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Anodal transcranial direct current stimulation over the right dorsolateral prefrontal cortex: Less risk taking or more reflective? A tDCS study based on a Bayesian-updating task☆

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A R T I C L E I N F O

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A B S T R A C T

To identify the causal role of the DLPFC in decision making, we used transcranial direct current stimulation (tDCS) to investigate the contribution of DLPFC to performance in an incentivized decision task where optimal decisions require Bayesian updating of beliefs. In this task, an impulsive reinforcement-based heuristic can either conflict or be aligned with Bayesian updating. Previous research showed that in case of conflict individuals rely on the faulty heuristic, hence committing many decision errors. Based on the involvement of the DLPFC in inhibitory control we hypothesized that tDCS of the DLPFC would influence individual's use of the reinforcement heuristic in case of conflict. 364 participants (158 in the original study; 206 in the replication study) received the anodal or cathodal tDCS stimulation to the right, left DLPFC or sham. While we observed improved decision making in first-draw decisions following anodal stimulation to the right DLPFC, our study did not find evidence indicating that tDCS stimulation over the DLPFC affected inhibition of reinforcement.

1. Introduction

Research on economic decision making has shown that judgments and decisions often do not result from extensive deliberation and application of well-considered strategies, but rather from spontaneous and implicit processes (Hastie, 2001; Obrecht & Chesney, 2016). As an example, optimal decision making under uncertainty requires the integration of all available information to obtain appropriate probability judgments (beliefs), which calls for the use of Bayes' rule (Bayes & Price, 1763). This is particularly true if the outcomes of previous decisions deliver information on underlying uncertain events. However, if those outcomes also provide feedback in a success/failure format (e.g., in the form of absolute or relative performance, profits and losses, etc.), human beings have a

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tendency to focus on past performance only. Previously successful decisions are repeated, and those that led to failure are revised, creating a simple ‘‘win-stay, lose-shift’’ decision rule. This ‘‘reinforcement heuristic,’’ which might be an effective shortcut in simple settings, can conflict with normative behavior in more complex settings, hence committing many decision errors (Charness & Levin, 2005; Achtziger & Alós-Ferrer, 2014).

Psychophysiological evidence suggests that reinforcement processes are related to extremely fast and unconscious brain responses (Holroyd & Coles, 2002). More specifically, an EEG study (Achtziger et al., 2015) found that the reinforcement process is evident in the feedback-related negativity, an event-related component of the EEG, observed as early as 250 ms after win/lose feedback on a decision is presented. This finding implies that the reinforcement heuristic corresponds to a very quick, highly automatic pre-conscious process, in line with evidence that decision errors due to the reinforcement heuristic are much faster than correct decisions (Achtziger & Alós-Ferrer, 2014). These results suggest that the detection of a conflict between opposing decision rules and the inhibition of the automatic process is needed in order to control detrimental reinforcement learning.

Brain region of interest is the dorsolateral prefrontal cortex (DLPFC) which has been reliably associated with executive functions and decision-making processes. For instance, Knoch et al. (2006) applied TMS to lower the activity of the right DLPFC and found risk-seeking behavior in decision making after the TMS stimulation. Similar results were found in study of Fecteau et al. (2007a), indicating that participants receiving right anodal/left cathodal tDCS showed a risk-averse response style. Fecteau et al. (2007b) found that after simultaneous tDCS stimulation over the right and left DLPFC participants became more risk averse as measured by the Balloon Analog Risk Task compared to sham stimulation.

More recently, the dorsolateral prefrontal cortex has been considered a crucial brain region for inhibitory control (Wu et al., 2022). A number of studies have associated DLPFC to response inhibition (Brevet-Aeby et al., 2016; Figner et al., 2010; Heatherton & Wagner, 2011). For example, Steinbeis, Bernhardt, & Singer (2012) examined children’s decision while they played two different games, only one of which required participants to exert self-control. Neuroimaging results demonstrated left DLPFC activation only when children played the game which required exertion of self-control. Perrotta et al. (2021) demonstrated increased activity in DLPFC favored a reduction of errors in the context of a classic Stroop task, a task that has frequently been implicated in the literature as a measure of response inhibition. Importantly, recent stimulation studies indicated that DLPFC was related to inhibition of impulsive responses measured by the cognitive reflection test (CRT), for instance, Oldrati, Patricelli, Colombo, and Antonietti (2016) indicated that after unilateral cathodal stimulation to the left DLPFC, participants were more likely to provide incorrect impulsive responses in the CRT. Another study applied bilateral stimulation to the DLPFC and found that anodal stimulation to the right DLPFC was associated with more correct CRT items (Edgcumbe, Thoma, Rivolta, Nitsche, & Fu, 2019), indicating that after the stimulation participants were more involved in analytical thinking. Accordingly, we are interested in exploring the role of DLPFC in inhibition of automatic processes in decision making. To further demonstrate the causal relationship between DLPFC activity and inhibition of impulsive decision processes, we stimulated DLPFC activity using transcranial direct current stimulation (tDCS) and examined subsequent effects on performance in a Bayesian updating task. Since both the right DLPFC and the left DLPFC have been found influenced inhibitory control (e.g. Brevet-Aeby et al., 2016; Oldrati et al., 2016), by applying different polarities of tDCS over the right or left prefrontal cortex, we explored whether unilateral stimulation could affect inhibitory control in decision making.

tDCS is a noninvasive method of brain stimulation which has attracted increasing attention in the past decade. tDCS creates a continuous, low intensity electric current on the scalp, which penetrates the underlying cortex and produces a temporary hypo/hyperactivity in a target cortical region (Nitsche & Paulus, 2000). Anodal stimulation increases the cortical excitability, whereas cathodal stimulation decreases spontaneous activity (Parkin, Ekhtiari, & Walsh, 2015). Most modulation studies have used bilateral stimulation, concluding that stimulation on the DLPFC influenced individuals’ impulsive control (e.g. Loftus, Yalcin, Baughman, Vanman, & Hagger, 2015). However, as a traditional brain stimulation paradigm, bilateral stimulation has difficulty in identifying which unilateral stimuli actually causes the effect (e.g., Xiong, She, Zhao, & Zhang, 2020).

In the present study, we sought to investigate the contribution of DLPFC in inhibition of automatic processes in decision making. To formally test the causal relationship between the DLPFC and inhibition of impulsiveness, we adopted unilateral stimulation techniques to precisely examine DLPFC function in a decision task, in which an impulsive reinforcement-based heuristic can either conflict or be aligned with Bayesian updating. Specifically, the present study explored whether anodal or cathodal tDCS over the right or left DLPFC could modulate individuals’ use of the reinforcement heuristic in case of conflict. We relied on the task described in Charness and Levin (2005) and further developed by Achtziger and Alós-Ferrer (2014). This task is especially well-suited to create two types of decision situations. In one type, the rational decision strategy to maximize expected payoff (i.e., integrating prior probabilities and new information by following Bayes’ rule) conflicts with the reinforcement heuristic. In these situations, repeating successful decisions (“win-stay”) and switching to an alternative option after failure (“lose-shift”) hence can be defined as an error because base rate information is neglected. In the second type of situations, the two decision strategies are aligned (i.e., prescribe choosing the same option) and decisions are rather easy.

