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# The medial prefrontal cortex contributes to representing shared goals among group Members: Evidence from tDCS

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ABSTRACT

People often generalize the actions of known group members to unfamiliar members based on their goals. This goal-based action generalization is constrained by the belief that group members have a shared goal, which typically results in a nongraded pattern where the extent of generalization does not gradually increase with the prevalence of action goals. In the present study, 90 healthy participants (aged 15–27) were randomly assigned to three equal groups, each receiving one of three types of transcranial direct current stimulation (tDCS) targeting the medial prefrontal cortex (mPFC): anodal (anodal electrode over Fpz, return electrode over Oz), cathodal (reverse montage), or sham stimulation. In the implicit task, cathodal stimulation—diminishing mPFC excitability—weakened the representation of the shared-goal belief, leading to a graded generalization pattern in which expectations increased with action prevalence. In contrast, both anodal and sham stimulation produced the typical nongraded pattern. In the explicit task, both anodal and cathodal stimulation produced the similar graded generalization, while sham stimulation preserved the nongraded pattern. These findings suggest that the medial prefrontal cortex (mPFC) is involved in representing the belief that group members have a shared goal. This study advances our understanding of how the mPFC contributes to social cognition by integrating beliefs with statistical evidence to guide action expectations.

## 1. Introduction

People's social lives are closely linked with their expectations of how others will behave. However, this association entails a significant challenge in the context of determining how past experiences with and available knowledge regarding individuals can predict future encounters, which is known as the problem of inductive generalization (Andrews, 2008; Kalish, 2012). While the previous actions taken by an individual can serve as a helpful indicator of their behavior in similar situations, we may not have sufficient experience with novel individuals to form expectations concerning their future actions (Bodenhausen et al., 2012; Vijayakumar et al., 2021). In these cases, we often turn to our knowledge of or experience with social groups to support our expectations regarding the actions taken by novel individuals.

Research has reported that the behaviors exhibited by novel individuals are anticipated according to the social groups to which they belong (Duan et al., 2021; Grigoryan, 2020; Liberman et al., 2017; Powell and Spelke, 2013). Specifically, group members are generally assumed to exhibit similar characteristics or behaviors (Liberman et al., 2017). On the basis of this belief, both adults and infants can generalize the actions taken by or attributes of familiar members to unfamiliar members, resulting in the expectation that group members act similarly, a phenomenon that is known as action generalization (Duan et al., 2021; Powell and Spelke, 2013; Ranganath and Nosek, 2008). Subsequent studies have provided more direct evidence regarding action generalization among group members (Duan et al., 2021; Xu et al., 2019). In these studies, after observing group members' actions, participants were required to identify an action performed by a new member that was either consistent or inconsistent with those performed by other members. The results revealed that consistent actions were identified more quickly than were inconsistent actions, thus indicating action generalization among group members. More importantly, although both the action goal (i.e., the approached target) and movement (i.e., how to achieve the goal) can be treated as generalized properties during the

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process of action generalization, people primarily generalize action goals rather than superficial movements among members of a social group (i.e., goal-based action generalization; Yin et al., 2022, 2023). This effect was observed only when the new member belonged to the same well-established social group (Yin et al., 2022). These results indicate that people do generalize actions among group members on the basis of the action goal.

Goal-based action generalization can be viewed as a unique type of inductive generalization. In inductive generalization, the observed exemplars are treated as samples of evidence (Lawson and Fisher, 2011; Rhodes et al., 2008). As more evidence is observed, the tendency to generalize the target properties increases (Lawson, 2014), thus exhibiting a graded relationship with the prevalence of the evidence. Specifically, a graded pattern implies a strictly monotonic relationship between the prevalence of evidence and the extent of generalization, where an increase in evidence consistently leads to an increase in generalization. Hence, it is reasonable to expect the extent of goal-based action generalization within social groups to be proportional to the statistical prevalence of relevant actions among observed group members. However, this expectation has not been supported by previous studies (Hu et al., 2023). Hu and colleagues (2023) manipulated the action prevalence by presenting varying proportions of group members performing the same action and reported that the extent of goal-based action generalization is not highly sensitive to the statistical prevalence of a specific action goal. Instead, the action goal is typically generalized to a new group member only when all the sampled group members pursue the same goal. This result indicates that the relationship between the prevalence of goals and the extent of their generalization deviates from strict monotonicity, thus exhibiting a nongraded pattern of action generalization. This nongraded pattern is observed when the generalization pattern includes plateaus or non-increases despite increasing prevalence, representing a deviation from a graded pattern. These findings imply that goal-based action generalization is driven by additional factors in addition to statistical evidence.

In addition to their ability to acquire new information or evidence, individuals possess an intuitive understanding of social groups, which includes prior beliefs regarding how group members are likely to act (Chalik et al., 2014; Chalik and Dunham, 2020; Hu et al., 2023; Rhodes and Chalik, 2013). Researchers have proposed that individuals believe that group members act in pursuit of a shared goal (Henderson, 2009; Spencer-Rodgers et al., 2007), which is referred to as the belief in shared goals. This belief is rooted in the understanding that social groups are typically organized with the aim of addressing coordination challenges by allowing members to work together to achieve collective goals, such as in the case of a group of individuals playing football. Hu and colleagues (2023) noted that this belief contributes more to goal-based action generalization than does evidence concerning the prevalence of an action does, thereby resulting in a nongraded pattern. Specifically, when all observed group members pursue the same goal, this observation is in line with the belief in shared goals, thus leading to the generalization of the goal to other unknown group members. Conversely, if any group member deviates from such pursuit of the same goal, this belief becomes inconsistent with the observed evidence. Accordingly, people may become uncertain regarding the properties to be generalized and unclear concerning which goal unknown group members are likely to pursue.

Although the belief that group members have a shared goal plays a critical role in goal-based action generalization, the brain regions that are involved in the process of representing this specific instance of group-related belief have not yet been identified clearly. Previous studies have reported that the medial prefrontal cortex (mPFC) is associated with the representation of group-related beliefs (Molenberghs and Morrison, 2014; Morrison et al., 2012; Sellaro et al., 2015). For example, Morrison et al. (2012) reported that in comparison with out-group labels, the classification of in-group labels resultes in increased activation in the mPFC, thereby suggesting that the mPFC is involved in the processing of group-related beliefs. Furthermore, Sellaro et al. (2015) found that enhancing mPFC excitability via transcranial direct current stimulation (tDCS) can significantly decreased implicit bias toward out-group members, suggesting that the mPFC is a critical component in representing group-related beliefs and counteracting stereotype activation. Recently, Vijayakumar and colleagues (2021) reported increased mPFC activation when participants generalized beliefs regarding other group members' preferences to new individuals, further highlighting the importance of the mPFC in the processes of representing and applying group-related beliefs. Therefore, the mPFC may also be involved in the process of representing the belief that group members have a shared goal, which represents a specific type of group-related belief. The present study aimed to provide evidence regarding the potential causal relationship between the mPFC and the representation of this belief by using tDCS.

