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# Effects of transcranial direct current stimulation over the right dorsolateral prefrontal cortex on fairness-related decision-making

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## Abstract

Neuroimaging studies suggest that the right dorsolateral prefrontal cortex (rDLPFC) is an important brain area involved in fairness-related decision-making. In the present study, we used transcranial direct current stimulation (tDCS) over the rDLPFC to investigate the effects of changed cortical excitability on fairness norm enforcement in social decision-making. Participants received anodal, cathodal or sham stimulation before performing a modified ultimatum game task, in which participants were asked to accept or reject the proposer's offer and self-rate the intensity of their anger at offers on a 7-point scale. The results showed that the rejection rate of unfair offers and anger level were higher in the anodal compared to the sham and cathodal groups and that the level of anger at unfair offers can predict the rejection rate. Furthermore, the fairness effect of RTs was more prominent in the anodal group than in the sham and cathodal groups. Our findings validate the causal role of the rDLPFC in fairness-related decision-making through tDCS, suggesting that strengthening the rDLPFC increases individuals' reciprocal fairness in social decision-making, both in subjective rating and behaviors.

**Key words:** fairness-related decision-making; transcranial direct current stimulation (tDCS); right dorsolateral prefrontal cortex (rDLPFC); ultimatum game (UG)

## Introduction

Fairness is an important principle in human society. Traditional economic models suggest that individuals are rational and selfish and thereby tend to seek maximum utility (Edwards, 1954). However, many studies have found that individuals are also affected by subjective experiences, such as the perception of unfairness, which elicits 'irrational' behaviors with strong concerns about others' benefits and punishing norm violators at the expense of personal costs (Feng *et al.*, 2015). Simple but sophisticated tasks using game theory as a framework have been used to study social decision-making in the laboratory (Rilling and Sanfey, 2011). The ultimatum game (UG) is a useful experimental tool for examining individuals' responses to fairness (Güth *et al.*, 1982). In the UG, two players must divide a sum of money, with one player specifying the division (i.e. the proposer). The other player then has the option of accepting or rejecting this offer (i.e. the responder). If the offer is accepted by the responder, the money will be distributed as proposed; if rejected, neither individual will receive any money. Per the self-interest maximization principle, if motivation is purely based on self-interest, then the responder

will accept any offer. However, previous studies have primarily shown that responders reject unfair offers (Güth *et al.*, 1982; Güth and Kocher, 2014), and the rejection rate increases as unfairness increases (Camerer, 2003). Therefore, rejecting unfair offers in the UG can be regarded as a prosocial preference in social decision-making to enforce fairness norms at a personal cost (Knoch and Nash, 2015; Achtziger *et al.*, 2016).

Researchers have explained the reasons why individuals reject unfair offers in the UG from different perspectives, such as cognitive, emotional and motivational. The inequity aversion theory claims that people prefer equitable outcomes and are willing to forgo some material payoff in favor of more equitable outcomes (Fehr and Schmidt, 1999). Furthermore, the strong reciprocity model holds that negative reciprocity reflects prosociality because individuals who reject an offer sacrifice their own resources to punish unfair behavior, which may enforce a fair social norm and promote human cooperation (Bowles and Gintis, 2004). In addition, the emotion model suggests that negative emotions caused by unfair offers lead to rejecting behaviors in the UG (Pillutla and Murnighan, 1996). While the inequality aversion

theory and strong reciprocity model explain individuals' obedience to fairness norms from a motivational perspective, the emotion model explores fairness enforcement behavior from an emotional perspective (Hu and Mai, 2021). The dual-system theory integrates cognitive and emotional factors in social decision-making (Evans, 2003; Lieberman, 2007). This theory posits that there are interactions between two systems in the processing of social decision-making—a more intuitive, bottom-up emotional system, associated with automatic processes, and a more deliberate, top-down rational system, associated with controlled processes (Loewenstein and O'Donoghue, 2004). Under the framework of the dual-system theory, there are two explanations for the rejection of unfair offers in the UG. The first explanation suggests that the pursuit of self-interest by accepting any offer is an automatic response. Therefore, the deliberate system is triggered to override selfish impulses to comply with fairness norms when rejecting unfair offers (Myrseth *et al.*, 2009; Martinsson *et al.*, 2014). Another explanation suggests that the pursuit of fairness by rejecting unfair offers is an automatic response. Therefore, the deliberate system is involved in controlling this impulse to maximize personal interests by accepting unfair offers (Rubinstein, 2007; Rand *et al.*, 2012). Both hypotheses have been substantiated with empirical evidence (Van't Wout *et al.*, 2010; Dunn *et al.*, 2012; Achtziger *et al.*, 2016); however, there is no consensus on which goal, self-interest or fairness enforcement, is the prepotent response of social decision-making (Sütterlin *et al.*, 2011; Halali *et al.*, 2014; Bear and Rand, 2016).

Recent studies have applied brain imaging and brain stimulation methods to explore the neural substrates of cognitive and emotional processes involved in fairness-related decision-making and found that the right dorsolateral prefrontal cortex (rDLPFC) plays a crucial role in the trade-off of motivational conflict between economic self-interest and fairness norm enforcement (Sanfey *et al.*, 2003; Knoch *et al.*, 2006; Baumgartner *et al.*, 2011; Buckholtz and Marois, 2012; Hu *et al.*, 2016). This brain area is thought to be related to executive control, goal maintenance, inhibition of prepotent responses and emotional regulation, particularly in response to social pain situation (Miller and Cohen, 2001; Knoch and Fehr, 2007; Zhao *et al.*, 2021). Previous neuroimaging studies have shown that the rDLPFC is strongly involved in the regulation of individual responses to unfair offers in the UG (Sanfey *et al.*, 2003). For example, Sanfey *et al.* (2003) found that the rDLPFC was activated when responders decided whether to accept or reject an unfair offer, and they interpreted this finding as a cognitive goal of accumulating as much money as possible during the task. Therefore, they suggest that when faced with unfair offers, people's prepotent response is to reject them. Further, rDLPFC activity is involved in controlling this impulse to gain more resources in social decision-making.