In previous research, decision errors (defined as deviations from Bayes’ rule) in alignment situations were usually rare (Achtziger & Alós-Ferrer, 2014; Charness & Levin, 2005; Hügelschäfer & Achtziger, 2017) and are defined as “understanding errors”. In contrast, under conflict between Bayes’ rule and the reinforcement heuristic participants often followed the simple heuristic instead of Bayes’ rule, which was not surprising in view of the high automaticity of reinforcement learning (Achtziger et al., 2015; see above). The interpretation of this type of errors as “reinforcement errors” was supported by the observation that not presenting affective (i.e., positive or negative) feedback on a decision outcome (win/lose), and hence making it impossible to rely on the reinforcement heuristic, led to a strong decrease of errors rates (Achtziger & Alós-Ferrer, 2014; Charness & Levin, 2005).

Overall, in a between-subjects design, we measured decision-making in the Bayesian updating task following unilateral tDCS with anode/cathode applied to either the right DLPFC, left DLPFC or a sham stimulation. Given that our research was exploratory, we formed our hypotheses mainly based studies of Oldrati et al., (2016) and Edgcumbe et al., (2019). We predict that rates of reinforcement errors would be lower in the anodal right DLPFC condition compared to sham and rates of reinforcement errors would be higher in the cathodal left DLPFC condition compared to sham. We also expect that the decision times in the anodal right DLPFC condition would be longer compared to the sham condition and the decision times in the cathodal left DLPFC condition would be shorter compared to the sham. We did not predict differential stimulation effects on error rates in case of alignment of the reinforcement heuristic and Bayes' rule. Since in these situations, inhibition control is less likely involved, error rates are not due to the failure of inhibitory control (Achtziger & Alós-Ferrer, 2014; Achtziger et al., 2015; Charness & Levin, 2005; Hügelschäfer & Achtziger, 2017), there is no need (and not much room) for an improvement of decision making.

2. Method

2.1. Participants

163 healthy subjects with no history of neurological or psychiatric problems were recruited via online advertisement among Zhejiang University of Finance and Economics. All the participants were naïve to tDCS and decision task, had normal or corrected-to-normal vision, and provided their written informed consent, which was approved by the Zhejiang University of Finance and Economics ethics committee. In exchange for participation, they received a payment based on the outcomes of their decisions (see below) plus a show-up fee of 20 RMB. Five participants were excluded from data analysis (Three of them did not properly follow the instructions of the decision task. The other two reported they were left-handed). Thus 158 participants (87 females, age range 18–22, $M = 19.60$, $SD = 1.67$) were considered for data analysis, 29 in the anodal RDLPFC condition, 33 in the cathodal RDLPFC condition, 30 in anodal LDLPFC, 32 in cathodal LDLPFC, and 34 in the sham condition. Average earnings were 52.67 RMB yuan ($SD = 2.16$, approximately 7.82 US dollars) including the show-up fee. None of the participants reported any adverse side effects concerning pain on the scalp or headaches after the experiment.

2.2 Transcranial direct current stimulation (tDCS)

tDCS applied a weak direct current to the scalp *via* two saline-soaked surface sponge electrodes (5 cm × 7 cm; 35 cm^2). The current was constant and was delivered by a battery-driven stimulator (NeuroConn, Ilmenau, Germany). It was adjusted to induce cortical excitability of the target area without any physiological damage to the participants.

We chose the right F4/left F3 and Pz to place the electrodes, according to the international EEG 10–20 system (Fig. 1). We stimulated the unilateral DLPFC instead of the DLPFC bilaterally because we aimed to distinguish the impact of the right or left DLPFC from the effects of changing the balance of activity across both DLPFCs. The parietal cortex was chosen to construct the current circuit together with the DLPFC because of its reasonable spatial and functional distance from our target region, which decreased the possibility of stimulation interaction or task interference (Simon et al., 2002).

Participants assigning to different treatments received different stimulations. For right anodal stimulation, the anodal electrode was placed over F4, while the cathodal electrode was placed over Pz. For left anodal stimulation, the anodal electrode was placed over F3, and the cathodal electrode was also placed over Pz. For right cathodal and left cathodal stimulation, the placements were reversed. The anodal electrode was placed over Pz, and the cathodal electrode was placed over F4 or F3 (Fig. 1). For sham stimulation, the same procedures were applied, but the current lasted only for the first 30 s. This brief duration of stimulation could hardly modulate cortical excitability, but the participants may have felt the initial itching and believed they were receiving stimulation. This kind of sham

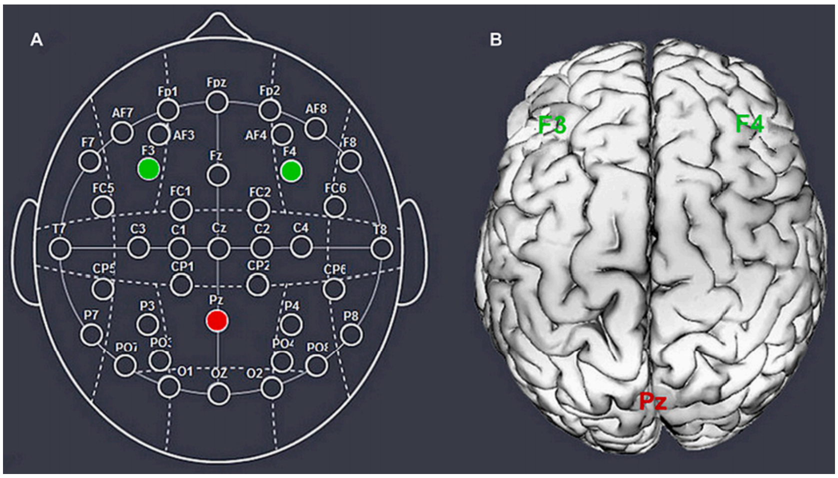

Fig. 1. Schematic and locations of the electrode positions. Schematic of the electrode positions based on the EEG 10–20 system (A) and locations of the dorsolateral prefrontal cortex and the parietal cortex of the human brain (B).

stimulation has been proved to be reliable (Gandiga, Hummel & Cohen, 2006). The constant current was 2 mA in intensity, with 15 s of ramp up and down, which has been shown to be safe and effective by previous studies (Nitsche & Paulus, 2000; Nitsche, Liebetanz, et al., 2003, Nitsche, Nitsche, et al., 2003). After 20 min of stimulation, the tDCS device was taken off, and the participant was asked to complete several tasks. Our study adopted offline tDCS stimulation. We limited our study to the offline stimulation because previous studies indicated that when a direct current is delivered for a sufficient period of time (i.e., at least 9–10 min), the neuromodulatory effects can remain for longer than 1 h after the stimulation (Nitsche & Paulus, 2000; Nitsche, Liebetanz, et al., 2003, Nitsche, Nitsche, et al., 2003; Nitsche et al., 2008).

2.3. Decision task

The decision task is based on the paradigm introduced by Charness and Levin (2005), as developed in Achtziger and Alós-Ferrer (2014). Participants are presented with two urns, the left urn, and the right urn, both filled with 6 balls which could be black or white. The urns are presented on the computer screen, with masked colors for the balls (see Fig. 2).