To determine the role of the mPFC in representing the belief that group members have a shared goal, the present study employed tDCS to alter the excitability of the mPFC. Subsequently, changes in the pattern of goal-based action generalization were evaluated. If the mPFC is involved in the process of representing the belief in shared goals, then cathodal stimulation—which diminishes mPFC excitability—would be expected to weaken this representation. As a result, participants would rely more heavily on the observed evidence from group members' actions in the process of forming expectations about others, thus leading to a graded relationship between the extent of goal-based action generalization and the prevalence of goal-directed actions (i.e., the extent of action generalization consistently increases as the prevalence of the action goal rises). In contrast, anodal stimulation enhances mPFC excitability and may thus strengthen the representation of the belief in shared goals. However, since this belief is likely already active by default in the absence of stimulation, further enhancement may not lead to additional effects on action generalization. Consequently, a nongraded pattern of action generalization would still be observed under conditions of anodal stimulation (i.e., the generalization pattern includes plateaus or non-increases despite increasing prevalence). Given the clearer hypotheses concerning the inhibitory effects of cathodal stimulation, our primary focus was on its impact. Moreover, under conditions of sham stimulation, which serves as the control condition in this research, the typical nongraded pattern of action generalization should still be observed because the belief in shared goals remains available. To classify these patterns, following a methodology consistent with previous research (Hu et al., 2023), it is essential to compare goal-based action generalization across low, medium, and high prevalence conditions.

To fully evaluate whether the mPFC contributes to representing the belief in shared goals among group members, both implicit and explicit measurements were employed in the current study. Social cognition relies on two types of dissociated information processing, i.e., implicit and explicit process (Apperly and Butterfill, 2009; Frith and Frith, 2008), and numerous studies have highlighted differences between implicit and explicit action expectations (Paulus et al., 2017; Schuwerk et al., 2015). Similar to previous studies (Hu et al., 2023; Yin et al., 2022), the implicit task employed in this research used computer-animated scenarios in which participants observed goal-directed actions that were performed by cartoonized agents and were asked to identify the action of a new group member as quickly as possible. If participants implicitly generalized the target property (i.e., the action goal) to the new agent, they were expected to identify actions that were in line with the previously observed goal more quickly. Since this task did not require explicit prediction, the belief in shared goals would be activated implicitly and influence generalization via automatic processing. However, the explicit task involved realistic video clips that focused on two social groups in party scenarios. The participants were explicitly asked to predict behavior by rating the likelihood that a new group member would approach one of two targets. This task requires conscious access to the belief in shared goals, and thus involves controlled processing (Kovács et al., 2014).

## 2. Methods

### 2.1. Participants

To be conservative and ensure that the results were reliable, a medium conventional effect size ($f = 0.25$) was planned for this experiment. A power analysis using G*Power 3.1 (Faul et al., 2009), with an alpha level of 0.05 and a power of 0.80, indicated that a minimum effect size of 28 was needed in each between-subjects condition. Therefore, we recruited 30 valid participants for each tDCS stimulation type, resulting in 90 valid participants in total. Four additional participants were excluded from the analysis due to incomplete investigations. All participants were of Han ethnicity, the majority ethnic group in China. Participants were randomly assigned to one of three tDCS stimulation types: anodal (15 men and 15 women, $M_{age} = 20.90$, $SD = 2.47$), cathodal (15 men and 15 women, $M_{age} = 22.13$, $SD = 2.35$), or sham (13 men and 17 women, $M_{age} = 19.33$, $SD = 1.40$). Participants had no history of neurological or psychiatric disorders, substance abuse or dependence, brain surgery, tumor, or intracranial metal implantation. Additionally, none of the participants were taking medication acutely or chronically, pregnant, susceptible to seizures or migraines, or fitted with pacemakers or other implanted devices. Each participant received approximately 80 RMB as compensation upon completion of the experiment.

None of the participants had prior experience with tDCS. Before the testing session, participants received both verbal and written explanations of the procedure and potential adverse effects, such as tingling skin sensation, skin reddening, and headaches. Importantly, participants were not informed about the specific type of stimulation they would receive or the experimental hypotheses, in line with previous studies suggesting that blinding participants to the type of stimulation can reduce expectancy effects (Berlim et al., 2013; Dedoncker et al., 2016). All participants provided written informed consent for participation. The study adhered to the ethical principles of the Declaration of Helsinki. Additionally, the local Ethics Review Board at the author's university approved the protocol.

### 2.2. Apparatus

The present experiment utilized the 2001&4X1-C3A developed by Soterix Medical in the United States. A pair of surface sponge electrodes (5 cm × 7 cm) were soaked in physiological saline solution (0.90 % sodium chloride) for 4–5 min before being applied to the target area for cortical stimulation. The electrode placement for tDCS targeting the mPFC was determined according to the international EEG 10–20 system.

For anodal stimulation, the anodal electrode was placed over the Fpz, while the return/cathodal electrode was placed over the Oz. The rationale for choosing the Oz as the return electrode position is that previous studies have suggested that increasing electrode separation on the head effectively decreases the current shunted through the head and increases the depth of the current density (Guo et al., 2019; Sellaro et al., 2015). For cathodal stimulation, the placement was reversed: the anodal electrode was placed over the Oz, and the cathodal electrode was placed over the Fpz. In both types of active stimuli (either anodal or cathodal), a constant current of 1.5 mA was delivered (Wu et al., 2022). As suggested, the stimulation duration for tDCS studies was typically between 5 and 20 min (Boggio et al., 2009). In the present study, each participant received 20 min of stimulation. During the stimulation, participants remained at rest and were instructed to relax quietly without performing any task, in accordance with established offline tDCS protocols (Jiang et al., 2024; Thair et al., 2017; Živanović et al., 2021). It has been shown that if tDCS is applied for at least 9–13 min, its effect can be stably sustained for over an hour (Nitsche et al., 2008). Consequently, the 20-min stimulation duration ensured that the intervention remained effective throughout the entire experiment. As shown in Fig. 1, the mPFC region showed a strong field intensity in both the anodal and cathodal stimulation conditions, indicating that the electrical stimulation significantly altered the activity level in this brain area.

