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Modulating the activity of vmPFC alters altruistic behavior: A tDCS study

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ABSTRACT

For centuries, scientists have pondered why people would help others at a cost to themselves even in the absence of expectation for future benefit. While a growing body of neuroimaging studies has suggested that the ventromedial prefrontal cortex (vmPFC) may be particularly critical for the regulation of altruistic behavior. However, evidence is still lacking in the field of neuroscience regarding the causal link between the region of vmPFC and pure altruistic behavior. In the present study, we designed a modified dictator game with a binary choice in the contexts of gain and loss that aimed to provide a simple and direct measure of participants' altruistic tendency. Using tDCS, we found that modulating the activity of vmPFC could significantly alter altruistic behaviors. Specifically, anodal stimulation of the vmPFC resulted in increasing altruistic choices compared with the cathodal stimulation, and the effect was found both in the gain and loss contexts. In addition, the subsequent inferences about others' altruistic behaviors were correlated with their own choices, and cathodal vmPFC stimulation resulted in a lower inference than sham stimulation in the gain context.

1. Introduction

Altruism is the unselfish concern about other people. People do this only out of a desire to help, rather than motivated by duty, loyalty, or religion. Although altruistic behaviors may endanger their own health and well-being, such behaviors are often done unselfishly and without any expectations of reward. It is described in terms of "pure altruism". Unlike "strategic altruism", pure altruism does not allow for the possibility of extrinsic gain, which may come through avoiding punishment, reciprocity of recipient, enhanced gains from cooperation or reward from future interactions [1-4].

Why do pure altruistic behaviors exist? A large body of literature has attempted to explain this issue from different perspectives. Psychologists have suggested that altruistic behavior brings about intangible gains, such as psychological well-being, self-esteem, the experience of meaning in life, increased energy and engagement with the environment, overall life-satisfaction [5-9]. From an evolutionary perspective, the emotional rewards that people experience when helping others may serve as a proximate mechanism that evolved to facilitate prosocial behavior, which may have carried short-term costs but long-term benefits for survival over human evolutionary history [10].

Due to the use of neuroimaging techniques, the neural basis of altruism has been demonstrated in neuroscience studies. Previous functional magnetic resonance imaging (fMRI) studies on neural correlates of altruistic behaviors usually found involvement of regions that established elements of the reward and value-computation networks [11,12]. Concretely, Karns et al. [13] found that in young adult female participants, self-reported altruism was associated with "neural pure altruism" in ventromedial prefrontal cortex (vmPFC) and nucleus accumbens (NuAcc). A meta-analysis of fMRI on altruism showed that compared to selfish decisions, NuAcc, vmPFC, orbitofrontal cortex (OFC), subgenual area of the anterior cingulate cortex (sgACC) and anterior cingulate cortex (ACC) are more active when an individual makes altruistic choices, and the vmPFC has been linked to the overall value of a prosocial decision [14].

A growing number of neuroimaging studies examining decision-making and evaluation processes has consistently implicated the medial prefrontal cortex (MPFC), and different regions within the MPFC may be differentially tuned to different types of evaluative information [15]. Of special importance is the vmPFC, a region that involved in calculating the subjective value of multiple reward types [16,17]. Recent researches have suggested that the common value calculation in

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interpersonal decision-making may also reflect in vmPFC activity [18-20]. For example, when individuals arbitrate between their own and others' welfare, the neural modulation that tracks with the predicted subjective value is restricted to the vmPFC [20]. The activation of the vmPFC is found to be positively correlated with the performer's experienced meaningfulness from his or her altruistic behavior [12]. Besides, studies have suggested that vmPFC plays a critical role in social cognition and empathy [21,22]. Empathic emotion has been demonstrated as a vital source of altruistic motivation that predicts increased helping [23,24]. Lesion studies provide evidence that selective damage to the vmPFC impairs social emotions crucial for moral judgments and prosocial economic decisions [25-28].

The vmPFC is usually believed to play a critical role in mediating value-based decision-making [16], and it associates with the anticipation and receipt of monetary rewards in many studies [29,30]. Several studies focus on both gains and losses, and reveal that they are coded in a similar set of regions, including the vmPFC [31-33]. The vmPFC exhibits a pattern of "neural loss aversion", the (negative) slope of the decrease in activity for increasing losses was greater than the slope of the increase in activity for increasing gains in a majority of participants [31]. Another study by De Martino et al. [34] shows that vmPFC activity correlated with the "rational" choice in the gambling task, and lower levels of vmPFC activity were associated with larger framing effects. Lesion study also showed that vmPFC damage alters decision-making for prospective gains and losses [35].