The task consists of choosing one of the two urns (left or right) by pressing one of two keys on a keyboard, where upon the program drew one of the balls from the chosen urn randomly and the color of the drawn ball (black or white) is revealed. Depending on counterbalancing, the participant is paid for drawing black or white balls only. Participants earn 0.5 RMB yuan for every successful draw. In each round, the participants make two draws with replacement. After the color of the first drawn ball is revealed, the ball is replaced into the respective urn and the participant is asked to choose the left or right urn for a second draw. Again, a ball is randomly extracted from the chosen urn and paid if it is of the appropriate color.

The distribution of black and white balls in the two urns varies depending on the state of the world (*Up* and *Down*) which is not revealed to the participant. Participants know that both states had a prior probability of 50% and that the state of the world is constant across the two draws of one round but is randomized according to the prior for each new round. This means that the first draw is uninformed, but by observing the result of the first draw (black or white ball) the decision maker could draw conclusions about the most likely state of the world. Table 1 presents the distribution of balls in the two urns for a participant who is rewarded for drawing black balls (in the other counterbalance condition, i.e., being rewarded for a white ball, the distribution of balls was the opposite).

A person who decides rationally in a Bayesian sense would update the prior of 50% (on the state of the world) after observing the color of the first drawn ball (i.e., feedback on her decision), and would base the second draw on the derived posterior probability of the state of the world to maximize expected payoffs. A person who relies on the reinforcement heuristic, however, would follow the "win-stay, lose-shift" principle. She would stay with the same urn if it has yielded a rewarded ball (=positive feedback) in the first draw; otherwise (in case of drawing a non-rewarded ball; after negative feedback) she would choose the other urn ("shift") for the second draw (see Achtziger & Alós-Ferrer, 2014).

According to the distribution of black and white balls in the urns, after a first draw from the right urn Bayes' rule and the reinforcement heuristic are aligned. In this case, the ball reveals the state of the world perfectly (the right urn contained balls of only one color; see Table 1) and the prescription for the second draw is simple: stay with the right urn in case of having drawn a rewarded ball, otherwise switch to the left urn. We classify the (rare) mistakes after a first draw from the right urn as *understanding errors.*

In contrast, a first draw from the left urn does not fully reveal the current state of the world, but its outcome (color of the ball) could be used as information to update prior beliefs about the state of the world. By design, when drawing from the left urn in the first draw, Bayesian updating and the reinforcement heuristic are directly opposed; both decision strategies conflict. Simple computations show that, to maximize the expected payoff, the decision maker should switch to the right urn after drawing a rewarded ball and stay with the left urn after drawing a non-rewarded ball.[1] If a participant commits a mistake in this context, this error is classified as a *reinforcement error* since the reinforcement heuristic obviously dominates a choice that would be in accordance with Bayes' rule.

Participants repeat the two-draw decisions 60 times (i.e., there were 60 rounds in total). Following Charness and Levin (2005) and Achtziger and Alós-Ferrer (2014), we include both forced first draws (where the choice of the urn was dictated by the computer program) and free first draws (where participants could choose the urn in the first draw on their own). Forced first draws are originally implemented in order to ensure a sufficient number of first draws from the left urn (which were the interesting situations with conflicting decision strategies). After an initial draw from the right urn, the state of the world is revealed and the optimal decision coincides with the "win-stay, lose-shift" rule of thumb. A simple computation reveals that the total expected payoff for the two draws is maximized by starting with the right urn and then deciding accordingly for the second draw. Hence, a Bayesian optimizer should always start with the right urn[2] if given a choice and failing to do so is also a mistake, which we classify as a *first-draw error*. In addition, more recent studies have shown systematic differences in behavior between forced and free draws (e.g., Alós-Ferrer, Hügelschäfer, & Li, 2017), which might be due to different feelings of autonomy (Alós-Ferrer, Hügelschäfer, & Li, 2016). To avoid confounding forced choices and learning effects, participants make forced draws and free draws alternately.

[1] For example, if a black ball was extracted from the left urn, the updated probability of being in the state "up" was $(1/2)(4/6)/[(1/2)(4/6) + (1/2)(2/6)] = 2/3$, hence choosing the left urn again delivered an expected payoff of $(2/3)(4/6) + (1/3)(2/6) = 5/9$, while switching to the right urn delivered a higher expected payoff of $(2/3)(1) + (1/3)(0) = 6/9$ (see Alós-Ferrer, Hügelschäfer, & Li, 2015; Hügelschäfer & Achtziger, 2017).

[2] For a Bayesian updater, the total expected payoff for both draws when starting with the left urn is: $(1/2)[(4/6)(1 + 1) + (2/6)(0 + 4/6)] + (1/2)[(2/6)(1 + 0) + (4/6)(0 + 2/6)] = 38/36$. The total expected payoff when starting with the right urn is $(1/2)[1(1 + 1)] + (1/2)[1(0 + 2/6)] = 42/36$.

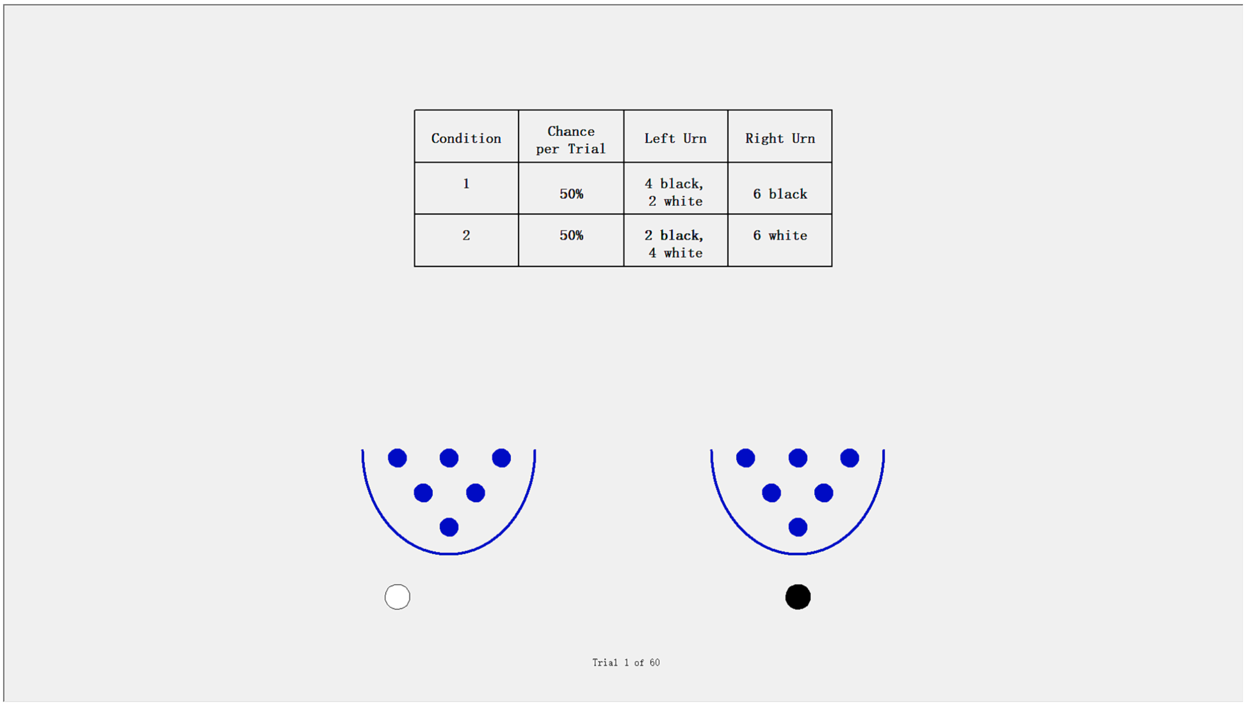

Fig. 2. Screenshot of the decision task interface.