### 2.3. Procedure and design

A single-blind experiment was conducted to investigate the effect of a single session of tDCS. Although the experimenters administered the stimulation according to the assigned condition, they were not aware of the study's hypotheses, minimizing potential experimenter bias. The participants were randomly assigned to different tDCS stimulation types and received 20 min of stimulation corresponding to the assigned condition. After the end of the stimulation, the electrodes were removed from the brain scalp, and the adopted behavioral measurement task, lasting approximately 60 min, was conducted to implicitly assess goal-based action generalization (Hu et al., 2023; Yin et al., 2022). Then, participants were asked to complete the questionnaire survey on

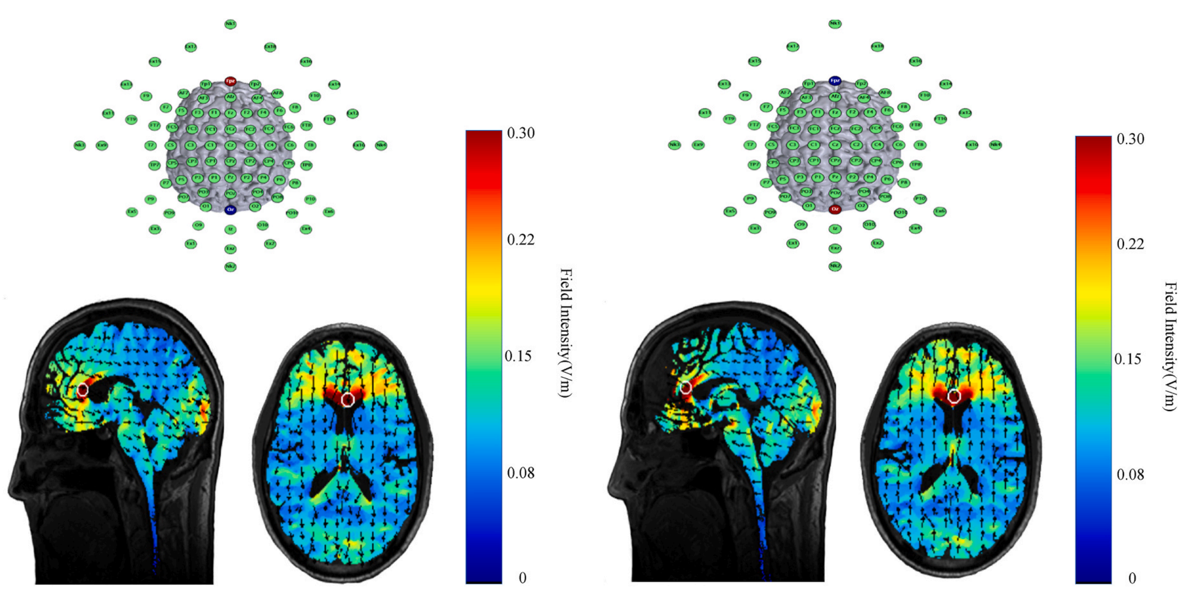


**Fig. 1.** Field intensity depicted by HD-Explore. The left panel shows the field intensity in the anodal stimulation, and the right panel shows the field intensity in the cathodal stimulation.

goal-based action generalization (i.e., the explicit measurement of goal-based action generalization), lasting approximately 10 min. After completing all tasks, participants were properly debriefed and asked to indicate the extent to which they perceived that the stimulation affected their behavior (ranging from 1 = not at all to 4 = extremely) and how much the stimulation affected their general emotional state, as measured by a multidimensional mood state questionnaire (MDBF) comprising 30 items with three subscales indexing mood, alertness, and calmness (Steyer et al., 1997).

#### 2.3.1. Implicit measurement of goal-based action generalization

Computer-animated events served as stimuli and were created using Blender 2.81a, an open-source software. Each event comprised two groups of cartoonized agents with distinct appearances and two objects, namely, an apple and a banana, constructed as targets. The agents were randomly selected from six animated figures with different colors and shapes. Each agent was rendered with two eyes as facial features, with a size of 1.5° × 1.5°. All stimuli were presented on a gray background using a 15.6-inch LED monitor (1920 × 1080-pixel resolution; 120 Hz refresh rate) on a laptop computer, with a viewing distance of 60 cm. Custom software written in Python with the PsychoPy libraries was used to present the stimuli.

Each trial began with the presentation of a fixation cross (1.5° × 1.5°) at the center of the screen for 500 ms. Subsequently, two groups, each comprising five agents, were presented. Initially, the agents in each group appeared near one another in the top two corners of the screen; they subsequently made synchronized movements around a circular path for 1600 ms (see Fig. 2 and supplementary videos; "introducing social groups"). After this introduction, all of the agents moved to the top of the platforms, and four agents from the same group acted as exemplars, performing goal-directed actions successively, moving from the center to the periphery; all of these actions lasted 12,600 ms (see Fig. 2; "group members' actions"). Specifically, each exemplar initially moved to the lower side of the screen. Then, the agent turned to the left or right (balanced within each participant) to approach one of two target objects, a red apple and a yellow banana, which were placed in the lower left-hand and right-hand corners of the screen, respectively. Finally, the exemplar returned to the starting point. The position of the objects was counterbalanced across participants.

Next, a plate was presented to cover the two objects, and their positions were swapped. This phase, referred to as "plate loading", lasted 1200 ms and is shown in Fig. 2. Swapping the position of the two objects served to dissociate generalizing action goals from generalizing action movements. This change required the goal to be reached using a new movement, while the old movement would now lead to a new goal. If participants implicitly generalize the target property (i.e., the action goal) to the new agent, then an old (i.e., consistent) goal achieved through a new (i.e., inconsistent) movement should be judged more quickly than a new (i.e., inconsistent) goal achieved through an old (i.e., consistent) movement. This is because the former aligns with the internal expectation of shared goals—reflecting goal-based action generalization (Yin et al., 2022, 2023). Subsequently, a new agent at the outermost position moved to the lower part of the screen and stopped, and a question mark was presented above this agent for 2000 ms (see Fig. 2, "waiting"). No explicit instructions were given to the participants at this stage. Finally, the last agent started to move again toward the left or right object on the screen at a constant velocity and reached the object after 750 ms. The participants were instructed to quickly identify whether this agent moved toward the left or right object by pressing "F" or "J" on a standard keyboard (see Fig. 2, "action identification"). If the participants did not respond within 2000 ms, the program automatically proceeded to the next trial.