Non-invasive methods such as transcranial direct current stimulation (tDCS) provide the means to illuminate the causal impact of particular areas of the neocortex on cognitive processing. To date, only a few published studies have addressed the causal correlation between vmPFC and altruistic tendency. Zheng et al. [36] found that anodal activation of vmPFC by tDCS could significantly increase the altruistic behaviors in a one-shot dictator game. Liao et al. [37] found that the anodal stimulation to mPFC increased the propensity for the decider to help the pain-taker and the cathodal stimulation to mPFC showed a reverse effect.

Although these studies suggested that vmPFC appears to play a crucial role in altruism, the current evidence is still rare. In addition, none of the tDCS studies has distinguished the altruistic behaviors in the gain and loss contexts. Whether modulating the activity of vmPFC would result in different effects in the gain and loss contexts is required to be further examined. The present study aimed to further demonstrate the causal involvement of vmPFC in altruistic behavior. In this paper, we designed a modified dictator game, in which participants were asked to choose between an equal and altruistic wealth allocation as the role of dictators. We aimed to use tDCS to modulate the altruistic behaviors of participants when facing gains or losses.

2. Materials and methods

2.1. Participants

A priori power analysis was conducted using G*Power 3.1 [38]. With alpha = 0.05 and power = 0.80, the sample size to detect a medium to large effect size ($f^2 = 0.15$; [39]) is approximately N = 72 for one-way ANOVA with three groups. A total of 90 students (52 females; mean age 20.66 years, ranging from 19 to 24 years) participated in our experiment. All participants were right-handed, had normal or corrected normal vision with no history of psychiatric illness or neurological disorders, and were naive to tDCS and our experimental task. The experiment lasted approximately 1 h. The overall payment consisted of a fixed show-up fee of 30.0 CNY (approximately equal to US $4.65) plus the reward gained from the distributive tasks. On average, participants received 62.0 CNY (ranging from 55 to 65 CNY, approximately equal to US $9.6) according to their performance. Written informed consent was obtained prior to participation, and all methods were carried out in accordance with the approved protocol. No participants reported any adverse side effects involving scalp pain or headaches.

2.2. Transcranial Direct Current Stimulation (tDCS)

tDCS is a non-invasive, painless, and well-tolerated stimulation paradigm used as a tool to modulate cortical excitability and behavior without any physiological damage to the participants. In general, anodal stimulation increases cortical excitability both during and after stimulation, and cathodal stimulation leads to a decrease in excitability within the cortex [40]. Direct current was induced by two saline-soaked surface sponge electrodes (5 cm × 7 cm; 35 cm^2) and delivered by a battery-driven, constant-current stimulator (Starlab, Spain).

In our study, participants were randomly assigned to one of the three stimulation treatments, with thirty participants (17 females; mean age 20.87 years, ranging from 19 to 24 years) in the anodal stimulation group, thirty participants (18 females; mean age 20.50 years, ranging from 19 to 24 years) in the cathodal stimulation group, and thirty participants (17 females; mean age 20.60 years, ranging from 19 to 23 years) in the sham stimulation group. There was no significant difference in the three groups with respect to the self-reported equity preference and the number of participation in volunteer activities and active blood donations (Table 1). In line with previous neuroscience research targeting the vmPFC [36,41], the anodal electrode was placed over the Fpz position according to the international 10–20 system for electrode placements, while the cathodal return electrode was placed over the Oz position in the anodal stimulation group. The polarity was reversed for cathodal stimulation (Fig. 1A-C). The stimulation lasted for 20 min. For sham stimulation, the procedures were the same, but the current lasted only for the first 30 s, and there was no current for the rest of the stimulation period without the participants' knowledge. This method of sham stimulation has been shown to be reliable [42]. The current was constant and had an intensity of 1.5 mA with 30 s of ramping up and down. The safety and the effectiveness of these parameter settings had been shown in previous studies [43,44]. After the stimulation, the tDCS was taken off, and the participants were asked to complete the following task.

2.3. Experimental task and procedure

The experiment was based on a modified dictator game with a binary choice that aimed to provide a simple and direct measure of participants' altruistic behavior with little requirement for strategy or working memory. The experiment was modified from Yang et al. [45]. Participants were asked to choose between an equal and an altruistic wealth allocations (A and B). They were informed to play the role of dictators with five other receivers who were matched anonymously and randomly, and all members of their group would be paid according to the choices made by themselves. They were also told that the five other receivers were in another labs in order to avoid any communication or collaboration. The formal experiment was not started until the subjects were assured that they believed in the experimental design and fully understood the experiment. In each trial, option A was an equal

Table 1
Participants demographics for the sham, anodal and cathodal groups. Descriptive data are presented as mean ± s.e.