Table 1
Urn compositions depending on the state of the world.

State (Prob)	Left Urn	Right Urn
Up (50%)	●●●●○○	●●●●●●
Down (50%)	●●○○○○	○○○○○○

Note. For a participant who is paid for black balls.

2.4 Procedure

The study was conducted in group sessions at the university's laboratory using z-Tree (Fischbacher, 2007). A session lasted about 1.5 h (Fig. 3). Participants were randomly assigned to one of the five tDCS conditions (anodal right DLPFC vs. cathodal right DLPFC vs. anodal left DLPFC vs. cathodal left DLPFC vs. sham) and one of two counterbalance conditions (payment for black balls vs. payment for white balls). All participants received a single-blinded stimulation session, with tDCS applied on the DLPFC for 20 min, and then completed decision task programmed by z-Tree (Fischbacher, 2007). After the decision task, they were asked to complete a questionnaire including an explicit test and personal information.

At the beginning of each session, participants were asked to read the instructions of the decision task carefully. Those described the rules of the decision task in detail, including screenshots of the computer program. Afterwards participants answered control questions to ensure they understood the rules of the decision task properly. Next, they proceeded with tDCS stimulation which last for 20 min (for sham condition, the stimulation lasted for 30 s, but participants in that condition needed to wear tDCS device for 20 min till participants in the other conditions completed the stimulation), before continuing with the decision task immediately afterwards. The decision task took around 10 min. Subsequently, participants filled in a computerized questionnaire, which included a mood scale consisting of 8 adjectives (see Taylor & Gollwitzer, 1995), the Faith in Intuition scale (Epstein, Pacini, Denes-Raj, & Heier, 1996), Raven's test (Raven, 1941) and demographic questions.

3. Results

3.1. Equivalence of conditions

We found no differences in mood, faith in intuition, Raven's test, or percentage of females and males among the four groups (according to one-way ANOVAs and chi-square test, all $ps \geq 0.177$). Hence, there were no differences between the conditions that could explain our findings alternatively.

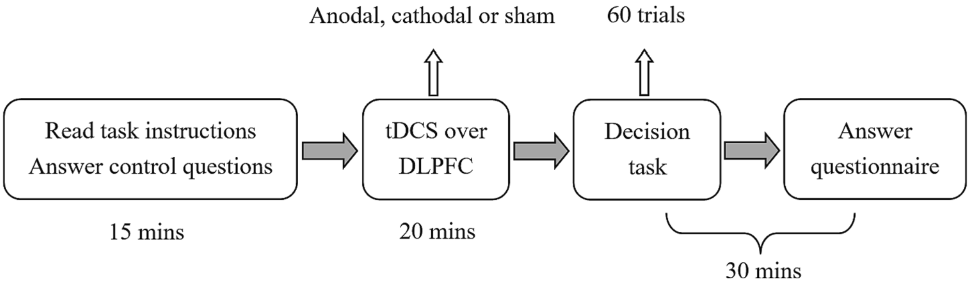

Fig. 3. Experimental design.

3.2. Main analysis

3.2.1. TDCS effects on reinforcement errors

For the tests reported below, the unit of analysis is the individual-level error rate. That is, for each participant and each relevant class of errors, we computed the participant's percentage of errors and treated it as one observation. To examine the effect of stimulation on the reinforcement error rates, we conducted non-parametric[3] Kruskal-Wallis tests. For further pairwise comparisons of error rates, we relied on non-parametric, two-tailed Wilcoxon Rank-Sum tests. According to the hypotheses, we were mainly interested in the comparison between the anodal RDLPFC condition and the sham condition, and the comparison between the cathodal LDLPFC condition and the sham condition. Multiple comparisons were adjusted by false discovery rate (FDR).

Fig. 4 depicts participants' average individual second-draw error rates in case of conflict between the reinforcement heuristic and Bayes' rule depending on stimulation condition. We found that the reinforcement error rates were not different across stimulation conditions.

Specifically, the rate of reinforcement errors was not significantly different among participants in five stimulation conditions, according to a Kruskal-Wallis test, $\chi^2(4) = 0.64$, $p = .959$. Pairwise comparison indicated that the reinforcement error rates in the anodal right DLPFC condition and in the cathodal left DLPFC were not significantly different from the error rates in the sham condition as shown in Table 2.

3.2.2. TDCS effects on 2nd-draw response-times in case of conflict

Besides errors, we recorded the time participants took for making decisions. We replicated the observation by Achtziger and Alós-Ferrer (2014) that decisions were significantly slower under conflict vs. alignment.[4] We computed non-parametric[5] Kruskal-Wallis tests on individual mean decision times with stimulation condition as a between factor. For second-draw decisions, we mainly focused on the decision times in case of conflict. Pairwise comparisons of the decision times relied on non-parametric, two-tailed Wilcoxon Rank-Sum tests, adjusted by FDR.

Fig. 5 shows participants' average individual second-draw decision times in case of conflict depending on stimulation condition. The Kruskal-Wallis test for second-draw decision times yielded no significance, $\chi^2(4) = 0.76$, $p = .944$. Pairwise comparisons yielded no significant differences (p_{adj}s $= 0.923$).

3.3. Exploratory analysis

We observed a tendency of the stimulation condition to affect first-draw error rates (e.g., Table 3), thus we also run further tests to examine the stimulation effect although we had no expectation on that since inhibition of automatic processes was not involved for first-draw decisions.

3.3.1. TDCS effects on first-draw errors

The unit of analysis is the individual-level error rate. To compare the first-draw error rates across stimulation conditions, we conducted non-parametric Kruskal-Wallis tests. Pairwise comparisons of the error rates relied on non-parametric, two-tailed Wilcoxon

[3] We relied on non-parametric tests since error rates did not follow a normal distribution. The distribution of this variable was skewed, and further (naturally) bounded between 0 and 100. Accordingly, the requirements for parametric tests were not fulfilled.

[4] We computed the mean reaction time for second draws for each participant conditional on each of the five stimulation conditions (sham vs. anodal RDLPFC vs. anodal LDLPFC vs. cathodal RDLPFC vs. cathodal LDLPFC) and conducted non-parametric Wilcoxon Signed-Rank (WSR) test (two-sided) to compare the average response times in case of conflict vs alignment. These tests showed that in each of these stimulation conditions, the 2nd-draw response times were significantly slower in conflict situations than in aligned situations (in sham condition, $z = 4.88$, $p < .001$; in anodal RDLPFC, $z = 4.64$, $p < .001$; in anodal LDLPFC, $z = 4.29$, $p < .001$; in cathodal RDLPFC, $z = 4.26$, $p < .001$; in cathodal LDLPFC, $z = 4.68$, $p < .001$).

[5] Again, the reason for relying on non-parametric tests was the extremely skewed distribution of decision times, which violated the assumption of normally distributed data necessary for computing parametric tests.