The experiment employed a repeated-measures design with two factors: action prevalence and goal consistency. Action prevalence referred to the proportion of exemplars that approached the same target and had three levels: low, medium, and high. Goal consistency referred to whether the identified target of the last agent matched the goal of the majority and had two levels: consistent and inconsistent. The goal-based action generalization effect was calculated by subtracting the mean reaction time of the consistent goal condition from that of the inconsistent goal condition. The prevalent action was randomly determined before the experiment in the low prevalence condition. After swapping the targets, consistent goal indicated an inconsistent movement and vice versa. Therefore, the design of the experiment was 3 (action prevalence: low vs. medium vs. high) × 2 (goal consistency: consistent vs. inconsistent) repeated measures, with all conditions presented in a random order. Each condition comprised 20 trials. The presentation of the exemplars' group on the left or right and the position of the target approached by the majority were balanced within each condition. Twelve additional trials were included in which the identified agent belonged to a different group to emphasize the manipulation of social groups further. These trials were not analyzed but served as fillers. Therefore, each participant completed 132 trials in total. To control for the potential influence of the order in which the minority was presented, the exemplars who did not follow the majority were randomly determined. Participants were given 2 min to practice before the main experiment, during which filler trials were also included.

#### 2.3.2. Explicit measurement of goal-based action generalization

Participants were shown a sequence of six videos featuring two groups of five individuals at a party who were tasked with retrieving food or drinks. After each video, participants were asked two questions. To ensure diversity, two different party scenarios were presented. In one scenario, ten individuals were situated in a room with six apples and six bananas placed on separate tables at a short distance from them. The ten individuals were divided into two social groups of five, identified by matching waistcoats, and were seated at opposite corners of the room. At the beginning of the video, the group members interacted with each other to emphasize their social group identity. Subsequently, four individuals from the same group proceeded individually to the front of the room and then turned left or right to retrieve food from one of the tables. The prevalence of food selection varied in the videos. In the high prevalence condition, four individuals chose the same food item, whereas in the medium prevalence condition, three individuals chose the same item, while the fourth chose the alternative. In the low prevalence condition, two individuals chose each food item. After retrieving their food, the individuals returned to their original seats. A new group member then approached the table, faced the participant, and paused.

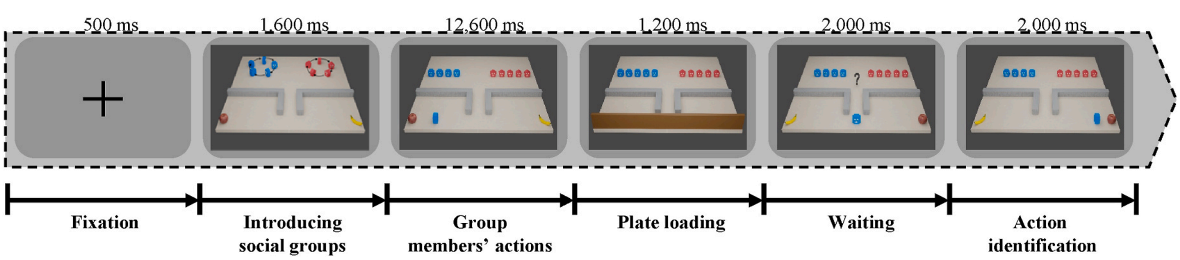


**Fig. 2.** An example trial sequence for implicit measurement of goal-based action generalization.

The participants were asked to answer two questions—"How likely is this person to fetch an apple?" and "How likely is this person to fetch a banana?" (rated from 1 = completely unlikely to 7 = completely likely)—to avoid measuring only a specific kind of individual goal and recognizing that the other goal may be generalized as well. In a separate scenario, the food items were replaced with drinks, namely, Cola and Sprite. Each participant watched a total of six videos, with two videos for each prevalence condition: one depicting a food scenario and the other depicting a drink scenario.

The goal-based action generalization index was constructed to measure participants' predictions of the fifth person following the majority to approach the same goal, except in the low prevalence condition, where this was randomly determined prior to the investigation. The index was computed by averaging the mean ratings of both food and drink scenes (α = 0.79), with items related to the likelihood of fetching the minority's food or drink being reverse-coded.

## 3. Results and discussion

### 3.1. Influences of stimulation on psychological state

One-way ANOVA with stimulation type (anodal vs. sham vs. cathodal) as the independent variable was conducted on the perception of the influence of stimulation on behavior, mood, alertness, and calmness. None of the main effects were significant (behavior: $F(2, 87) = 2.31$, $p = 0.106$, $\eta_p^2 = 0.05$; mood: $F(2, 87) = 1.70$, $p = 0.189$, $\eta_p^2 = 0.04$; alertness: $F(2, 87) = 1.75$, $p = 0.180$, $\eta_p^2 = 0.04$; calmness: $F(2, 87) = 1.59$, $p = 0.210$, $\eta_p^2 = 0.04$). Hence, the effects of the stimulation reported below cannot be attributed to differences in psychological state.

### 3.2. Implicit measurement of goal-based action generalization

To better examine the influence of tDCS stimulation on the pattern of action generalization, the goal-based action generalization effect (i.e., reaction time of inconsistent goal minus reaction time of consistent goal) was calculated after excluding trials with incorrect responses and reaction times less than 150 ms (exclusion rate = 2.61 %). Detailed reaction time and accuracy results were reported in the Supplementary Material. The generalization effect data were analyzed using a 3 (stimulation type: anodal vs. sham vs. cathodal; between-subjects) × 3 (action prevalence: low vs. medium vs. high; within-subjects) factorial ANOVA. Results for each participant and condition are presented in Fig. 3a. The two-way interaction effect was not significant ($F(4, 174) = 1.25$, $p = 0.294$, $\eta_p^2 = 0.03$). After excluding the condition of high action prevalence and keeping the critical two conditions of low and medium action prevalence, in which the nonsignificant difference would show nongraded