Stimulation type	Sham (n = 30)	Anodal (n = 30)	Cathodal (n = 30)	Statistics
Gender (male/female)	13/17	13/17	12/18	
Equity preference	3.87 ± 0.124	4.10 ± 0.130	4.07 ± 0.135	$\chi^2(2) = 1.896$, p = 0.388
Volunteer activities	5.57 ± 0.561	4.77 ± 0.644	4.77 ± 0.646	$\chi^2(2) = 1.804$, p = 0.406
Active blood donations	0.43 ± 0.164	0.67 ± 0.182	0.27 ± 0.082	$\chi^2(2) = 2.955$, p = 0.228

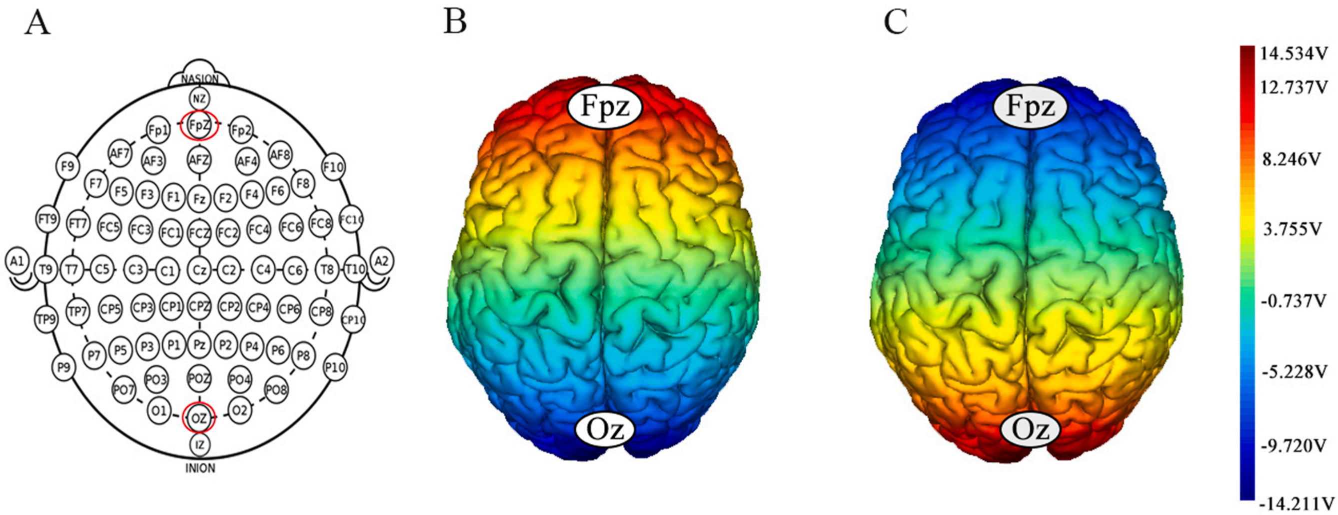

Fig. 1. Schematic drawing of electrode positions suited for tDCS of the vmPFC of the human brain. (A) Stimulation of the respective cortices according to the 10–20 system. (B) The electrode placement of anodal stimulation. The anodal electrode was placed over Fpz and the cathodal electrode was placed over Oz. (C) The electrode placement of cathodal stimulation. The cathodal electrode was placed over Fpz and the anodal electrode was placed over Oz.

allocation, namely the participant and five other receivers could get the same amount of payoffs. Option B was an altruistic allocation, in other words, compared to the equal allocation, the participants could sacrifice a portion of their payoffs to bring in more payoffs for five other receivers. The experiment was applied in two contexts, gain and loss. Each context consisted of 10 trials. The parameters of each choice were displayed in Table 2.

Consider a population of $n+1$ individuals. In a simple model, an individual derives positive utility from his/her own earnings as well as from aggregate payoffs (i.e., the sum of own payoffs and the other n receivers' payoffs):

$$U_i(x, y_1, y_2, ..., y_n) = x + \gamma_i(x + \sum_j y_j) \quad (2\ \ \text{-}1)$$

Table 2
The decision-making task.

No.	Option A Yours	Option A Five others'	Option B Yours	Option B Five others'	γ*
Gain Context					
1	50	50	25	75	0.250
2	50	50	25	85	0.167
3	50	50	25	95	0.125
4	50	50	25	105	0.100
5	50	50	25	115	0.083
6	50	50	25	125	0.071
7	50	50	25	135	0.063
8	50	50	25	145	0.056
9	50	50	25	155	0.050
10	50	50	25	165	0.045
Loss Context					
1	-50	-50	-75	-25	0.250
2	-50	-50	-73	-25	0.225
3	-50	-50	-70	-25	0.190
4	-50	-50	-68	-25	0.168
5	-50	-50	-65	-25	0.136
6	-50	-50	-63	-25	0.116
7	-50	-50	-60	-25	0.087
8	-50	-50	-58	-25	0.068
9	-50	-50	-55	-25	0.042
10	-50	-50	-53	-25	0.025