However, researchers have another perspective on the prepotent response of individuals in making social decisions. Knoch *et al.* (2006) found that after disrupting the rDLPFC through low-frequency repetitive transcranial magnetic stimulation, individuals were more willing to accept unfair offers in a shorter response time during the UG. This finding suggests that the rDLPFC plays a role in overriding humans' selfish impulses to maintain and enforce the fairness norm. Findings from other studies support this hypothesis (Knoch *et al.*, 2010; Baumgartner *et al.*, 2011; Cheng *et al.*, 2015). For example, Knoch *et al.* (2010) demonstrated that resting-state alpha activity in the rDLPFC is positively correlated with the rejection of unfair offers in the UG. Furthermore, Baumgartner *et al.* (2011) indicated that when fairness and economic self-interest are in conflict, participants who make costly

normative decisions at a much higher frequency display significantly higher activity in the DLPFC. In addition, Cheng *et al.* (2015) demonstrated that greater DLPFC activity was observed when participants rejected, rather than accepted, unfair offers in the UG. Moreover, another study using transcranial direct current stimulation (tDCS) found that the rDLPFC is most likely involved in inhibiting self-interest when individuals are confronted with a direct reward (Constantin *et al.*, 2019). Taken together, responders in the UG need to deal with a conflict between fairness goals and self-interest. Thus, the questions are as follows: Which of these should be given priority? And which motivational impulse should be controlled? To answer these questions, we modified the cortical excitability of the rDLPFC using tDCS to examine how rDLPFC activity affects responders' decisions in the UG. tDCS is a noninvasive neuromodulatory technique that delivers weak electrical currents through a pair of electrodes placed on the scalp. The electrical currents affect the excitability of cortical neurons beneath the electrodes in a polarity-dependent fashion: anodal stimulation typically enhances neural excitability, whereas cathodal stimulation reduces it (Jacobson *et al.*, 2012; Filmer *et al.*, 2014). Researchers found that the activation time of the cerebral cortex depends on the intensity and duration of stimulation. These effects were quite stable with the change in activity of the cerebral cortex, lasting for up to 1 hour after stimulation (Jacobson *et al.*, 2012).

In the current study, we applied tDCS over the rDLPFC during a repeated one-shot UG to reveal the causal contribution of this region to fairness-related decision-making and verify whether the fairness preference is an automatic response or control processing. If the rDLPFC is involved in fairness norm enforcement, which requires overriding selfish impulses, enhancing neural excitability of this brain region would increase the rejection rate and reaction time for unfair offers, while disruption of this region should decrease the rejection rate and reaction time of unfair offers relative to the sham-stimulation condition. Alternatively, if rDLPFC activity is involved in cognitive control related to the inhibition of fairness impulses, enhancing neural excitability of this brain region would decrease the rejection rate and reaction time of unfair offers, while disrupting this region should increase the rejection rate and reaction time of unfair offers relative to the sham-stimulation condition. Therefore, the two hypotheses make opposite predictions of how tDCS in the rDLPFC will affect the responder's behavior in the UG.

## Materials and methods
### Participants

Eighty-one healthy university students (50 females) with a mean age of 21.4 years (s.d. = 1.9) participated in the study. None of the participants had a psychiatric or neurological history or took medications at the time of testing. All participants provided written consent and were paid for their participation. The study protocol was approved by the Institutional Review Board of the Department of Psychology at Renmin University of China. All participants were naïve to tDCS and the experimental tasks. Participants were randomly assigned to three stimulation groups (30 in anodal, 25 in cathodal and 26 in sham). Data from four participants were excluded because they did not seriously assess their emotions during the anger intensity rating phase of the task (see below for more details). After this exclusion, data from 77 participants [anodal ($n = 27$), cathodal ($n = 25$) and sham ($n = 25$) tDCS] were analyzed. An *a priori* sample size estimation was conducted using G*Power v.3.1 (Faul *et al.*, 2009). According to the
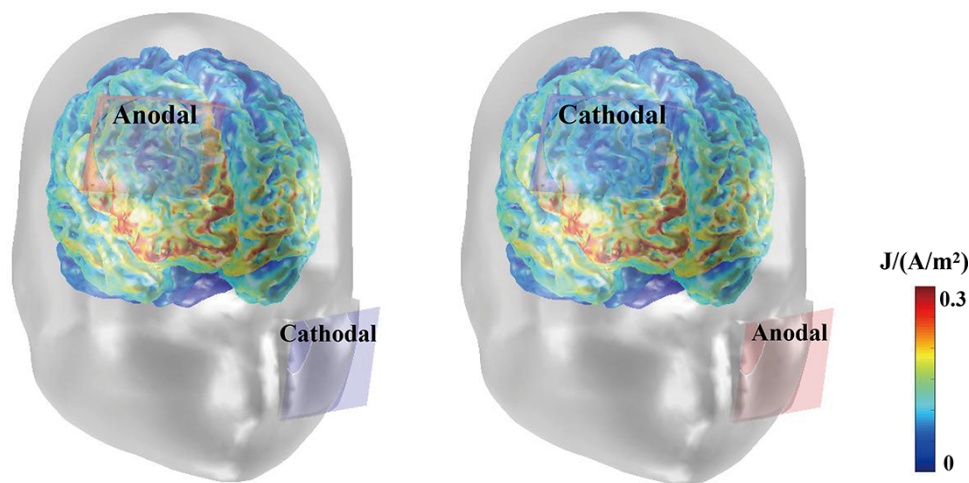
**Fig. 1.** Computational model of tDCS-induced electric field. A simulation of the electrical field induced by tDCS over the rDLPFC was computed using Comets2. The anode or cathode (35 cm$^2$) was placed over the rDLPFC corresponding to F4 electrode according to the 10–20 EEG system. The colors denote the simulated electrical potential.

analysis [$d = 0.25$, $\alpha = 0.05$, $\beta = 0.9$, analysis of variance (ANOVA): repeated measures, within-between interaction], a total sample size of 54 participants was required to detect a reliable effect.

