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Research report

Modulating activity in the prefrontal cortex changes decision-making for risky gains and losses: A transcranial direct current stimulation study

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HIGHLIGHTS

- Modulation of DLPFC by tDCS changed risk decision-making.
- A risk-measurement table was designed for testing risk preference.
- An asymmetric effect was tested in the gain frame vs. the loss frame.
- Right anodal/left cathodal tDCS decreased risk aversion in the gain frame.
- Right anodal/left cathodal tDCS increased risk aversion in the loss frame.

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ABSTRACT

When making choices under uncertainty, people usually consider both the risks and benefits of each option. Previous studies have found that weighing of risks and benefits during decision-making involves a complex neural network that includes the dorsolateral prefrontal cortex (DLPFC), but the causal effect of this network on risk decision-making has remained unclear. This experiment was based on a risk-measurement table designed to provide a direct measure of risk preference, with a weighted value of the choices (denoted as weighted risk aversion, WRA) as an index of the participant's degree of risk aversion. We studied whether bifrontal transcranial direct current stimulation (tDCS) applied over the right and left prefrontal cortex can change the balance of risky vs. safe responses under both gain frame and loss frame. A total of 60 volunteers performed risk tasks while receiving either anodal over the right with cathodal over the left DLPFC, anodal over the left with cathodal over the right DLPFC, or sham stimulation. The participants tended to choose more risky options in the gain frame and more safe options in the loss frame after the right anodal/left cathodal tDCS. We also found that right anodal/left cathodal tDCS significantly decreased the WRA values compared with those associated with sham stimulation. These findings extend the notion that DLPFC activity is critical for risk decision-making, indicating an asymmetric role of the right DLPFC in the gain frame vs. the loss frame of risk decision-making.

1. Introduction

Human beings are continually confronted with various types of risk decision-making under uncertainty conditions. Studies of brain imaging indicate that risk decision-making is associated with activity in the dorsolateral prefrontal cortex (DLPFC). However, these experiments do not demonstrate a direct causal relationship between brain structure and behaviour. By modulating activity in the DLPFC, brain stimulation technologies make it possible to detect its effect on risk decision-making more accurately.

Knoch et al. [1] used transcranial magnetic stimulation (TMS) and found that participants receiving stimulation over the right DLPFC engaged in significantly riskier decision-making. Fecteau et al. [2] indicated that transcranial direct current stimulation (tDCS) applied over the bilateral DLPFC led to decreased risk taking compared with sham stimulation. Fecteau et al. [3] also determined that participants receiving either type of bilateral DLPFC tDCS adopted a risk-averse response style. Boggio et al. [4] found

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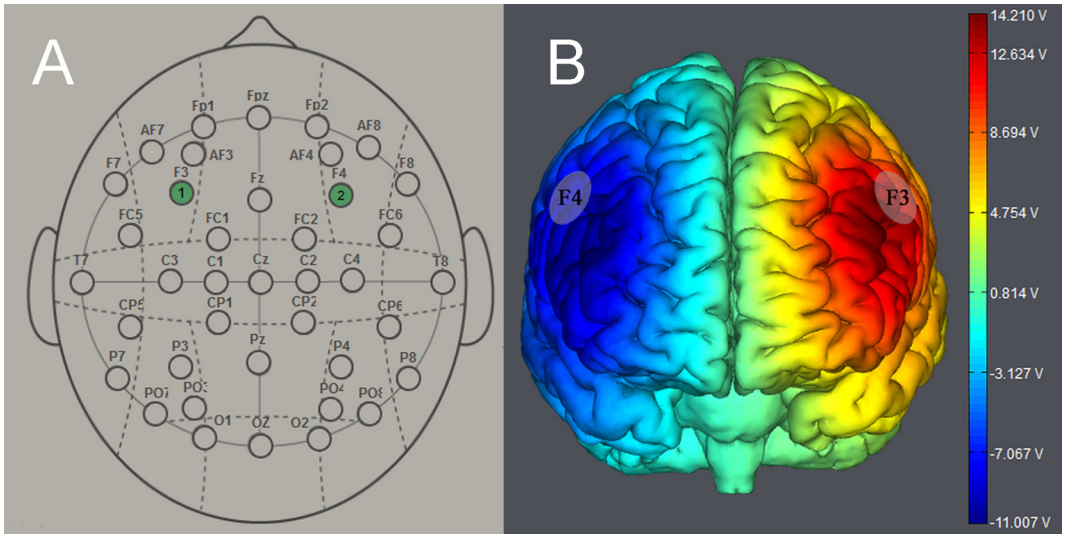

Fig. 1. Schematic drawing of electrode positions suited for tDCS of the dorsolateral prefrontal cortex. a. Stimulation of the respective cortices according to the 10–20 system. b. The electrode placement of left anodal/right cathodal stimulation. The anodal electrode was placed over F3 and the cathodal electrode was placed over F4. The axis represents the range of input voltage from −11.007 to 14.210 v.

that older participants receiving left anodal/right cathodal tDCS chose high-risk prospects more often relative to those receiving sham or right anodal/left cathodal stimulation.

All of these experiments adopted a between-subject design and general psychological tasks, such as Rogers' risk task [5] and the balloon analogue risk task (BART). In addition, existing tDCS studies of risk decision-making have not distinguished between the frames of gain and loss. Psychological studies show that one of the basic phenomena of choice under both risk and uncertainty is that losses loom larger than gains [6,7]. This asymmetry leads to psychological and behavioural differences between the frames of gain and loss. In this paper, we designed a risk-measurement table to describe the participants' risk preference and applied it within two frames of gain and loss. Our experiment adopted a within-subject design to avoid interference from heterogeneity among the participants. We aimed to use tDCS to modulate the activity in the DLPFC and compare the same participant's risk attitude before and after the stimulation when facing gains or losses.