Notes: The table presents the 10 decisions in the gain context (given in rows) and 10 decisions in the loss context. "Yours" refers to the dictator's payoff and "Five others'" to the five receivers' payoffs. The final column includes the unique critical values of γ* that makes the option A and option B indifferent.

where x is the individual i's own payoffs, and y_j, $j = 1,.,n$ denote the other n receivers' payoffs, The parameter γ measures the marginal utility of aggregate earnings. In each round of the gain context, option A was the same, where the proposer and each of the five receivers could receive 50 points. Option B offered less to the proposer, but the amount to each recipient increased, thus increasing the total revenue. Hence, the strong preference for aggregate earnings might give higher utility to option B. The same logic applied to the loss context. The bounds for each decision were shown in the last column in Table 2, which made option A and option B indifferent. The γ^* was controlled within a certain range to make the gain and loss contexts comparable.

The entire experiment was conducted in three stages (Fig. 2). In the first stage, participants received one of the three stimulation patterns for 20 min. In the second stage, after receiving experimental instructions, participants completed a short quiz to ensure that the task and the payoffs representation were understood. Then they had to complete the experimental task. The experimental software E-prime (Version 3.0, Psychology Software Tools, Inc.) was used to present the tasks as well as to automatically calculate the final payoffs. The choices were mixed up in random order and presented one by one. Each trial began with a presentation of a single centrally located black fixation cross for 500 ms. Then the decision screen with two options followed. Participants were required to make their decisions by pressing either 'f' or 'j' button of a standard keyboard. The equal options and the altruistic options were counterbalanced on the left and right sides of the screen. After the participants finished their task, the computer randomly selected one choice as the basis for the task reward. In the third stage, all participants were asked to complete the questionnaires concerning their personal information and a post-experiment questionnaire before they finally

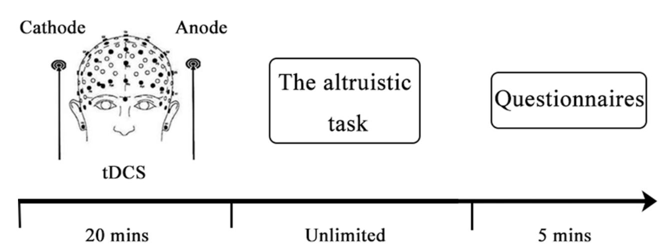

Fig. 2. Schematic representation of the experimental design. After 20 min of stimulation, each participant was then asked to complete the altruistic task and questionnaires.

received their payoffs. The post-experiment questionnaire consisted of four questions, two in the gain context and two in the loss context. The first question: What percentage of students do you think would choose the equal options in the experiment? The second question: What percentage of students do you think would choose the altruistic options in the experiment?

2.4. Data analysis

The participants' selections in the distributive task represented their willingness to increase the interests of others at the expense of themselves, indicating their altruism tendency. The choice was coded as a dummy variable and was set to 1 if a participant made an altruistic choice and 0 otherwise. The times of altruistic choices in the gain and loss contexts were not normally distributed, as assessed by Shapiro-Wilk's test ($ps < 0.001$). Therefore, non-parametric tests were performed to analyze the data.

3. Results

3.1. Behavioral data (Sham group)

In the sham stimulation group, altruistic behavior did exist. In the gain context, the altruistic options were chosen 1.533 times (SE = 0.428) in 10 trials. Specifically, nearly half of the participants (13 out of thirty) had at least one altruistic choice, and there was one participant who chose the altruistic option in all 10 trials. In the loss context, the altruistic options were chosen 1.800 times (SE = 0.411) in 10 trials. Specifically, half of the participants (15 out of thirty) had at least one altruistic choice. The specific distribution of the times of altruistic choices across participants was shown in Fig. 3A-B. The times of altruistic behaviors did not show a significant difference between the gain context and the loss context (Wilcoxon rank-sum test, $z = -1.238$, $p = 0.216$).