## tDCS parameters

tDCS was applied using a battery-driven direct current stimulator (NeuroConn, Germany) and two sponge electrodes (area: $5 \times 7$ cm each) soaked in saline solution. For the rDLPFC stimulation, the active electrode was placed on F4, according to the international 10–20 EEG system (Knoch *et al.*, 2008; Gross *et al.*, 2018; Speitel *et al.*, 2019), and the reference electrode was placed over the left cheek. In the anodal and cathodal groups, stimulation was applied at an intensity of 1.5 mA for 20 min. In the sham group, stimulation was applied for 15 s, and the electrodes were similarly placed for the other two groups for 20 min. Participants were blinded to the tDCS parameters. At the stimulation onset, the fade-in and fade-out times were both 15 s. The result of a simulation of electrical activity as induced by the tDCS setup is shown in Figure 1 using the 'Comets2' toolbox for MATLAB (Lee *et al.*, 2017).

## Experimental procedure

After the stimulation, participants were asked to participate as a responder in the UG on the computer. They received 150 monetary offers proposed by different volunteers in a database. As illustrated in Figure 2, each trial began with a fixation cross presented on the screen for 500 ms. Then, a picture of a 10-yuan bill appeared for 1000 ms, indicating that the initial total amount was 10 yuan. After the fixation presented for a randomized period of time between 800 and 1500 ms, the offer was presented for 2000 ms, depicting a distribution of 10 yuan between the proposer and the responder (participant). When the text 'Accept' and 'Reject' appeared on the screen, participants were required to make a choice by pressing the F or J key on the keyboard with their left or right index finger. Pressing the F key represented accepting the offer, and pressing the J key represented rejecting the offer. After participants made a choice, the outcome appeared as feedback for 1000 ms. If participants accepted the offer, the money was split as proposed. If rejected, neither player received anything. In addition, when a 'rating' screen appeared, participants were asked to evaluate the intensity of their anger at the current offer on a scale from 1 (*not at all*) to 7 (*very intense*). The emotion

rating occurred randomly five times for each type of offer. Among all participants, one participant rated '1' for all types of offers, one participant rated '7' for all types of offers and two participants rated being angrier about fair offers than unfair offers. We believe that these four participants did not seriously rate their emotions; thus, their data were excluded from further analyses.

The entire task was divided into three blocks of 50 trials each with a brief break between blocks. There were 30 trials for each of the two fair offers (5–5, 6–4), 30 trials for each of the two unfair offers (8–2, 9–1) and 30 trials for filling offers (7–3). The 3–7 offer was not included in the data analysis because previous studies reported that responders in the UG held diverse opinions about whether this offer could be considered fair (Halko *et al.*, 2009; Hewig *et al.*, 2011; Hu and Mai, 2021; Luo *et al.*, 2014), resulting in difficulty classifying this type of offer. Unknown to the participants, all offers they received were generated by the computer program rather than actual people in a random sequence. Before the formal task, participants completed 10 practice trials to familiarize themselves with the UG task. The entire task lasted for about 15 min. Before the experiment, participants were informed that they would be paid 30 Chinese yuan for their participation and the cumulative outcome based on their decisions during the task. Upon finishing the experiment, each participant was paid roughly 60 Chinese yuan, regardless of their decisions in the UG task. Participants were also asked about the plausibility of the cover story, and no participant expressed suspicion about it. The stimuli were presented and behavioral data were recorded using E-Prime 2.0 software (PST, Inc., Pittsburgh, PA, USA).

## Data analysis

The rejection rates, reaction times (RTs) and anger intensity ratings were each analyzed using a mixed two-way repeated-measures analysis of variance (ANOVA) with one between-subjects factor (tDCS group: anodal, cathodal and sham) and one within-subject factor (the fairness of the offer: fair and unfair). *Post hoc* testing of significant main effects was performed using Bonferroni adjustments. A simple effect analysis was used to test for significant interactions. Partial eta-squared ($\eta_p^2$) values were calculated to indicate the effect size in the ANOVA models, with 0.05 representing a small effect, 0.1 representing a medium effect and 0.2 representing a large effect (Cohen, 1973). All statistical
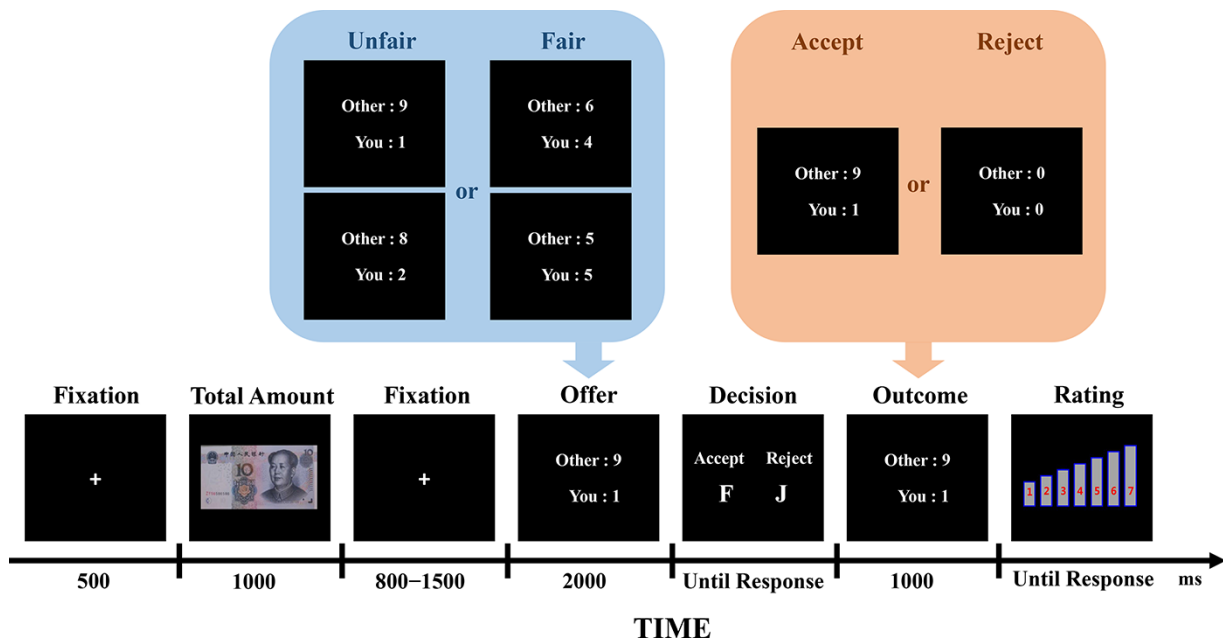
**Fig. 2.** Schematic illustration of a single trial of the multi-round one-shot UG task.