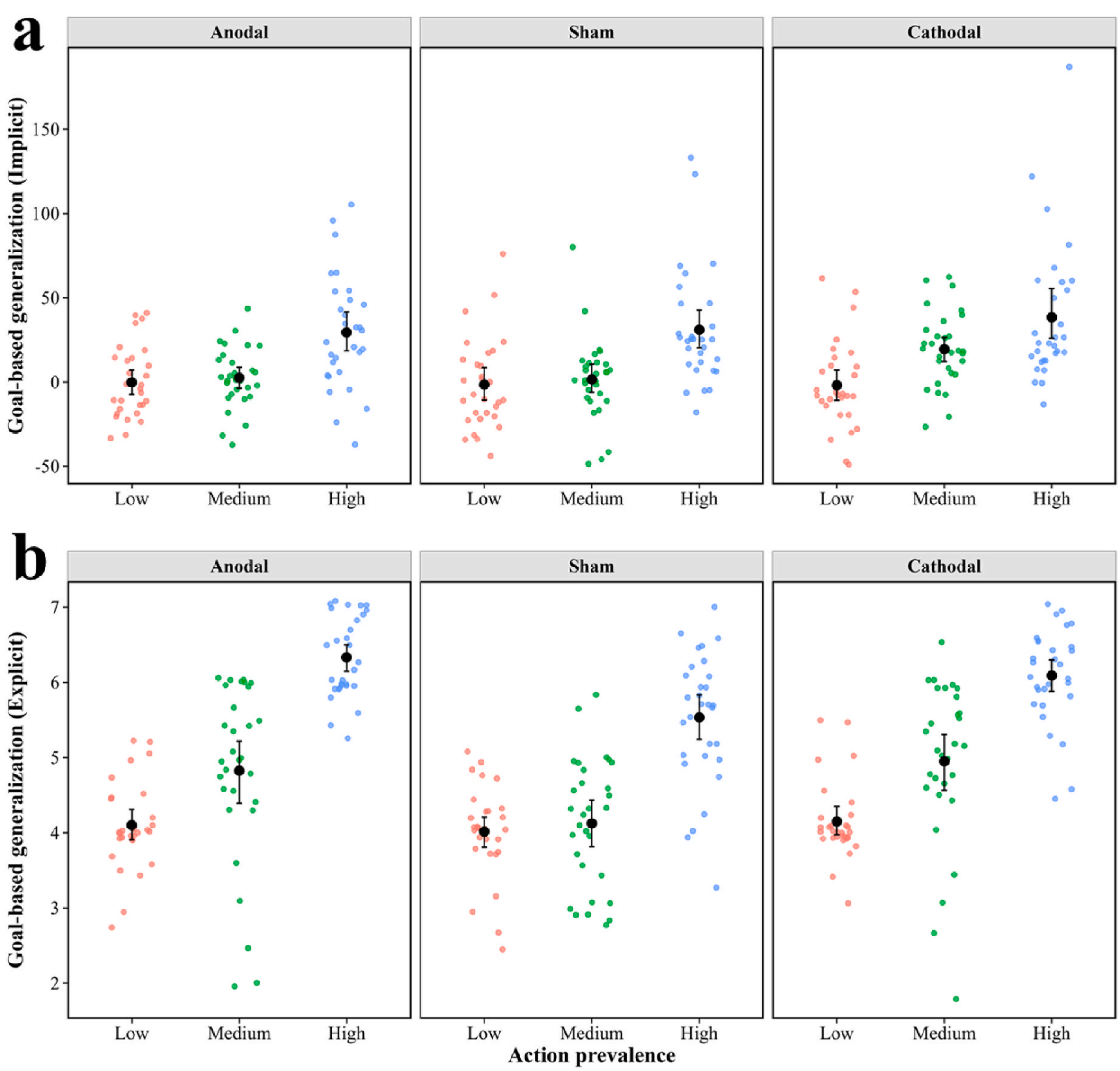


**Fig. 3.** Goal-based action generalization measured in the implicit **(a)** and explicit **(b)** task as a function of action prevalence and stimulation type.

generalization, the two-way interaction effect became significant ($F$(2, 87) = 3.22, $p$ = 0.045, $\eta_p^2 = 0.07$), suggesting that the stimulation type modulates the influence of action prevalence on goal-based action generalization.

To classify the pattern of action generalization, the goal-based action generalization effect was compared across low, medium, and high prevalence conditions for each stimulation type. In the sham stimulation condition, it revealed that the goal-based action generalization effect was significantly greater at high prevalence ($M$ = 31 ms, $SE$ = 6) than in the medium ($M$ = 1 ms, $SE$ = 4; $t$(29) = 4.15, $p$ < 0.001, Cohen's $d$ = 0.74, 95 % CI of $d$ = [0.29, 1.20]) and low ($M$ = −2 ms, $SE$ = 5; $t$(29) = 4.63, $p$ < 0.001, Cohen's $d$ = 0.82, 95 % CI of $d$ = [0.37, 1.27]) prevalence conditions. However, there was no significant difference between the medium and low prevalence conditions ($t$(29) = 0.41, $p$ = 1.000, Cohen's $d$ = 0.08, 95 % CI of $d$ = [−0.41, 0.57]) in terms of the goal-based action generalization effect. Moreover, the goal-based action generalization effect was only significantly greater than zero at high prevalence ($t$(29) = 4.95, $p$ < 0.001, Cohen's $d$ = 0.90, 95 % CI of $d$ = [0.47, 1.33]). In contrast, the goal-based action generalization effect was not significantly different from zero in both medium ($t$(29) = 0.37, $p$ = 0.715, Cohen's $d$ = 0.07, 95 % CI of $d$ = [−0.29, 0.43]) and low ($t$(29) = −0.30, $p$ = 0.762, Cohen's $d$ = −0.06, 95 % CI of $d$ = [−0.41, 0.30]) prevalence conditions, indicating an absence of generalizing action goals.