3.2. Effects of tDCS over the vmPFC

The results showed that altruistic behaviors from all three stimulation conditions were significantly different from zero both in the gain and loss contexts (gain context: anodal $p < 0.001$, cathodal $p = 0.043$, sham $p = 0.001$; loss context: anodal $p < 0.001$, cathodal $p = 0.004$, sham $p < 0.001$). The Kruskal-Wallis H test showed that the times of altruistic behaviors in gain context were affected by stimulation of vmPFC [$\chi^2(2) = 9.663$, $p = 0.008$, Fig. 4A]. Anodal stimulation resulted in significantly more altruistic choices than cathodal stimulation (2.167 vs. 0.800; Bonferroni-adjusted $p = 0.006$). No significant differences were found between anodal and sham stimulation (Bonferroni-adjusted $p = 0.521$) or between cathodal and sham stimulation (Bonferroni-adjusted $p = 0.245$). The results indicated that anodal tDCS stimulation increased altruistic choices compared with the cathodal tDCS in gain context. The times of altruistic behaviors in loss context was also affected by stimulation of vmPFC [$\chi^2(2) = 9.610$, $p = 0.008$, Fig. 4B]. Anodal vmPFC stimulation resulted in significantly more times of altruistic behaviors than cathodal stimulation (2.667 vs. 0.800 Bonferroni-adjusted $p = 0.006$), while the differences between anodal and sham stimulation (Bonferroni-adjusted $p = 0.475$) and the differences between cathodal and sham stimulation (Bonferroni-adjusted $p = 0.276$) were not significant. The results indicated that anodal tDCS stimulation also increased altruistic choices than cathodal stimulation in loss context.

The times of altruistic behaviors after tDCS stimulation did not show a significant difference between gain and loss contexts (anodal: Wilcoxon rank-sum test, $p = 0.284$; cathodal: $p = 0.566$). The gain-loss difference was calculated as ($Gain_{altruistic} - Loss_{altruistic}$) based on the previous studies [34,60]. The Kruskal-Wallis H test showed that the gain-loss difference was not affected by stimulation of vmPFC [$\chi^2(2) = 0.830$, $p = 0.660$].

Considering the analysis of aggregated mean data might reduce non-systematic variance, a generalized linear mixed model (GLMM) was also conducted to examine the robustness of the association between vmPFC and altruistic behaviors. Logistic binary regression was selected as link function. *tDCS* (anodal, cathodal, sham), *Context* (gain, loss), and their interaction were included in the model as fixed factors. *Participant* was included as random intercept and random slope, with the participant random slope estimated with respect to *Context*. *Altruistic* (yes/no) was used as the dependent variable. Bonferroni adjusted pairwise comparisons were employed to analyze significant effects. The analysis showed a significant fixed effect of *tDCS* ($F(2,1794) = 5.796$, $p = 0.003$). Adjusted pairwise comparisons (Table 3) showed that participants who received cathodal stimulation were less likely to make an altruistic decision compared to those who received anodal stimulation ($p = 0.013$). The fixed effect of *Context* and the interaction between *Context* and *tDCS* did not reach a significant level ($ps > 0.05$). Those results were consistent with the analysis of aggregated mean data, revealing that participants who received anodal stimulation were more likely to make an altruistic decision, and those who received cathodal stimulation did the opposite.

The correlation analysis showed that the subsequent inferences of others' altruistic behaviors were significantly correlated with the times of their own altruistic behaviors both in the gain and loss contexts (gain: Spearman rho = 0.496, $p < 0.001$, Fig. 5A; loss: Spearman rho = 0.544, $p < 0.001$, Fig. 5B). In the sham stimulation group, participants believed that others would engage in altruistic behavior. In the gain context, participants believed that 24.00% (SE = 0.184) of participants would

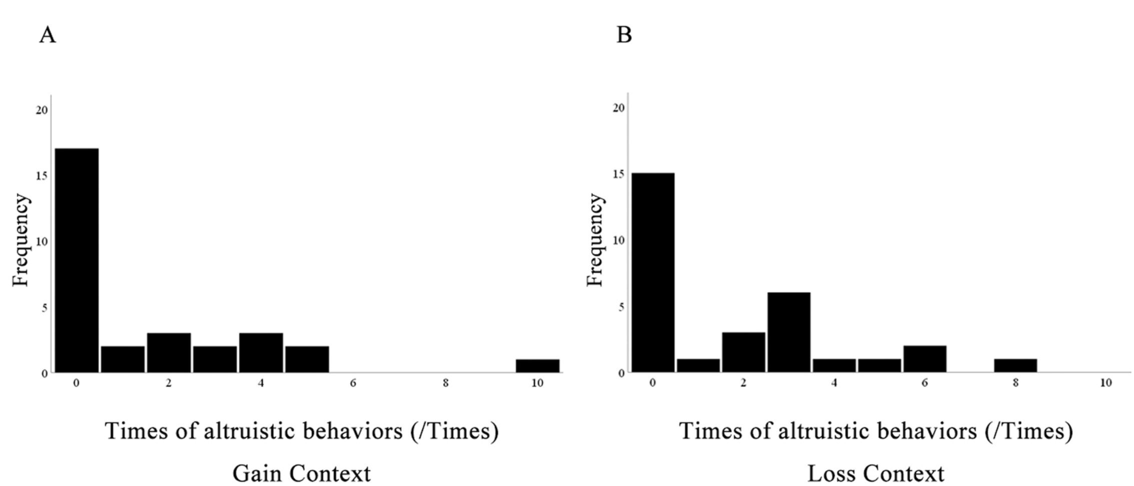

Fig. 3. The distribution of the times of altruistic choices across participants in the gain context (A) and in the loss context (B).