analyses were conducted using SPSS 24.0 (SPSS Inc., Chicago, IL, USA). To evaluate the relationship between behavioral responses and self-reported emotions, Pearson correlation coefficient was calculated between rejection rates of unfair offers and anger intensity ratings among all participants.

## Results

### Rejection rates

The rejection rates for each condition are shown in Figure 3A. An ANOVA of the rejection rates revealed a reliable main effect of fairness, $F(1,74) = 279.64$, $P < 0.001$, $\eta_p^2 = 0.791$, indicating that the rejection rate of unfair offers ($M \pm$ s.d., $0.69 \pm 0.31$) was higher than that of fair ones ($0.17 \pm 0.21$). The main effect of the tDCS group was also significant, $F(2,74) = 3.21$, $P = 0.046$, $\eta_p^2 = 0.08$. Notably, the interaction effect of the tDCS group × fairness was statistically significant, $F(2,74) = 4.86$, $P = 0.01$, $\eta_p^2 = 0.116$. A simple effect analysis was conducted to investigate the interaction. The results showed a tDCS effect on the unfair condition, $F(2,74) = 5.22$, $P = 0.008$, $\eta_p^2 = 0.124$, but not on the fair condition, $F(2,74) = 0.68$, $P = 0.511$, $\eta_p^2 = 0.018$. *Post hoc* comparisons showed that the rejection rate of unfair offers was higher in the anodal group ($0.84 \pm 0.20$) than in the sham group ($0.61 \pm 0.31$, $P = 0.020$) or the cathodal group ($0.61 \pm 0.35$, $P = 0.021$), while no difference was found between the cathodal and sham groups ($P = 1.000$).
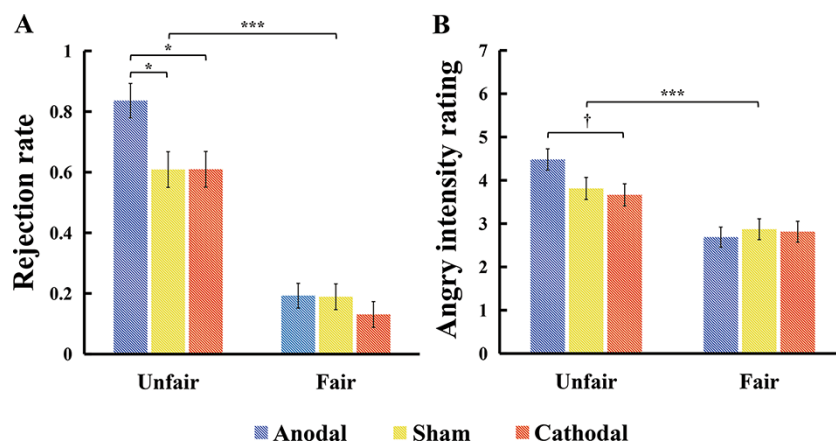
### Anger intensity ratings

The anger intensity ratings for each condition are shown in Figure 3B. The ANOVA of the anger intensity rating showed that the main effect of fairness was statistically significant, $F(1,74) = 130.17$, $P < 0.001$, $\eta_p^2 = 0.638$, indicating that participants experienced more intensive anger at unfair offers ($4.00 \pm 1.31$) than fair offers ($2.79 \pm 1.19$). The main effect of the tDCS group was not statistically significant, $F(2,74) = 0.62$, $P = 0.539$, $\eta_p^2 = 0.017$. The interaction effect of the tDCS group × fairness was statistically significant, $F(2,74) = 8.41$, $P = 0.001$, $\eta_p^2 = 0.185$. Consequently, a simple effect analysis was conducted to investigate this interaction. The results showed that the tDCS effect

was not statistically significant in the fair condition, $F(2,74) = 0.16$, $P = 0.856$, $\eta_p^2 = 0.004$ but marginally significant in the unfair condition, $F(2,74) = 3.06$, $P = 0.053$, $\eta_p^2 = 0.076$. *Post hoc* comparisons showed that anger intensity in the unfair condition tended to be higher in the anodal group ($4.48 \pm 1.26$) than in the cathodal group ($3.66 \pm 1.28$, $P = 0.071$), but there was no difference between the anodal group and the sham group ($3.81 \pm 1.29$, $P = 0.189$) or between the cathodal and sham groups ($P = 1.000$).

Furthermore, to verify the emotion model of fairness processing, we examined whether the increase in individuals' anger intensity ratings was associated with a corresponding increase in rejection rates of unfair offers. A Pearson correlation analysis was conducted between the anger intensity rating and the rejection rate of unfair offers. The results showed a positive correlation between the anger intensity rating and rejection rate ($r = 0.228$, $P = 0.047$). To test whether anger intensity could predict rejection rate, a simple linear regression analysis was conducted. The results showed that the effect of anger intensity on the rejection rate was statistically significant, $\beta = 0.228$, $t = 2.024$, $P = 0.047$; $R^2 = 0.052$, adjusted $R^2 = 0.039$, $F(1, 75) = 4.096$, $P = 0.047$. The scatter plot is shown in Figure 4. Individuals who were angrier at unfair offers were more likely to reject them.