In the anodal stimulation condition, it revealed that the goal-based action generalization effect was significantly larger at high prevalence ($M$ = 29 ms, $SE$ = 6) than in the medium ($M$ = 3 ms, $SE$ = 3; $t$(29) = 3.56, $p$ = 0.004, Cohen's $d$ = 0.75, 95 % CI of $d$ = [0.22, 1.29]) and low ($M$ = 0 ms, $SE$ = 4; $t$(29) = 4.35, $p$ < 0.001, Cohen's $d$ = 0.83, 95 % CI of $d$ = [0.34, 1.31]) prevalence conditions. There was no significant difference between the medium and low prevalence conditions ($t$(29) = 0.54, $p$ = 1.000, Cohen's $d$ = 0.08, 95 % CI of $d$ = [−0.28, 0.43]). Moreover, the goal-based action generalization effect was significantly greater than zero only at high prevalence ($t$(29) = 4.79, $p$ < 0.001, Cohen's $d$ = 0.87, 95 % CI of $d$ = [0.45, 1.29]), while at both medium ($t$(29) = 0.79, $p$ = 0.434, Cohen's $d$ = 0.15, 95 % CI of $d$ = [−0.22, 0.50]) and low ($t$(29) = −0.04, $p$ = 0.972, Cohen's $d$ = −0.01, 95 % CI of $d$ = [−0.36, 0.35]) prevalence conditions, this effect was not significantly different from zero, suggesting the absence of goal-based action generalization.

In the cathodal stimulation condition, it revealed that the goal-based action generalization effect at high prevalence ($M$ = 38 ms, $SE$ = 8) was larger than that at both medium ($M$ = 19 ms, $SE$ = 4; $t$(29) = 2.58, $p$ = 0.045, Cohen's $d$ = 0.52, 95 % CI of $d$ = [0.01, 1.03]) and low ($M$ = −2 ms, $SE$ = 5; $t$(29) = 5.33, $p$ < 0.001, Cohen's $d$ = 1.09, 95 % CI of $d$ = [0.57, 1.61]) prevalence, and the goal-based action generalization effect was larger at medium than at low prevalence ($t$(29) = 4.44, $p$ < 0.001, Cohen's $d$ = 0.58, 95 % CI of $d$ = [0.25, 0.92]). In addition, the effect of the goal-based action generalization both in the high prevalence ($t$(29) = 5.03, $p$ < 0.001, Cohen's $d$ = 0.92, 95 % CI of $d$ = [0.49, 1.34]) and medium prevalence ($t$(29) = 4.86, $p$ < 0.001, Cohen's $d$ = 0.89, 95 % CI of $d$ = [0.46, 1.31]) conditions was above zero; however, this value in the low prevalence ($t$(29) = −0.40, $p$ = 0.690, Cohen's $d$ = −0.07, 95 % CI of $d$ = [−0.43, 0.29]) condition was not significantly different from zero, indicating an absence of goal-based action generalization.

### 3.3. Explicit measurement of goal-based action generalization

The mean goal-based action generalization index of each participant for each condition is shown in Fig. 3b. The 3 (stimulation type as a between-subject factor: anodal vs. sham vs. cathodal) × 3 (action prevalence as a within-subject factor: low vs. medium vs. high) ANOVA revealed that the main effect of stimulation type was significant ($F$(2, 87) = 12.20, $p$ < 0.001, $\eta_p^2 = 0.22$), showing that the goal-based action generalization was rated higher in the anodal stimulation ($M$ = 5.09, $SE$ = 0.09) than in the sham stimulation ($M$ = 4.56, $SE$ = 0.09; $t$(87) = 4.37, $p$ < 0.001, Cohen's $d$ = 0.48, 95 % CI of $d$ = [0.21, 0.75]), and the goal-based generalization was rated higher in the cathodal stimulation ($M$ = 5.06, $SE$ = 0.09) than in the sham stimulation ($t$(87) = 4.18, $p$ < 0.001, Cohen's $d$ = 0.46, 95 % CI of $d$ = [0.19, 0.73]), but no significant difference was found between anodal and cathodal stimulations ($t$(87) = 0.18, $p$ = 1.000, Cohen's $d$ = 0.02, 95 % CI of $d$ = [−0.25, 0.29]). The main effect of action prevalence was significant ($F$(2, 174) = 138.13, $p$ < 0.001, $\eta_p^2 = 0.61$). The post hoc comparisons showed that the goal-based action generalization index in the high prevalence condition ($M$ = 5.99, $SE$ = 0.07) was larger than that in the medium ($M$ = 4.63, $SE$ = 0.11; $t$(87) = 11.12, $p$ < 0.001, Cohen's $d$ = 1.23, 95 % CI of $d$ = [0.96, 1.50]) and low ($M$ = 4.09, $SE$ = 0.06; $t$(87) = 20.58, $p$ < 0.001, Cohen's $d$ = 1.72, 95 % CI of $d$ = [1.52, 1.93]) prevalence conditions, and the goal-based action generalization index in the medium prevalence condition was larger than that in the low prevalence condition as well ($t$(87) = 4.04, $p$ < 0.001, Cohen's $d$ = 0.49, 95 % CI of $d$ = [0.20, 0.79]). However, this effect was modulated by the stimulation type, as the interaction effect was significant ($F$(4, 174) = 2.49, $p$ = 0.045, $\eta_p^2$ = 0.05). To evaluate the pattern of action generalization, a simple-effects analysis was performed to test the effect of action prevalence (low vs. medium vs. high) under each stimulation type.

A significant main effect of action prevalence was observed in the sham stimulation condition ($F$(2, 87) = 55.83, $p$ < 0.001, $\eta_p^2 = 0.56$). The post hoc analyses showed that in the high prevalence condition, the extent of goal-based action generalization ($M$ = 5.53, $SE$ = 0.13) was significantly larger than that in the medium ($M$ = 4.13, $SE$ = 0.19; $t$(87) = 6.69, $p$ < 0.001, Cohen's $d$ = 1.28, 95 % CI of $d$ = [0.81, 1.74]) and low ($M$ = 4.02, $SE$ = 0.10; $t$(87) = 9.50, $p$ < 0.001, Cohen's $d$ = 1.38, 95 % CI of $d$ = [1.02, 1.73]) prevalence conditions. However, there was no significant difference between the medium and low prevalence conditions ($t$(87) = 0.46, $p$ = 1.000, Cohen's $d$ = 0.10, 95 % CI of $d$ = [−0.42, 0.62]). Thus, the nongraded generalization effect was replicated when no active stimulation was administered.