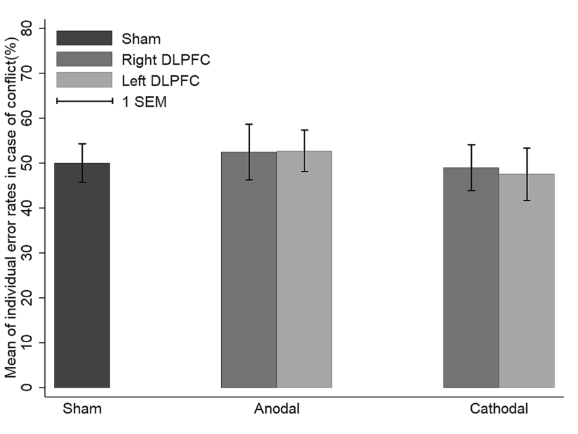

Fig. 4. Impact of stimulation on the reinforcement error rates. *p <.05, **p <.01, ***p <.001.

Table 2
Individual reinforcement error rates and WRS tests.

Conditions	Descriptive Statistics
Sham	$N = 34$, $M = 50.04\%$, $SD = 25.12\%$, $Mdn = 52.53\%$
Anodal RDLPFC	$N = 29$, $M = 52.51\%$, $SD = 33.26\%$, $Mdn = 46.67\%$
Cathodal RDLPFC	$N = 33$, $M = 48.99\%$, $SD = 29.33\%$, $Mdn = 53.33\%$
Anodal LDLPFC	$N = 30$, $M = 52.77\%$, $SD = 25.34\%$, $Mdn = 52.63\%$
Cathodal LDLPFC	$N = 32$, $M = 47.59\%$, $SD = 33.03\%$, $Mdn = 40.00\%$
WRS tests	Anodal RDLPFC vs Sham: $z = 0.30$, $p_{adj} = 0.817$
	Cathodal LDLPFC vs Sham: $z = 0.23$, $p_{adj} = 0.817$

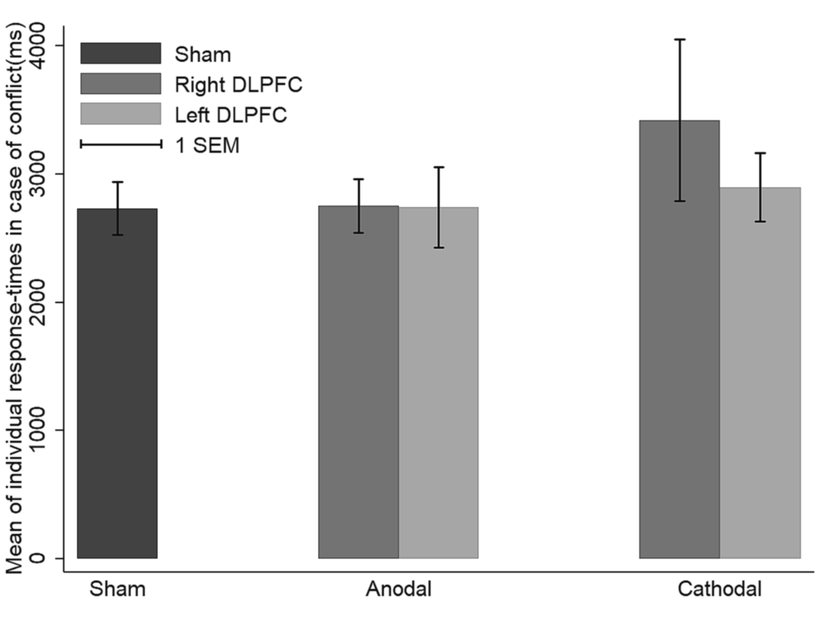

Fig. 5. Impact of stimulation on the second-draw decision times in case of conflict. *p <.05, **p <.01, ***p <.001.

Rank-Sum tests, adjusted by FDR. Fig. 6 presents participants' average individual first-draw error rates depending on stimulation condition. According to a Kruskal-Wallis test, $\chi^2(4) = 10.76$, p =.029, we indeed found a stimulation effect on the first-draw error rates among participants in different stimulation conditions.

Table 3
Individual first-draw error rates and WRS tests.

Conditions	Descriptive Statistics
Sham	$N = 32$, $M = 28.13\%$, $SD = 29.91\%$, $Mdn = 23.33\%$
Anodal RDLPFC	$N = 29$, $M = 13.10\%$, $SD = 20.47\%$, $Mdn = 3.33\%$
Cathodal RDLPFC	$N = 33$, $M = 22.73\%$, $SD = 26.29\%$, $Mdn = 13.33\%$
Anodal LDLPFC	$N = 30$, $M = 38.89\%$, $SD = 35.23\%$, $Mdn = 30.00\%$
Cathodal LDLPFC	$N = 34$, $M = 25.20\%$, $SD = 28.97\%$, $Mdn = 15.00\%$
WRS tests	Anodal RDLPFC vs Sham: $z = 2.25$, $p_{adj} = 0.048$
	Cathodal LDLPFC vs Sham: $z = 0.20$, $p_{adj} = 0.846$

Pairwise comparisons showed that the initial error rates for participants in the anodal RDLPFC condition were significantly lower compared to the sham. The comparison between the cathodal LDLPFC condition and the sham yielded no significant differences (Table 3).

3.3.2. TDCS effects on free 1st-draw response-times

Given the above stimulation effect on first-draw errors, we were also interested in that whether the neuro modulation influenced the first-draw decision times in case participants can freely choose the urns. We used the same statistical analysis for the 1st-draw decision times as we did for 2nd-draw decision times in the main analysis.

Fig. 7 depicts participants' average individual free first-draw decision times depending on stimulation condition. We found that there was a stimulation effect on the free first-draw decision times ($\chi^2(4) = 11.76$, $p = .019$) among the five stimulation conditions. Pairwise comparisons indicated that compared to the sham condition, the free first-draw decision times in the anodal RDLPFC condition were significantly shorter. Comparison between the cathodal LDLPFC condition and the sham condition yielded no significant differences (Table 4).

When we split the tests conditional on whether the free first draw decision was the right urn, the result showed a significant effect of stimulation on the free first-draw decision times in case the participants chose the right urn, $\chi^2(4) = 16.26$, $p = .003$. The free first-draw decision times of choosing the right urn in the anodal RDLPFC condition were significantly shorter compared to the sham. The comparison between the cathodal LDLPFC condition and the sham condition yielded no significant differences (Table 4). Note that the reduced sample sizes resulted from some participants who never started with the right urn when first draws were free. In case participants freely choose the left urn in the first-draw decisions, there was no stimulation effect on the decision times, $\chi^2(4) = 1.13$, $p = .889$. Hence, the stimulation effects on the free first-draw decision times were mainly driven by the decisions choosing the right urn.

4. Replication study

We ran a replication study to validate the above findings. We used exactly the same equipment, material, tDCS stimulation, decision task, design, experimental procedure and statistical analysis as the original study. In general, we repeated the above study with different participants.

