normal distribution by the Shapiro–Wilk test. We used the paired-samples t-test for normal distribution data and the Wilcoxon signed-rank test for non-normal distribution data and calculated Cohen's d (d) as the effect size. Finally, we investigated whether participants could identify the stimulation type (tSMS/sham) by the chi-square test. Multiple t-tests were performed, and the significance level was adjusted using the Bonferroni correction. Given that four comparisons were conducted, the adjusted significance level was set to 0.004 (0.05/12).

Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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Author contributions

A.T. and S.S. conceived and designed the research; A.T. collected the data; A.T. and S.S. analyzed the data; A.T., T.K and S.S. interpreted the results of the experiments. A.T. and S.S. wrote the main manuscript and prepared the

figures. A.T. and S.S. revised the manuscript. All authors read and approved the final version of the manuscript.

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Declarations

Competing interests
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