### Reaction times

Figure 5 illustrates the RTs of each condition. A significant main effect of fairness, $F(1,74) = 58.09$, $P < 0.001$, $\eta_p^2 = 0.44$, indicating that the RT in the unfair condition ($M \pm$ s.d., $1456.75 \pm 490.86$ ms) was longer than in the fair condition ($1193.73 \pm 344.46$ ms). Importantly, a significant interaction effect emerged between tDCS treatment and fairness, $F(2,74) = 3.41$, $P = 0.038$, $\eta_p^2 = 0.084$. Consequently, a simple effect analysis was conducted to investigate the interaction. Findings revealed that individuals in all three tDCS groups responded more slowly in the unfair condition than the fair condition [anodal: $F(1,74) = 44.56$, $P < 0.001$, $\eta_p^2 = 0.376$; sham: $F(1,74) = 10.71$, $P = 0.002$, $\eta_p^2 = 0.126$; cathodal: $F(1,74) = 11.17$, $P = 0.001$, $\eta_p^2 = 0.131$]. We further subtracted the RT in the unfair condition from the RT in the fair condition

**Fig. 3.** Mean rejection rates (A) and anger intensity ratings (B) in the fair and unfair conditions for three tDCS groups. Error bars indicate standard error of the mean (SEM). †$P < 0.1$, *$P < 0.05$, ***$P < 0.001$.
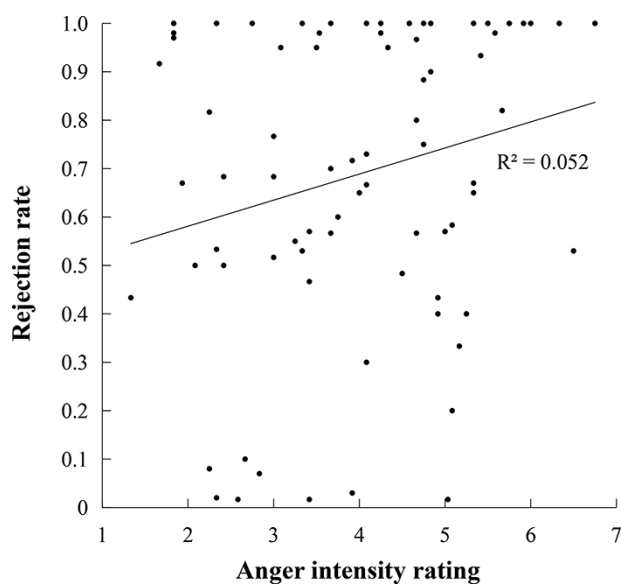


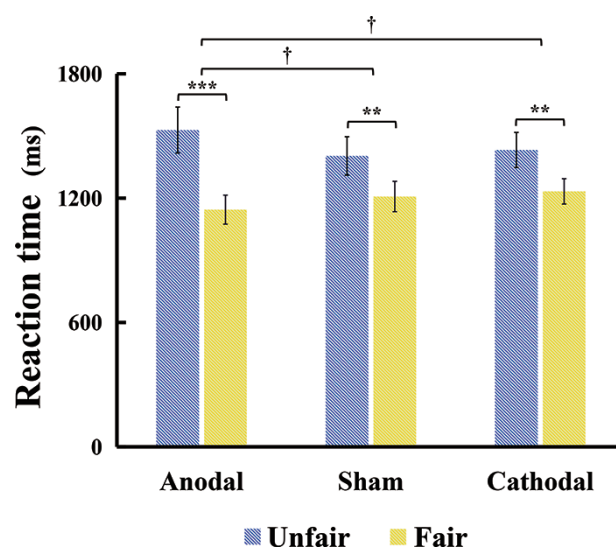**Fig. 4.** Linear regression of rejection rate as a function of the anger intensity rating in the unfair condition.



**Fig. 5.** Mean RTs in the fair and unfair conditions for three tDCS groups. Error bars indicate SEM. †$P < 0.1$, **$P < 0.01$, ***$P < 0.001$.

to reflect the fairness effect and compared the fairness effect between the three tDCS groups using a one-way ANOVA. Results showed a significant main effect of tDCS group, $F(2,74) = 3.41$, $P = 0.038$, $\eta_p^2 = 0.084$. *Post hoc* comparisons showed that the fairness effect in the anodal group ($384.00 \pm 414.92$ ms) marginally larger than that in the sham group ($195.60 \pm 189.39$ ms, $P = 0.078$) and the cathodal group ($199.76 \pm 230.45$ ms, $P = 0.088$), but there was no difference between the sham group and the cathodal group ($P = 1.00$).

## Discussion

This study aimed to explore the effect of changing rDLPFC excitability on individuals' fairness-related decision-making through tDCS stimulation. The results showed that the rejection rate of unfair offers and anger level were higher in the anodal compared to the sham and cathodal groups. Furthermore, the level of anger at unfair offers can predict the rejection rate. Additionally, the fairness effect of RTs was more prominent in the anodal group than in the sham and cathodal groups. Our results

support the controlled-processing hypothesis of the dual-system theory. Specifically, increasing the cortical excitability of the rDLPFC strengthens the inhibition of self-interest impulses, which promotes the processing of fairness, in turn, increasing fairness behavior and the maintenance of social norms.

The finding that individuals were more likely to reject unfair offers than fair offers was consistent with the findings in prior studies (Camerer, 2003). Importantly, enhancing the rDLPFC with anodal tDCS increased the rejection rates of unfair offers. This finding indicates that individuals need more cognitive control to override selfish impulses in social dilemmas that contain motivational conflict between economic self-interest and social norm enforcement. Enhancing the rDLPFC inhibits their self-interest motives by strengthening cognitive control, thus enabling people to implement and maintain fairness norms (Baumgartner *et al.*, 2011). In contrast, responders in the UG perceive fair offers as rewards, which are in accordance with both self-interest and social motives, so they simply accept these offers without much motivational conflict (Feng *et al.*, 2015).