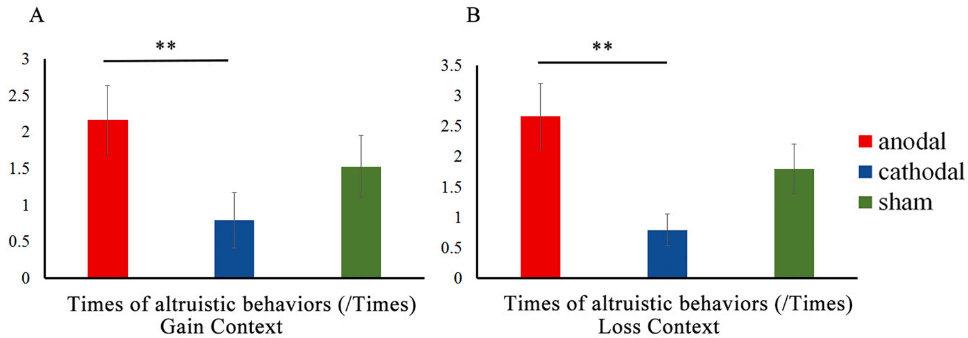

Fig. 4. Times of altruistic behaviors in the gain context (A) and loss context (B) after stimulation. Anodal vmPFC stimulation resulted in significantly more times of altruistic behaviors than cathodal stimulation. Error bars indicate SE. Asterisks indicate statistical significance of difference between treatments.

Table 3
Generalized liner mixed model: bonferroni adjusted pairwise comparisons.

Fixed Factor	β	SE	t	Adj.p	95% CI lower limit	95% CI uper limit
Context						
gain vs. loss	-0.016	0.018	-0.871	0.384	-0.051	0.020
tDCS						
anodal vs. sham	0.087	0.057	1.528	0.171	-0.032	0.206
anodal vs. cathodal	0.144	0.050	2.859	0.013	0.023	0.265
cathodal vs. sham	-0.057	0.033	-1.720	0.171	-0.132	0.017
*Context * tDCS*						
gain						
anodal vs. sham	0.082	0.060	1.358	0.273	-0.047	0.210
anodal vs. cathodal	0.134	0.053	2.514	0.036	0.006	0.262
cathodal vs. sham	-0.053	0.035	-1.491	0.273	-0.132	0.027
loss						
anodal vs. sham	0.092	0.067	1.374	0.245	-0.050	0.235
anodal vs. cathodal	0.155	0.060	2.600	0.028	0.012	0.298
cathodal vs. sham	-0.062	0.040	-1.546	0.245	-0.153	0.028
sham						
gain vs. loss	-0.017	0.032	-0.538	0.591	-0.079	0.045
anodal						
gain vs. loss	-0.028	0.048	-0.582	0.561	-0.122	0.066
cathodal						
gain vs. loss	-0.007	0.017	-0.430	0.667	-0.041	0.026

choose the altruistic options in the experiment, while in the loss context, 56.33% (SE = 0.272) of participants would choose the altruistic options. The Kruskal-Wallis H test showed that the inference of others' altruistic behaviors in the gain context was affected by stimulation of vmPFC [$\chi^2(2) = 6.385$, $p = 0.041$]. Cathodal vmPFC stimulation resulted in a significantly lower inference of others' altruistic behaviors than sham stimulation (13.07% vs. 24%; Bonferroni-adjusted $p = 0.059$). No significant differences were found between anodal and sham stimulation (Bonferroni-adjusted $p = 1.000$) or between anodal and cathodal stimulation (Bonferroni-adjusted $p = 0.133$). The results indicated that cathodal stimulation decreased the inference of others' altruistic choices than sham stimulation in the gain context. However, the tDCS stimulation effect on the inference of others' altruistic choices in the loss context was not significant ($p = 0.102$).

4. Discussion

Previous studies from different perspectives have discussed the issues of altruism that have important meaning for human well-being [10,46]. Many have focused on why people are willing to help others at a cost to themselves even in the absence of expectation for future benefit [47-49]. Through a growing body of neuroimaging evidence, the vmPFC may be particularly critical for the regulation of altruistic behaviors [12,13,50]. However, evidence is still lacking in the field of neuroscience regarding the causal link between altruistic behavior and the regions of the brain that are possibly related to it. In the present study, we designed a modified dictator game with a binary choice in the contexts of gain and loss that aimed to provide a simple and direct measure of participants' altruistic tendencies. We found that modulating the activity of vmPFC altered altruistic behaviors. Specifically, anodal vmPFC stimulation significantly increased altruistic behaviors compared to cathodal stimulation both in the gain and loss contexts. The inference of others' altruistic behaviors in the gain context was also affected by the stimulation of vmPFC. Cathodal vmPFC stimulation resulted in a significantly lower inference of others' altruistic behaviors than sham stimulation.