The main effect of action prevalence was significant in the anodal stimulation condition ($F$(2, 87) = 106.04, $p$ < 0.001, $\eta_p^2 = 0.71$). However, the pattern of results from the post hoc comparisons differed from those observed in the sham stimulation condition. Specifically, the goal approached by the majority in the high prevalence condition ($M$ = 6.33, $SE$ = 0.13) was more likely to be generalized to a new group member than that in the medium ($M$ = 4.83, $SE$ = 0.19; $t$(87) = 7.16, $p$ < 0.001, Cohen's $d$ = 1.37, 95 % CI of $d$ = [0.90, 1.83]) or low ($M$ = 4.10, $SE$ = 0.10; $t$(87) = 9.50, $p$ < 0.001, Cohen's $d$ = 1.38, 95 % CI of $d$ = [1.02, 1.73]) prevalence condition. In addition, the prevalent goal in the medium prevalence condition was more likely to be generalized to a new group member than that in the low prevalence condition ($t$(87) = 3.11, $p$ = 0.008, Cohen's $d$ = 0.66, 95 % CI of $d$ = [0.14, 1.17]). These findings suggest that when the excitability of brain region representing the belief in shared goals increased, the effect of action prevalence on generalization changes, with the extent of goal-based action generalization increasing as the prevalence of the action goal increases.

The main effect of action prevalence was significant in the cathodal stimulation condition ($F$(2, 87) = 77.57, $p$ < 0.001, $\eta_p^2 = 0.64$), showing a similar pattern to that of anodal stimulation. Specifically, the prevalent goal in the high prevalence condition ($M$ = 6.09, $SE$ = 0.13) was more likely to be generalized to a new group member than that in the medium ($M$ = 4.95, $SE$ = 0.19; $t$(87) = 5.42, $p$ < 0.001, Cohen's $d$ = 1.04, 95 % CI of $d$ = [0.57, 1.50]) or low ($M$ = 4.15, $SE$ = 0.10; $t$(87) = 12.16, $p$ < 0.001, Cohen's $d$ = 1.76, 95 % CI of $d$ = [1.41, 2.22]) prevalence condition, and the prevalent goal in the medium prevalence condition was more likely to be generalized to a new group member than that in the low prevalence condition ($t$(87) = 3.43, $p$ = 0.003, Cohen's $d$ = 0.73, 95 % CI of $d$ = [0.21, 1.24]). Therefore, similar to the anodal stimulation condition, when applying cathodal stimulation to diminish excitability in the brain region representing the belief in shared goals, the prevalent action goal is more likely to be generalized to a new group member as the prevalence of the action goal increases.

Importantly, in the low prevalence condition in which each goal could be considered the to-be-generalized property, the rating value was not significantly different from the mid-value (i.e., 4), indicating a lack of generalization in the sham ($t(29) = 0.16$, $p = 0.877$, Cohen's $d = 0.03$, 95 % CI of $d = [-0.33, 0.39]$), anodal ($t(29) = 0.95$, $p = 0.348$, Cohen's $d = 0.17$, 95 % CI of $d = [-0.19, 0.53]$) and cathodal ($t(29) = 1.58$, $p = 0.125$, Cohen's $d = 0.29$, 95 % CI of $d = [-0.08, 0.65]$) stimulation conditions.

The results from both the implicit and explicit measurements primarily focused on comparing goal-based action generalization effects across different levels of action prevalence within each stimulation type, in line with our hypothesis. Admittedly, an additional analysis examining the effect of stimulation type on goal-based action generalization within each action prevalence condition could offer further support for our conclusions. This is particularly relevant for the medium prevalence condition, where it is critical to assess whether the presence of a shared-goal belief alters the extent of action generalization. Detailed results of this analysis are provided in the Supplementary Material, offering additional evidence that the mPFC plays a role in representing the belief in shared goals.

## 4. General discussion

The present study examined whether the mPFC is the essential brain region involved in representing the belief that group members have a shared goal. The rationale is that if the mPFC supports this belief representation, then modulating its activity should alter the corresponding pattern of action generalization in which the extent of action generalization changes with the prevalence of observed actions. The results revealed that when sham stimulation was applied to the mPFC, the extent of goal-based action generalization and the prevalence of the action goal exhibited a nongraded relationship. That is, an action goal, as a target property, was generalized to a new group member only when all known group members approached the same goal. If any member deviated from that goal, the extent of goal-based action generalization did not gradually increase with the prevalence of the action goal. In the implicit measurement, cathodal stimulation induced a graded pattern, whereas anodal and sham stimulation still elicited nongraded goal-based action generalization. In contrast, in the explicit measurement, both anodal and cathodal stimulation led to a gradual increase in the extent of action generalization with increased prevalence of the action goal, a pattern not observed under sham stimulation. These findings suggest that cathodal tDCS stimulation weakens the representation of the shared-goal belief, with the extent of goal-based action generalization gradually increasing in conjunction with the statistical prevalence of the goal. If the belief in shared goals had remained available, the nongraded pattern would likely have persisted.

The findings of the present study provide evidence of the involvement of the mPFC in representing the belief that group members have a shared goal. Compared with sham stimulation, applying cathodal stimulation to the mPFC resulted in a graded pattern of goal-based action generalization, indicating that the representation of the shared-goal belief weakens. Owing to the belief of a shared goal, any deviation from the majority creates uncertainty about whether new members will pursue the same goal. As a result, the extent of goal-based action generalization does not gradually increase with the prevalence of the action goal, reflecting a nongraded pattern. In contrast, when the representation of the belief in shared goals is weakened, action generalization relies primarily on the accumulated evidence of action goals, resulting in a graded pattern. Hence, these findings provide evidence supporting the involvement of the mPFC in representing the belief in shared goals. Regarding the function of the mPFC in social cognition, previous studies have shown that the mPFC is associated with representing group-related beliefs (Molenberghs and Morrison, 2014; Morrison et al., 2012; Sellaro et al., 2015). More recently, research has shown that the mPFC is involved in the representation and utilization of group-related beliefs (Vijayakumar et al., 2021). Specifically, Vijayakumar and colleagues (2021) demonstrated that the mPFC is activated when new members' behavioral tendencies are predicted on the basis of established group-related beliefs about others' preferences. While these studies have established a link between the mPFC and the representation or utilization of group-related beliefs, it remains unclear whether the mPFC is specifically involved in representing the belief in shared goals, which is a specific type of group-related belief. The present study provides evidence that the mPFC is related to representing the belief that group members have a shared goal and enhances the understanding of the role of the mPFC in social cognition.