208 healthy subjects with no history of neurological or psychiatric problems were recruited via online advertisement among Zhejiang University of Finance and Economics. All the participants were naïve to tDCS and decision task, had normal or corrected-to-normal vision, and provided their written informed consent, which was approved by the Zhejiang University of Finance and Economics

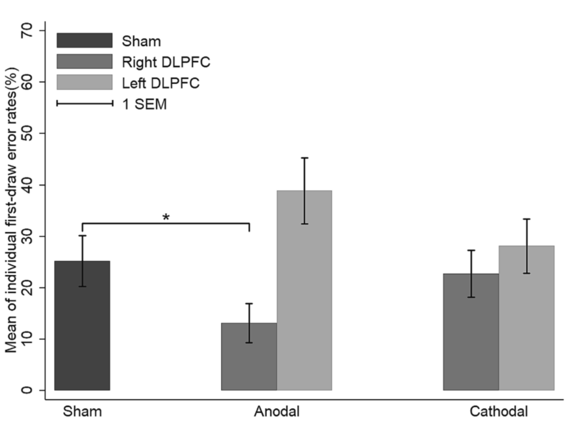

Fig. 6. Impact of stimulation on the first-draw error rates. *$p < .05$, **$p < .01$, ***$p < .001$.

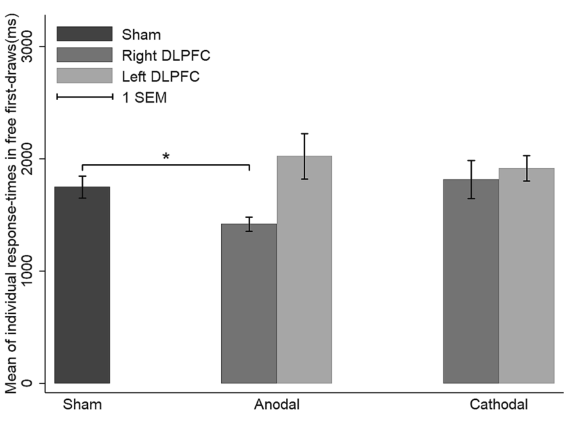

Fig. 7. Impact of stimulation on the free first-draw decision times. *p <.05, **p <.01, ***p <.001.

Table 4
Individual first-draw decision times and WRS tests.

Conditions	Descriptive Statistics (free first-draw)
Sham	$N = 34$, $M = 1785$, $SD = 547$, $Mdn = 1713$
Anodal RDLPFC	$N = 29$, $M = 1457$, $SD = 339$, $Mdn = 1432$
Cathodal RDLPFC	$N = 33$, $M = 1890$, $SD = 1001$, $Mdn = 1600$
Anodal LDLPFC	$N = 30$, $M = 1900$, $SD = 676$, $Mdn = 1693$
Cathodal LDLPFC	$N = 32$, $M = 1939$, $SD = 689$, $Mdn = 1837$
WRS tests	Anodal RDLPFC vs Sham: ($z = 2.66$, $p_{adj} = 0.016$)
	Cathodal LDLPFC vs Sham: (z = 0.58, $p_{adj} = 0.564$)
Conditions	Descriptive Statistics (free first-draw choosing the right urn)
Sham	$N = 33$, $M = 1751$, $SD = 569$, $Mdn = 1694$
Anodal RDLPFC	$N = 29$, $M = 1420$, $SD = 339$, $Mdn = 1361$
Cathodal LDLPFC	$N = 30$, $M = 1918$, $SD = 626$, $Mdn = 1807$
WRS tests	Anodal RDLPFC vs Sham: ($z = 2.59$, $p_{adj} = 0.020$)
	Cathodal LDLPFC vs Sham: ($z = 1.18$, $p_{adj} = 0.237$)

ethics committee. In exchange for participation, they received a payment based on the outcomes of their decisions (see below) plus a show-up fee of 20 RMB. Two participants were excluded from data analysis (they did not properly follow the instructions of the decision task). Thus 206 participants (112 females, age range 18–27, $M = 21.15$, $SD = 1.95$) were considered for data analysis, 42 (21 females) in the anodal RDLPFC condition, 41 (23 females) in the cathodal RDLPFC condition, 42 (23 females) in anodal LDLPFC, 40 (22 females) in cathodal LDLPFC, and 41 (23 females) in the sham condition. Average earnings were 52.87 RMB yuan ($SD = 2.36$, approximately 7.67 US dollars) including the show-up fee. None of the participants reported any adverse side effects concerning pain on the scalp or headaches after the experiment.

5. Results

5.1. Equivalence of conditions

In the replication study, we found no differences in mood, faith in intuition, Raven's test, or percentage of females and males among the four groups (according to one-way ANOVAs and chi-square test, all $ps \geq 0.143$). Hence, there were no differences between the conditions that could explain our findings alternatively.

5.2. Main analysis

5.2.1. TDCS effects on reinforcement errors

We followed the same statistical analysis in the original study: The unit of analysis is the individual-level error rate. To examine the effect of stimulation on reinforcement error rates, we conducted non-parametric Kruskal-Wallis tests. For further pairwise comparisons of error rates, we used non-parametric, two-tailed Wilcoxon Rank-Sum tests, adjusted by FDR.

Consistent with the original study, we found no significant tDCS effects on the reinforcement error rates, according to a Kruskal-Wallis test, $\chi^2(4) = 0.70$, $p = .951$. Pairwise comparison indicated that the reinforcement error rates in the anodal right DLPFC condition and in the cathodal left DLPFC were not significantly different from the error rates in the sham condition (Table 5).

5.2.2. TDCS effects on 2nd-draw response-times in case of conflict

We further examined the tDCS effect on second-draw decision times as what we did in the original study (we also used the same statistical analysis). We computed non-parametric Kruskal-Wallis tests on individual mean decision times with stimulation condition as a between factor. For second-draw decisions in case of conflict, the Kruskal-Wallis test yielded no significance, $\chi^2(4) = 0.62$, $p = .961$, which is consistent with our original study.

5.3. Exploratory analysis

5.3.1. TDCS effects on first-draw errors

We ran the same tests as in the original study to examine the stimulation effect on first-draw decisions in the replication. According to a Kruskal-Wallis test, $\chi^2(4) = 9.56$, $p = .049$, we found a significant stimulation effect on the first-draw error rates (Fig. 8).

Pairwise comparisons showed that first-draw error rates were significantly lower for participants in the anodal RDLPFC condition than in the sham condition. Compared to the sham condition, there were no significant differences for the initial error rates in the cathodal LDLPFC condition (Table 6). The results indicated that after anodal stimulation over the RDLPFC, the initial error rates were lowered compared to the sham condition, which was consistent with the findings in the original study.

5.3.2. TDCS effects on free 1st-draw response-times

As in the original study, we were interested in that whether the neuro modulation influenced the first-draw decision times in case participants can freely choose the urns and followed the same statistical analysis. Based on the Kruskal-Wallis tests, we found that there was a stimulation effect on the free first-draw decision times, $\chi^2(4) = 12.21$, $p = .016$. When we split the tests conditional on whether the free first draw decision was the right urn, the result showed a significant effect of stimulation ($\chi^2(4) = 10.62$, $p = .031$) on the free first-draw decision times in case choosing the right urn among participants in the five stimulation conditions (Fig. 9).