Furthermore, the response-time difference between the unfair and fair conditions across tDCS groups is consistent with previous

findings (Knoch *et al.*, 2006). Interestingly, in the current study, an enhanced fairness effect was found in the anodal group for RTs. For individuals in the anodal group, fair offers were in their self-interest and strengthened fairness motive, and thus they quickly accepted them. In contrast, for unfair offers, there was a conflict between self-interest and fairness motives, resulting in increased reaction time. Individuals with rDLPFC enhancement appeared to be more able to resist the temptation to be selfish and make decisions to maintain social fairness norms in a deliberate way. Our findings are in line with those of previous studies, which found that fairness preference was weakened by rTMS interference in the rDLPFC (Knoch *et al.*, 2006). Therefore, the findings of this study suggest that in a mix-motivated situation, self-interest impulses have a stronger impact on behavior, and social norm enforcement is a controlled process. Furthermore, in this study, the tDCS approach was used, which enabled us to reveal the causal role of rDLPFC activity in complying with the fairness norm when self-interest and fairness goals are in conflict. This strongly supports the fairness preference controlled-processing hypothesis of the dual-system theory. The controlled-processing hypothesis postulates that fairness preferences are products of the deliberation process that overrides self-interest motivation (Martinsson *et al.*, 2014).

Knoch *et al.* (2006) reported that individuals were more likely to accept unfair offers after rDLPFC interference by TMS. In the present study, however, we did not detect the effect of cathodal tDCS, which suppressed the rDLPFC. This may be because many higher-level cognitive functions do not occur in a single brain region. When the activity of one hemisphere is disturbed, the other hemisphere may compensate and partially control the activity, thus weakening the inhibitory effect of tDCS. Therefore, the cathodal effect is not as stable as the anodal effect (Jacobson *et al.*, 2012). In addition, the stimulation intensity of tDCS is far less than that of TMS; thus, tDCS cathodal stimulation may be unable to achieve the effect of TMS stimulation. Finally, previous studies have demonstrated that behavioral and perceptual effects of tDCS are determined by initial neural activation state (Grosbras and Paus, 2003; Campana *et al.*, 2006; Silvanto *et al.*, 2008). When individuals participate in cognitive experiments, initial state of neurons in their corresponding brain regions is highly activated. Therefore, it is difficult to inhibit the cortical excitability of these regions. In the present study, the rDLPFC was highly activated when individuals processed fairness information of received offers in the UG, and thus it was hard to suppress the neural activation of the rDLPFC by cathodal tDCS.

To shed light on the psychological processes underlying such behaviors in fairness-related decision-making, we also asked participants to evaluate their anger about the currently received offer. We found that participants were angrier about unfair offers after anodal stimulation of the rDLPFC. On the one hand, since the rDLPFC is associated with implementing fair behavior, enhancing this brain region would make people place more controls on selfish impulses and pay more attention to the fairness norm (Klaus *et al.*, 2012; Buckholtz, 2015; Chen *et al.*, 2019). In this condition, they regarded unfair offers as a barrier to fairness goal achievement and, thus, felt more intense anger. On the other hand, the rDLPFC is also related to perceptions and awareness of fairness. On enhancing this brain region, individuals may be stricter with the evaluation of fairness. Therefore, participants will perceive greater deviation in their judging standard and become angrier.

By combining psychological processes and behavioral patterns, in this study, we found that in the face of unfair offers, the degree of anger was positively correlated with the rejection rate,

which supported the emotion model. Using skin conductance recordings, Van't Wout *et al.* (2006) found that individuals had stronger emotional arousal when rejecting unfairness. Another study also found a positive correlation between the rejection of unfairness and self-reported anger (Srivastava *et al.*, 2009). The brain imaging study also provided supporting evidence that in the UG, unfair offers activated brain regions associated with emotion processing, such as the anterior insula. Notably, participants with stronger anterior insula activation to unfair offers rejected a higher proportion of unfair offers (Sanfey *et al.*, 2003). Therefore, our study indicates a dynamic process combining cognitive and affective factors in fairness-related decision-making. Specifically, enhancing rDLPFC activity increases cognitive control on selfish impulses, thus resulting in decision makers regarding fairness as a primary goal or using stricter fairness-judging standards that elicit more intensive anger about unfair offers; thus, they are more willing to reject such offers in a deliberate way.

This study has several limitations. First, we did not consider individual differences, which may have had moderating effects on decision-making in the UG. Previous studies found that a person with strong prosocial preferences may not need self-control to act in a prosocial way, whereas a strongly selfish individual may need self-control to act in a prosocial way (Bieleke *et al.*, 2016). Second, we did not assess participants' perceptions of fairness. In this study, the anger level was enhanced in the anodal stimulation group. This change may be due to the enhanced perception of fairness caused by increased DLPFC activity, which indirectly affected emotion. Finally, this study focused only on negative emotions. However, previous studies have shown that individuals experience different emotions during the UG (Tabibnia *et al.*, 2008; Hu and Mai, 2021). If we assessed emotions of different valence for receiving offers, we would obtain more information about the relationship between individuals' emotional experiences and fairness enforcement behaviors. In addition, individuals exhibit different fairness preference in social decision-making. It is reasonable to speculate that individuals may have different emotional experiences when faced with the same type of offer, which can affect their fairness preference represented by their behaviors (Ketelaar and Koening, 2007; Paivio, 2007; Frank *et al.*, 2009). Future research should address how such factors modulate the tDCS effect on fairness-related decision-making.

In conclusion, this study validates the causal role of the rDLPFC in fairness-related decision-making through tDCS, suggesting that strengthening the rDLPFC increases individuals' reciprocal fairness in social decision-making, both in subjective rating and behaviors, which provides strong evidence for the controlled-processing hypothesis of the dual-system theory.