More interestingly, the current study revealed a dissociation in the pattern of goal-based action generalization between implicit and explicit measurements following tDCS stimulation. Specifically, in the implicit measurement, only cathodal stimulation of the mPFC led to a graded pattern of goal-based action generalization. In contrast, both anodal and cathodal stimulation of the mPFC resulted in a graded pattern of action generalization in the explicit measurement. These results are consistent with previous findings highlighting the differences between implicit and explicit processing (Frith and Frith, 2008; Kurdi et al., 2023; Paulus et al., 2017; Schuwerk et al., 2015). This dissociation may be attributed to distinct patterns in the activation and processing of shared goal beliefs across these two types of measurements. Specifically, in the implicit measurement, the belief in shared goals is activated automatically and influences action generalization through automatic processing, which is less susceptible to modulation by cognitive control (Cohen et al., 2016; Schneider et al., 2014). In contrast, in the explicit measurement, the belief is explicitly activated and influences action generalization through controlled processing, making it more sensitive to changes in cognitive control (Kovács et al., 2014). Cathodal stimulation diminishes the excitability of the mPFC and weakens the representation of the shared-goal belief, a specific form of group-related belief (Sellaro et al., 2015). As a result, its influence on goal-based action generalization declines, prompting participants to rely more heavily on the observed evidence of group members' actions. This leads to a graded relationship between the extent of action generalization and the prevalence of action goal in both implicit and explicit measurements. Whereas, anodal stimulation enhances mPFC excitability, thereby strengthening its associated functions (Li et al., 2018; Yuan et al., 2023), particularly the representation of the shared-goal belief in the present study. Anodal stimulation has also been shown to improve cognitive control (Csifcsák et al., 2021; Yu et al., 2015). In the implicit measurement, where belief activation and its influence occur automatically and are relatively unaffected by cognitive control, the nongraded pattern of goal-based action generalization remains. However, in the explicit measurement, enhanced cognitive control may suppress the influence of shared goal beliefs on action generalization, shifting the pattern toward a graded one based on observed evidence. Future research should systematically examine the role of the mPFC across different measurements.

The results in the sham stimulus condition in this study are consistent with the findings in the broader domain of inductive generalization, which demonstrate that prior belief or knowledge about a target property influences the extent of generalization (Bright and Feeney, 2014; Rehder, 2009; Rehder and Hastie, 2001). Specifically, inductive generalization often exhibits a graded relationship between the extent of generalization and the prevalence of exemplars with the target property (Lawson, 2014). However, the belief or knowledge about the target property could interrupt this graded pattern (Hayes et al., 2019; Vasilyeva and Lombrozo, 2020; Voorspoels et al., 2015). For example, previous research has indicated that nongraded generalization occurs when people believe that evidence related to a target property is selected deliberately rather than randomly (Voorspoels et al., 2015). The present study extends the effect of a pre-existing belief or knowledge to goal-based action generalization. Specifically, the current study indicated that the belief of members in the same group having shared goals influences how the target property (i.e., the action goal) is generalized to new members. Only evidence consistent with this belief (i.e., all known group members pursuing the same goal) leads to a significant increase in action generalization.

Notably, the present findings carry meaningful practical implications. Our results indicate that the presence of even a single goal-violating member, whose action contradicts the belief in shared goals, can prevent action generalization from increasing with the accumulated evidence of approaching the same action goals. This pattern suggests that a small number of violators can trigger a rapid breakdown of group-consistent behavior (Dannals and Miller, 2017; Gelfand et al., 2024), mirroring the dynamics proposed by "broken windows theory" in social psychology (O'Brien et al., 2019). Furthermore, these findings offer valuable insights for management. To facilitate the rapid spread of majority-consistent actions, it may be more effective to downplay the belief in shared goals underlying these actions, as this reduces sensitivity to inconsistencies and promotes broader action generalization. Conversely, when the aim is to curb the spread of such actions, emphasizing the belief in shared goals can enhance individuals' sensitivity to deviations, making even minimal violations sufficient to disrupt generalization and slow the diffusion process.

Undeniably, the present study has several limitations. First, the placement of tDCS stimulation electrodes according to the international EEG 10–20 system and the use of relatively large electrodes, as in previous studies (Sellaro et al., 2015), may limit the precision of stimulation on mPFC. Follow-up studies could increase the focality of tDCS by adopting smaller sized electrodes or combining tDCS with other techniques (e.g., MRI localization). Second, it is important to acknowledge that while sham stimulation is widely used as a control condition (Razza et al., 2024; De Smet et al., 2021), the lack of an active control remains a significant limitation. Future research should include active stimulation of non-target brain regions to more effectively rule out potential nonspecific factors, such as arousal or changes in neural network dynamics, that may have influenced our findings. Third, the social groups in the present study were introduced through similarity in appearance and interaction between members, which is the definition of a task-oriented group. Thus, the findings related to the mPFC representing the belief that group members have a shared goal may be more applicable to task-oriented groups, and extending the findings to other types of groups (e.g., social category groups) requires extreme caution. Fourth, the present study examined the role of the mPFC in representing the belief of a shared goal within a small group of five members, and future research should explore the role of the mPFC in a larger group. Lastly, although the current study employed a single-blind design, which has been shown to reduce expectancy effects (Berlim et al., 2013; Dedoncker et al., 2016), this approach may not fully eliminate such expectancy-related influences on participants' responses. Future studies should consider adopting a double-blind design to more rigorously control for potential expectancy-related biases.

## 5. Conclusion

In conclusion, through the application of noninvasive brain stimulation via tDCS, the current study reveals the critical role of the mPFC in representing the belief that group members have a shared goal.

## CRediT authorship contribution statement

**Jipeng Duan:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Qingqing Ye:** Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Yinfeng Hu:** Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Ying Zhou:** Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Xinnan Zhang:** Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Jun Yin:** Writing – review & editing, Writing – original draft, Validation, Supervision, Funding acquisition, Data curation, Conceptualization.

## Ethics approval

The study was approved by the Research Ethics Board of the Department of Psychology at Ningbo University and was performed in accordance with the relevant guidelines and regulations.

## Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, we used ChatGPT-3.5 in order to improve the readability and language of the manuscript. After using this tool, we reviewed and edited the content as needed and take full responsibility for the content of the published article.

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## Declaration of competing interest

The authors declare no competing interests.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.neuropsychologia.2025.109246.

## Data availability

All data, analysis codes, and example trial videos for each condition can be accessed at https://osf.io/b2gm9/?view_only = 1be7145d2c704a39b7b8de39a87f134a.

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