Pairwise comparison showed that the free first-draw decision times of choosing the right urn in the anodal RDLPFC condition were significantly shorter compared to the sham. Compared to the sham condition, there were no significant differences of the decision times in the cathodal LDLPFC (Table 7). In case participants freely choose the left urn in the first-draw decisions, there was no stimulation effect on the decision times, $\chi^2(4) = 6.59$, $p = .159$. Note that the reduced sample sizes resulted from some participants who never started with the right urn when first draws were free. These results were consistent with our original study.

To sum up, our replication study validated the main findings of the original study. For the 2nd-draw decisions, neither the original study nor the replication study found significant stimulation effects on the 2nd-draw error-rates and the 2nd-draw response-times. Both the original and the replication study found that there were significant stimulation effects on the 1st-draw decisions. For the 1st-draw decisions, both studied showed that compared to the sham condition the initial error rates in the anodal RDLPFC condition were significantly lower. In the meanwhile, in the anodal RDLPFC condition the response times of 1st-draw decisions in case of choosing the right urn freely were shown significantly shorter than the sham.

6. Discussion

The purpose of the present study was to explore the role of DLPFC in decision making under uncertainty. We were especially interested in the stimulation effect of DLPFC on inhibiting automatic decision processes, which could in turn enhance improved analytical decision-making. To answer this question, we investigated whether anodal/cathodal stimulation to the right/left DLPFC influence decision-making in an incentivized decision task. Contrary to previous tDCS studies (Oldrati et al., 2016; Edgcumbe et al., 2019), we targeted a relatively complex decision task where optimal behavior involves Bayesian updating of beliefs. The task was taken from the literature and selected because it has been shown that an automatic process based on reinforcement influences decisions. When this process conflicts with Bayesian updating, error (namely the reinforcement error) rates are very high. When Bayesian updating and reinforcement are aligned, error rates are very low. Our predictions were formed based on the hypothesis that increasing

Table 5
Individual reinforcement error rates and WRS tests (replication study).

Conditions	Descriptive Statistics
Sham	$N = 41$, $M = 52.25\%$, $SD = 32.04\%$, $Mdn = 54.05\%$
Anodal RDLPFC	$N = 42$, $M = 52.30\%$, $SD = 28.94\%$, $Mdn = 54.44\%$
Cathodal RDLPFC	$N = 41$, $M = 55.17\%$, $SD = 30.05\%$, $Mdn = 56.52\%$
Anodal LDLPFC	$N = 42$, $M = 56.37\%$, $SD = 27.44\%$, $Mdn = 54.17\%$
Cathodal LDLPFC	$N = 40$, $M = 56.13\%$, $SD = 19.06\%$, $Mdn = 57.52\%$
WRS tests	Anodal RDLPFC vs Sham: $z = 0.08$, $p_{adj} = 0.933$
	Cathodal LDLPFC vs Sham: $z = 0.62$, $p_{adj} = 0.933$

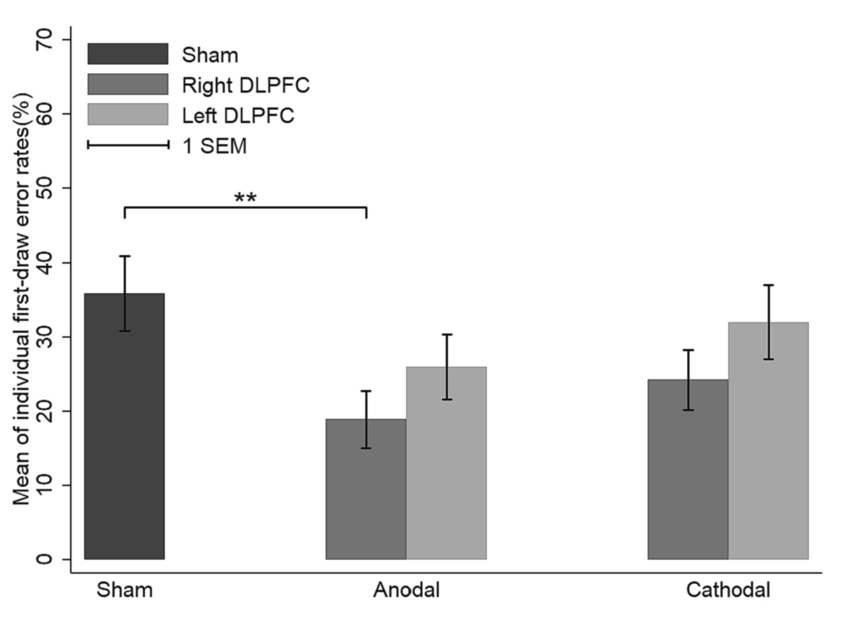

Fig. 8. Impact of stimulation on the first-draw error rates (replication study). *p <.05, **p <.01, ***p <.001.

Table 6
Individual first-draw error rates and WRS tests (replication study).

Conditions	Descriptive Statistics
Sham	$N = 41$, $M = 35.85\%$, $SD = 32.32\%$, $Mdn = 30.00\%$
Anodal RDLPFC	$N = 42$, $M = 18.89\%$, $SD = 25.18\%$, $Mdn = 5.00\%$
Cathodal RDLPFC	$N = 41$, $M = 24.23\%$, $SD = 25.88\%$, $Mdn = 13.33\%$
Anodal LDLPFC	$N = 42$, $M = 25.95\%$, $SD = 28.23\%$, $Mdn = 18.33\%$
Cathodal LDLPFC	$N = 40$, $M = 32.00\%$, $SD = 31.63\%$, $Mdn = 18.33\%$
WRS tests	Anodal RDLPFC vs Sham: $z = 2.86$, $p_{adj} = 0.008$
	Cathodal LDLPFC vs Sham: $z = 0.67$, $p_{adj} = 0.503$

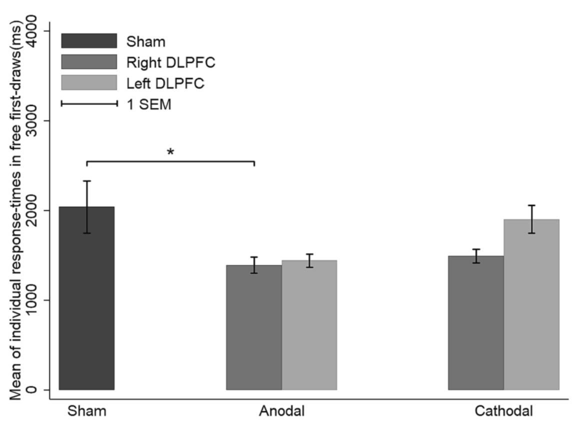

Fig. 9. Impact of stimulation on the free first-draw decision times (replication study). *p <.05, **p <.01, ***p <.001.

cortical excitability in the right DLPFC would reduce reliance on the automatic process, in particular leading to decreased reinforcement errors in case of conflict in the decision task. This was based on the parallel-competitive structure of dual-process theories, in which stating that reasoning errors occur because the analytic system does not manage to override the respective automatic process

Table 7
Individual first-draw decision times and WRS tests.