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## Conflict of interest

The authors declare no conflict of interest.

## References

Achtziger, A., Alós-Ferrer, C., Wagner, A.K. (2016). The impact of self-control depletion on social preferences in the ultimatum game. *Journal of Economic Psychology*, **53**, 1–16.

Baumgartner, T., Knoch, D., Hotz, P., Eisenegger, C., Fehr, E. (2011). Dorsolateral and ventromedial prefrontal cortex orchestrate normative choice. *Nature Neuroscience*, **14**, 1468–74.

Bear, A., Rand, D.G. (2016). Intuition, deliberation, and the evolution of cooperation. *Proceedings of the National Academy of Sciences*, **113**(4), 936–41.

Bieleke, M., Gollwitzer, P.M., Oettingen, G., Fischbacher, U. (2016). Social value orientation moderates the effects of intuition versus reflection on responses to unfair ultimatum offers. *Journal of Behavioral Decision Making*, **30**(2), 569–81.

Bowles, S., Gintis, H. (2004). The evolution of strong reciprocity: cooperation in heterogeneous populations. *Theoretical Population Biology*, **65**(1), 17–28.

Buckholtz, J.W. (2015). Social norms, self-control, and the value of antisocial behavior. *Current Opinion in Behavioral Sciences*, **3**, 122–9.

Buckholtz, J.W., Marois, R. (2012). The roots of modern justice: cognitive and neural foundations of social norms and their enforcement. *Nature Neuroscience*, **15**, 655–61.

Camerer, C.F. (2003). Strategizing in the brain. *Science*, **300**(5626), 1673–5.

Campana, G., Cowey, A., Walsh, V. (2006). Visual area V5/MT remembers 'what' but not 'where'. *Cerebral Cortex*, **16**(12), 1766–70.

Chen, S., Shi, J., Yang, X., Ye, H., Luo, J. (2019). Modulating activity in the dorsolateral prefrontal cortex changes punishment in the 3-player prisoner's dilemma: a transcranial direct current stimulation study. *Frontiers in Neuroscience*, **13**, 1160.

Cheng, X.M., Zheng, L., Li, L., *et al.* (2015). Power to punish norm violations affects the neural processes of fairness-related decision making. *Frontiers in Behavioral Neuroscience*, **9**, 344.

Cohen, J. (1973). Eta-squared and partial eta-squared in fixed factor ANOVA designs. *Educational and Psychological Measurement*, **33**(1), 107–12.

Constantin, S., Eva, T.M., Eva, J. (2019). Functions of the right dlpfc and right tpj in proposers and responders in the ultimatum game. *Social Cognitive and Affective Neuroscience*, **14**(3), 263–70.

Dunn, B.D., Evans, D., Makarova, D., White, J., Clark, L. (2012). Gut feelings and the reaction to perceived inequity: the interplay between bodily responses, regulation, and perception shapes the rejection of unfair offers on the ultimatum game. *Cognitive, Affective & Behavioral Neuroscience*, **12**(3), 419–29.

Edwards, W. (1954). The theory of decision making. *Psychological Bulletin*, **51**(4), 380–417.

Evans, J.S.B.T. (2003). In two minds: dual-process accounts of reasoning. *Trends in Cognitive Sciences*, **7**(10), 454–9.

Faul, F., Erdfelder, E., Buchner, A., Lang, A.G. (2009). Statistical power analyses using G*power 3.1: tests for correlation and regression analyses. *Behavior Research Methods*, **41**(4), 1149–60.

Fehr, E., Schmidt, K.M. (1999). A theory of fairness, competition, and cooperation. *The Quarterly Journal of Economics*, **114**(3), 817–68.

Feng, C., Yue-Jia, L., Krueger, F. (2015). Neural signatures of fairness-related normative decision making in the ultimatum game: a coordinate-based meta-analysis. *Human Brain Mapping*, **36**(2), 591–602.

Filmer, H.L., Dux, P.E., Mattingley, J.B. (2014). Applications of transcranial direct current stimulation for understanding brain function. *Trends in Neurosciences*, **37**(12), 742–53.

Frank, M.J., Cohen, M.X., Sanfey, A.G. (2009). Multiple systems in decision making: a neurocomputational perspective. *Current Directions in Psychological Science*, **18**, 236–54.

Grosbras, M.H., Paus, T. (2003). Transcranial magnetic stimulation of the human frontal eye field facilitates visual awareness. *European Journal of Neuroscience*, **18**(11), 3121–6.

Gross, J., Emmerling, F., Vostroknutov, A., Sack, A.T. (2018). Manipulation of pro-sociality and rule-following with non-invasive brain stimulation. *Scientific Reports*, **8**(1), 1827.

Güth, W., Schmittberger, R., Schwarze, B. (1982). An experimental analysis of ultimatum bargaining. *Journal of Economic Behavior & Organization*, **3**(4), 367–88.

Güth, W., Kocher, M.G. (2014). More than thirty years of ultimatum bargaining experiments: motives, variations and a survey of the recent literature. *Journal of Economic Behavior & Organization*, **108**(C), 396–409.

Halali, E., Bereby-Meyer, Y., Meiran, N. (2014). Between self-interest and reciprocity: the social bright side of self-control failure. *Journal of Experimental Psychology General*, **143**(2), 745–55.

Halko, M.L., Hlushchuk, Y., Hari, R., Schürmann, M. (2009). Competing with peers: mentalizing-related brain activity reflects what is at stake. *NeuroImage*, **46**(2), 542–8.

Hewig, J., Kretschmer, N., Trippe, R.H., *et al.* (2011). Why humans deviate from rational choice. *Psychophysiology*, **48**(4), 507–14.

Hu, J., Blue, P.R., Yu, H.B., *et al.* (2016). Social status modulates the neural response to unfairness. *Social Cognitive and Affective Neuroscience*, **11**, 1–10.