The present study provided empirical evidence that altruistic behaviors did exist. In the sham stimulation group, almost half of the participants had at least one altruistic choice. On average, the altruistic options were chosen 1.533 times out of 10 trials in the gains context, and 1.800 times out of 10 trials in the loss context. More importantly, we applied tDCS over vmPFC in our participants to determine the influence of vmPFC on altruism. Both the results of non-parametric analysis and the GLMM showed that enhancing the activation of the vmPFC significantly increased the altruistic behavior both in the gain and loss contexts compared to the cathodal stimulation. Our observation suggested a causal relationship between the activity of vmPFC and altruistic behaviors.

Our findings were largely consistent with those fMRI studies that neural correlates of altruistic behaviors usually found involvement of vmPFC [14,50]. Based on the previous studies, the activations in the vmPFC were suggested to provide the basis for one's "emotional bond" with other individuals' [51], and greater activity in vmPFC was associated with higher levels of self-reported experienced empathy as well as with daily helping behaviors [52]. Therefore, one possible mechanism underlying the observed effect might be that the activation of vmPFC influenced the participants' level of empathy for other receivers. On the other hand, the vmPFC played a necessary role in behavioral choice [34, 53], and was critical for balancing potential gains against losses to ensure optimal social decision-making [28,54]. A lesion in the vmPFC in humans might impair social cognition, judgment, and decision-making [26,28]. Thus, the tDCS stimulation might also modulate the valuation process in social decision-making. Taking all these into account, the stimulation effect might be interpreted as affecting the cognitive function of vmPFC involving emotion and evaluation, which were considered as important factors influencing altruistic behaviors.

So far, the specific effects of tDCS over vmPFC needed to be further developed. In the previous study, Zheng et al. [36] reported that anodal

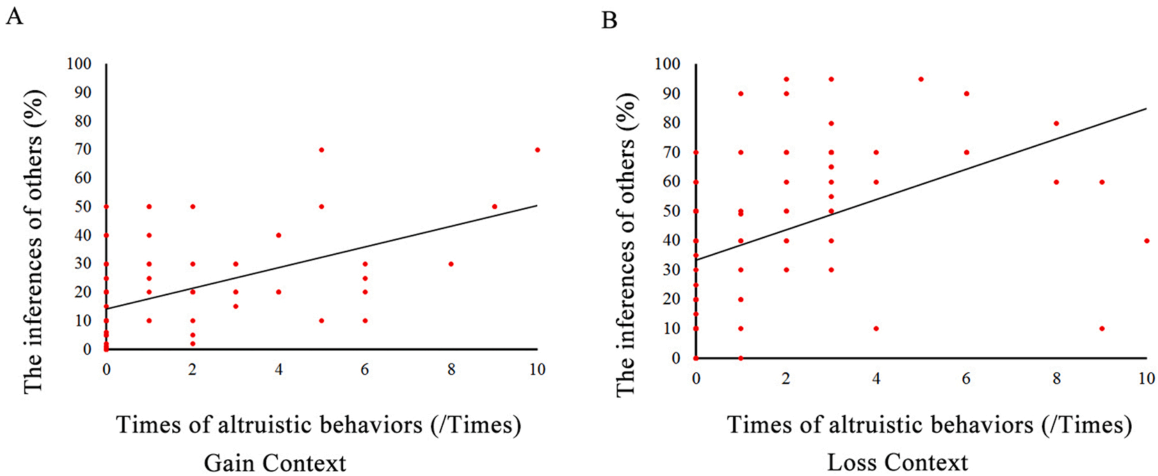

Fig. 5. The correlation analysis of the inferences of others' altruistic behaviors and their own altruistic behaviors in the gain context (A) and in the loss context (B).

activation of the vmPFC by tDCS could significantly increase the amounts transferred (DGgive) in the one-shot dictator game, while no such significant effect of cathodal stimulation was observed. The study implied that vmPFC might be specifically associated with decisions involving increased pure altruism. Liao et al. [37] demonstrated the causal involvement of mPFC in the decision-making of costly helping behavior, and results showed that the anodal stimulation to mPFC increased the propensity for the decider to help the pain-taker in this task and the cathodal stimulation to mPFC showed a reverse effect. The dictator game and the Pain vs. Gain were classic experimental designs to explore pure altruism [14]. In our study, in order to observe participants' altruistic behaviors in gain and loss contexts, we used the modified dictator game, in which, participants were asked to choose between two options, one fair option as a baseline and the other altruistic option. Our findings were in line with Liao et al. [37] that anodal stimulation to vmPFC increased altruistic behaviors and the cathodal stimulation to vmPFC showed a reverse effect. Together with our study, these researches provided evidence that altruism specifically depended on vmPFC activity.