Conditions	Descriptive Statistics (free first-draw choosing the right urn)
Sham	$N = 40$, $M = 2052$, $SD = 2048$, $Mdn = 1392$
Anodal RDLPFC	$N = 42$, $M = 1354$, $SD = 618$, $Mdn = 1148$
Cathodal RDLPFC	$N = 40$, $M = 1462$, $SD = 497$, $Mdn = 1349$
Anodal LDLPFC	$N = 42$, $M = 1434$, $SD = 492$, $Mdn = 1374$
Cathodal LDLPFC	$N = 40$, $M = 1958$, $SD = 1240$, $Mdn = 1627$
WRS tests	Anodal RDLPFC vs Sham: $z = 2.57$, $p_{adj} = 0.020$
	Cathodal LDLPFC vs Sham: $z = 0.26$, $p_{adj} = 0.795$

(for empirical evidence, see, e.g., De Neys & Glumicic, 2008; De Neys, Vartanian, & Goel, 2008). tDCS applied to the DLPFC has been shown to affect executive functions (Del Missier, Mäntylä, & Bruine de Bruin, 2010; Del Missier, Mäntylä, & Bruin, 2012) that include impulsivity control (for a review, see, Greenwood, Blumberg, & Scheldrup, 2018). Greater resistance to automatic responses relies on the engagement of inhibitory control during decision-making (Del Missier, Mäntylä, & Bruin, 2012).

Our study examined the decision performance in the Bayesian-updating task following unilateral tDCS with anode/cathode applied to either the right DLPFC, left DLPFC or a sham stimulation (offline stimulation). Based on previous studies (Oldrati et al., 2016; Edgcumbe et al., 2019), we were interested in the effects of anodal stimulation over the right DLPFC and the effects of cathodal stimulation over the left DLPFC on reinforcement error rates and decision time in second draws in case Bayesian updating conflicted with reinforcement heuristic. However, our study did not find any stimulation effects on reinforcemet errors in second-draw decisions. Furthermore, we did not find any significant differences on second-draw decision times in case of conflict across these five stimulation conditions either.

We did not find evidence indicating DLPFC stimulation affected inhibition of automatic processes as previous studies. Various tasks that were used to assess inhibitory performance might explain the above inconsistency. For example, Beeli, Casutt, Baumgartner, & Jäncke (2008) found that cathodal tDCS of the right DLPFC increased false alarms in a go/no-go task(GNGT), indicating reduced inhibitory control. However, the application of anodal tDCS to the DLPFC did not affect inhibitory control. In another study with a stop-signal task (Stramaccia et al., 2015), both anodal and cathodal tDCS of the DLPFC had no significant effect on inhibitory control. In addition, Weidacker, Weidemann, Boy, & Johnston (2016) showed an improvement in GNGT performance after application of cathodal tDCS, wheras no significant effect after anodal stimulation was observed. Two studies adopted Cognitive Reflection Test (CRT) to measure the inhibitory performance, Oldrati et al. (2016) observed a decrease in CRT following unilateral cathodal stimulation to the left DLPFC and Edgcumbe et al. (2019) found an improvement in CRT after anodal stimulation to the right DLPFC. Different from the above studies, our study adopted an incentive decision-making tasks in which several cognitive processes interact. In case Bayesian updating conflicts with reinforcement heuristic, the use of reinforcement leads to decision errors. We mainly use the reinforcement errors to indicate inhibitory performance. However, in case of conflict participants easily relied on the use of reinforcement and not that involved in Bayesian reasoning which required the inhibition of automatic responses. Thus for future studies relatively easy decision tasks (like CRT) consisting of multiple decision processes would be more likely to make participants engage in inhibiting impulsive processes.

Additionally, the use of different stimulation modes may also lead to the aforementioned inconsistency. The current method of unilateral DLPFC stimulation in our study provides a more precise measurement of the target effect. As a traditional brain stimulation paradigm, bilateral stimulation has difficulty in separating effects from anodal and return electrodes (e.g., Xiong, She, Zhao, & Zhang, 2020). Sellaro et al. (2015) showed that using an irrelevant brain region as a return electrode was possible. Therefore, we placed the return electrode on Pz, for which there is no evidence that it is related to economic decision making. Different from previous tDCS studies (e.g., Edgcumbe et al., 2019), we excluded the tDCS effect attributed to the interaction resulted from modulating the excitability of bilateral brain regions and only showed the effect of a specific unilateral neural region.

While we did not expect stimulation effects on first-draw decisions since cognitive inhibition was not involved in the decision processes, our results showed that stimulation with the anode over the right DLPFC indeed boosted first-draw decision performance compared to the sham condition. Specifically, in first-draw decisions, when participants had the chance to freely choose the urns, anodal stimulation to the right DLPFC increased the probability choosing the right urn, which was the optimal decision in that case. We also analyzed the decision times in first-draw decisions. The results indicated that anodal stimulation to the right DLPFC lowered the response times of the first-draw decisions when participants can freely choose the urns. Further analysis showed that the effect was only limited to first-draw decisions in case participants freely chose the right urn, which was the optimal decision. We did not find the same result pattern for forced draws in case participants chose the right urn.

We indeed observed improved decision performance (e.g., lower error rates & shorter decision times in free first-draw decisions) after anodal stimulation to the right DLPFC, although that decision improvement was not consistent with our hypothesis. It seems that the improved decision performance might be due to altered preference for certainty after the anodal stimulation to the right DLPFC. In our decision task a first draw from the right urn revealed the state of the world since the right urn always contained balls of only one color. In contrast, after a draw from the left urn, there still remained uncertainty whether the state was up or down. We found that after the anodal stimulation participants preferred to choose the right urn more frequently in case they were given the chance, like showing a preference for certainty, which in turn lead to fewer first-draw errors and faster decision times. In the meanwhile, choosing the right urn for the first draw represented the optimal choice. As Edgcumbe et al. (2019) showed that logic thinking was reduced following bilateral anodal tDCS to the left DLPFC, the observation of first-draw decision improvement might also be caused by enhanced logic thinking or reasoning ability. For the above two possible explanations of the improved decision performance in first-draw decisions, the present study cannot exclude one explanation in favor of the other.

Previous research has tried to find ways to support decision makers in controlling the reinforcement heuristic. Some studies found effective interventions, like asking decision maker to set goals that instigate analytical thinking processes (Hügelschäfer & Achtziger, 2017) or being under the implemental mindset (Li, Hügelschäfer & Achtziger, 2019), whereas increasing monetary incentives (Achtziger & Alós-Ferrer, 2014; Alós-Ferrer, Jaudas & Ritschel, 2021; Alós-Ferrer et al., 2022; Alós-Ferrer & Garagnani, 2023) and altering self-control resources (Alós-Ferrer, Hügelschäfer & Li, 2015) have not proven successful. The present study explored whether tDCS modulation over the DLPFC could inhibit the use of the heuristic. Different from our hypothesis, we did not find evidence supporting that the DLPFC stimulation influenced the use of reinforcement heuristic. Unexpectedly, we observed enhanced decision performance in first-draw decisions after the anodal stimulation to the right DLPFC. Given the fact that our research was exploratory, future studies are still needed to further reveal the role of DLPFC in more complex economic decision making.

7. Conclusion

To explore the role of DLPFC in inhibition of automatic processes in economic decision making, we conducted a tDCS study with 364 participants received the anodal or cathodal stimulation to the right, left DLPFC or sham. We did not find evidence indicating that stimulation to the DLPFC affected inhibition of impulsive processes. While we observed improved decision performance in first-draw decisions after the anodal stimulation to the right DLPFC, the enhacement was not due to the hypothesized tDCS effect on inhibition of automatic processes.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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