Hu, X., Mai, X. (2021). Social value orientation modulates fairness processing during social decision-making: evidence from behavior and brain potentials. *Social Cognitive and Affective Neuroscience*, **16**(7), 670–82.

Jacobson, L., Koslowsky, M., Lavidor, M. (2012). tDCS polarity effects in motor and cognitive domains: a meta-analytical review. *Experimental Brain Research*, **216**(1), 1–10.

Ketelaar, T., Koening, B. (2007). Emotion, Justice, and strategic commitments. In: Ee Cremer, D. editor. *Advances in the Psychology of Justice and Affect*. Charlotte, NC: Information Age Publishing.

Klaus, F., Phillipps, C.B., Peter, T., *et al.* (2012). Neural responses to advantageous and disadvantageous inequity. *Frontiers in Human Neuroscience*, **6**, 165.

Knoch, D., Pascual–Leone, A., Meyer, K., Treyer, V., Fehr, E. (2006). Diminishing reciprocal fairness by disrupting the right prefrontal cortex. *Science*, **314**, 829–32.

Knoch, D., Nitsche, M.A., Fischbacher, U., Eisenegger, C., Pascual-Leone, A., Fehr, E. (2008). Studying the neurobiology of social interaction with transcranial direct current stimulation—The example of punishing unfairness. *Cerebral Cortex*, **18**(9), 1987–90.

Knoch, D., Gianotti, L.R.R., Baumgartner, T., Fehr, E. (2010). A neural marker of costly punishment behavior. *Psychological Science*, **21**(3), 337–42.

Knoch, D., Fehr, E. (2007). Resisting the power of temptations. *Annals of the New York Academy of Sciences*, **1104**, 123–34.

Knoch, D., Nash, K. (2015). Self-control in social decision making: a neurobiological perspective. In: Gendolla, G., Tops, M., Koole, S. editors. *Handbook of Biobehavioral Approaches to Self-Regulation*. New York: Springer, 221–34.

Lee, C., Jung, Y.J., Lee, S.J., Im, C.H. (2017). COMETS2: an advanced MATLAB toolbox for the numerical analysis of electric fields generated by transcranial direct current stimulation. *Journal of Neuroscience Methods*, **277**, 56–62.

Lieberman, M.D. (2007). Social cognitive neuroscience: a review of core processes. *Annual Review of Psychology*, **58**, 259–89.

Loewenstein, G.F., O'Donoghue, T. (2004). Animal spirits: affective and deliberative processes in human behavior. Working Papers 04–14, Cornell University, Center for Analytic Economics.

Luo, Y., Wu, T.T., Broster, L.S., *et al.* (2014). The temporal course of the influence of anxiety on fairness considerations. *Psychophysiology*, **51**(9), 834–42.

Martinsson, P., Myrseth, K.O.R., Wollbrant, C. (2014). Social dilemmas: when self-control benefits cooperation. *Journal of Economic Psychology*, **45**, 213–36.

Miller, E.K., Cohen, J.D. (2001). An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience*, **24**(1), 167–202.

Myrseth, K.O.R., Fishbach, A., Trope, Y. (2009). Counteractive self-control: when making temptation available makes temptation less tempting. *Psychological Science*, **20**(2), 159–63.

Paivio, A. (2007). *Mind and Its Evolution: A Dual Coding Theoretical Approach*. Mahwah. NJ: Lawrence Erlbaum Associates.

Pillutla, M.M., Murnighan, J.K. (1996). Unfairness, anger, and spite: emotional rejections of ultimatum offers. *Organizational Behavior and Human Decision Processes*, **68**(3), 208–24.

Rand, D.G., Greene, J.D., Nowak, M.A. (2012). Spontaneous giving and calculated greed. *Nature*, **489**(7416), 427–30.

Rilling, J.K., Sanfey, A.G. (2011). The neuroscience of social decision-making. *Annual Review of Psychology*, **62**(1), 23–48.

Rubinstein, A. (2007). Instinctive and cognitive reasoning: a study of response times. *The Economic Journal*, **117**(523), 1243–59.

Sanfey, A.G., Rilling, J.K., Aronson, J.A., Nystrom, L.E., Cohen, J.D. (2003). The neural basis of economic decision-making in the ultimatum game. *Science*, **300**(5626), 1755–8.

Silvanto, J., Muggleton, N., Walsh, V. (2008). State-dependency in brain stimulation studies of perception and cognition. *Trends in Cognitive Sciences*, **12**(12), 447–54.

Speitel, C., Traut-Mattausch, E., Jonas, E. (2019). Functions of the right DLPFC and right TPJ in proposers and responders in the ultimatum game. *Social Cognitive and Affective Neuroscience*, **14**(3), 263–70.

Srivastava, J., Espinoza, F., Fedorikhin, A. (2009). Coupling and decoupling of unfairness and anger in ultimatum bargaining. *Journal of Behavioral Decision Making*, **22**(5), 475–89.

Sütterlin, S., Herbert, C., Schmitt, M., Kübler, A., Vögele, C. (2011). Overcoming selfishness: reciprocity, inhibition, and cardiac-autonomic control in the ultimatum game. *Frontiers in Psychology*, **2**, 173.

Tabibnia, G., Satpute, A.B., Lieberman, M.D. (2008). The sunny side of fairness: preference for fairness activates reward circuitry (and disregarding unfairness activates self-control circuitry). *Psychological Science*, **19**(4), 339–47.

Van't Wout, M., Kahn, R.S., Sanfey, A.G., Aleman, A. (2006). Affective state and decision-making in the ultimatum game. *Experimental Brain Research*, **169**(4), 564–8.

Van't Wout, M., Chang, L.J., Sanfey, A.G. (2010). The influence of emotion regulation on social interactive decision-making. *Emotion*, **10**(6), 815–21.

Zhao, J., Mo, L., Bi, R., *et al.* (2021). The VLPFC versus the DLPFC in downregulating social pain using reappraisal and distraction strategies. *Journal of Neuroscience*, **41**(6), 1331–9.