Besides, our results showed that the altruistic behaviors of dictators were consistent in the gain and loss contexts, and the modulation of altruistic behaviors by vmPFC did not differ significantly between the two contexts. This finding was consistent with Baquero et al. [55] that most dictators were hardly affected by the gain/loss context, specifically, dictators would not be bounded by responders' increased requirements in the loss domain, and thus their offers in the loss situation would be comparable to those in the gain situation. However, they identified a small "compassion effect" for the dictators, whereby dictators were somewhat more generous in the loss game. This finding did not conflict with our results that the altruistic options were chosen 1.800 times in the loss context, whereas altruistic options were chosen 1.533 times in the gain context. The dictators seemed a little more generous in the loss game. Our tDCS results showed that the effects of stimulation on the vmPFC were both found in the gain and loss contexts. It might support the idea that gains and losses were coded in the same brain regions including vmPFC [31,32]. We speculated that the insignificant difference between gain and loss contexts might be related to the experimental design. On the one hand, compared to the standard dictator game, our experiment was based on a modified dictator game with a binary choice, in which the choice sets were limited. On the other hand, the current experiment amplified the altruistic factor, where sacrificing own interests could lead to more payoffs for the other five. We hypothesized that participants were more concerned with deciding whether to make an altruistic choice in the experiment, rather than mainly focusing on the loss of self-interest.

In addition, we examined how individuals inferred others' altruistic decisions in the gain and loss contexts. We found that the inferences of others' altruistic behaviors were highly correlated with one's own decisions. Those who chose altruistic options more often tended to believe that there were more participants who chose altruistic behaviors. It is consistent with the previous result that the participants appeared to infer others' performance from their own behaviors [56]. By using tDCS, our research also showed a possible effect of the stimulation on the inference of others' altruistic behaviors in the gain context. The decision-value signals in the vmPFC could encode the values of the options for other individuals [18]. A previous fMRI study had found vmPFC activation increased for high contribution inferences, and decreased for low contribution inferences in the donation task, which meant that the activation of vmPFC as a key structure for evaluating others' outcomes was significantly affected by judgments of their intentions [57].

Although the current study revealed that altering excitability in the vmPFC changed participants' altruistic behaviors and their inference of others' altruistic behaviors both in the gain and loss contexts, some limitations deserve discussion. Firstly, the stimulation of Fpz may cause cortical excitability changes in other areas of mPFC besides vmPFC. Thus, it would be valuable for further studies to focus on refining and distinguishing the role of the mPFC in altruistic behaviors. Secondly, the return electrode was set to the occipital lobe, which was related to the perception and processing of visual information. Direct electrical stimulation of this area may produce visual sensation [58], which may not have interaction with altruistic decisions. However, two electrodes of opposite polarity on the scalp may produce confusion bias. Future studies can further validate its effectiveness by using different electrode settings, for instance, one electrode is positioned on the scalp, and the other on the mastoid or the right deltoid muscle. Thirdly, our results showed that altruistic behaviors of dictators were consistent in the gain and loss contexts while the modulation of altruistic behaviors by vmPFC did not differ significantly between the two contexts. As the gain-loss framing effect has been found under uncertainty [33,59], causal evidence on whether vmPFC would alter behaviors in gain and loss contexts in gambling task remains to be explored. Fourthly, our research showed a possible effect of the stimulation on the inference of others' altruistic behaviors in the gain context. However, whether the stimulation on vmPFC could modulate the inferences of others' altruistic behaviors remains to be further clarified. In this study, the participants were required to make altruistic decisions before inferring others' behaviors. The inferences might be based on their own decisions. Since the stimulation had significantly altered their altruistic decisions, the subsequent inferences about others might also be influenced. Future tDCS study remains to be seen whether the stimulation on vmPFC could have a direct effect on the inferences of others.

5. Conclusion

The present study is part of an attempt to understand the social brain and the associated moral behaviors. Specifically, we sought to illustrate the role of vmPFC in pure altruism, which has important meaning for human well-being. Our finding suggested that tDCS induced modulation of the cortical excitability, targeting the vmPFC, affected the altruistic behaviors by enhancing (anodal)/inhibiting (cathodal), and the effects of tDCS stimulation were found both in the contexts of gain and loss. The subsequent inferences about others' altruistic behaviors were highly correlated with their own choices.

CRediT authorship contribution statement

Jiaxin Yu: Investigation, Software, Writing – original draft. **Yan Wang**: Writing – review & editing, Conceptualization, Funding acquisition. **Jianling Yu**: Investigation, Writing – review & editing. **Lulu Zeng**: Investigation. **Wanjun Zheng**: Writing – review & editing. **Hang Ye**: Writing – review & editing.

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