2. Materials and methods

2.1. Subjects

We recruited 60 healthy college students (35 females; mean age 21.4 years, ranging from 17 to 28 years) to participate in our experiment. All participants were right handed and naïve to tDCS and risk tasks, with no history of psychiatric illness or neurological disorders. The participants were randomly assigned to receive right anodal/left cathodal tDCS ($n = 20$, 11 females), left anodal/right cathodal tDCS ($n = 20$, 14 females) or sham stimulation ($n = 20$, 10 females). The final payoff was a fixed show-up fee of 50 RMB Yuan (approximately 8.17 US dollars) plus the reward (or penalty) gained from the tasks. The participants received 52.6 RMB Yuan (approximately 8.52 US dollars) on average, fluctuating according to their performance. Participants gave informed written consent before entering the study, which was approved by the Zhejiang University ethics committee. No participants reported any adverse side effects concerning pain on the scalp or headaches after the experiment.

2.2. Transcranial direct current stimulation (tDCS)

Transcranial direct current stimulation (tDCS) applied a weak direct current to the scalp via two saline-soaked surface sponge electrodes (35 cm^2). The current was constant and delivered by a battery-driven stimulator (Starlab, Spain), which was controlled through a Bluetooth signal. It was adjusted to induce cortical excitability of the target area without any physiological damage to the participants. Various orientations of the current had various effects on the cortical excitability. Generally speaking, anodal stimulation enhances cortical excitability, whereas cathodal stimulation restrains it [8].

Participants were randomly assigned to one of three treatments. For right anodal/left cathodal stimulation, the anodal electrode was placed over the right F4 according to the international EEG 10–20 system, while the cathodal electrode was placed over the left F3. For left anodal/right cathodal stimulation the placement was reversed. The anodal electrode was placed over F3 and the cathodal electrode was placed over F4 (Fig. 1A and B). For sham stimulation, the procedures were the same but the current lasted only for the first 30 s. The participants may have felt the initial itching, but there was actually no current for the rest of the stimulation. This method of sham stimulation has been shown to be reliable [9]. The current was constant and of 2 mA intensity with 15 s of ramp up and down, the safety and efficiency of which was shown in previous studies. After the participant finished the first of two tasks, the laboratory assistant put a tDCS device on his/her head for stimulation and removed him/her from the computer screen. After 15 min of stimulation, the participant was then asked to complete the second task with the stimulation being delivered for another 3 min. The reason we chose a bifrontal electrode montage was to provide stimulation able to enhance the activity of one side of the DLPFC while simultaneously diminishing the other side (Fig. 2).

2.3. Task and procedure

The experiment was based on a risk-measurement table that aims to provide a simple and direct measure of participants' risk preference with little requirement for strategy or working memory. The risk-measurement table, modified from Holt and Laury [10], consists of 16 choices (Table 1). In each choice, participants

Table 1
The risk-measurement table.

Row No.	Option A		Option B		a^*	Weight
	A_1 prob. 1/2	A_2 prob. 1/2	B_1 prob. 1/2	B_2 prob. 1/2		
1	7	13	5	16	0.0478	0.0204
2	7	13	5	17	0.0773	0.0330
3	7	13	5	18	0.0973	0.0415
4	7	13	5	19	0.1115	0.0476
5	8	12	6	15	0.0625	0.0267
6	8	12	6	16	0.0997	0.0425
7	8	12	6	17	0.1240	0.0529
8	8	12	6	18	0.1406	0.0600
9	9	11	7	14	0.0905	0.0386
10	9	11	7	15	0.1406	0.0600
11	9	11	7	16	0.1712	0.0730
12	9	11	7	17	0.1911	0.0815
13	10	10	8	13	0.1644	0.0701
14	10	10	8	14	0.2406	0.1026
15	10	10	8	15	0.2812	0.1199
16	10	10	8	16	0.3047	0.1299

choose between two options. Each option could have two different realisations (A_1 or A_2 and B_1 or B_2) with the same probability of 1/2 over the 16 rows. Option A is safer and has a lower expected value (the "safe" option). Option B is riskier and has an expected value a little higher (the "risky" option). The table was applied in two frames, gain and loss. For example, in the gain frame, if the participant chose option A in the first choice, then he/she was rewarded 7 or 13 yuan at a probability of 1/2. If he/she chose option B, then he/she was rewarded 5 or 16 yuan at the same probability. In the loss frame, the reward was translated into a penalty. Both rewards and penalties were included in the final payoff, encouraging the participants to earn as much as possible.

We hypothesised that the participants had the following common utility function (utility being the perceived ability of something to satisfy needs or wants):

$$U(x) = -e^{-ax}$$

in which parameter a is called the coefficient of absolute risk aversion (RA), and x is the reward or penalty. RA varies from person to person. For each choice, if the expected utility of choosing option A is higher than that of choosing option B, the participant will choose option A; otherwise he/she will choose option B. Therefore, each choice has a unique critical value of a (denoted as a^*) that makes the two options indifferent:

$$\frac{1}{2}U(A_1) + \frac{1}{2}U(A_2) = \frac{1}{2}U(B_1) + \frac{1}{2}U(B_2)$$

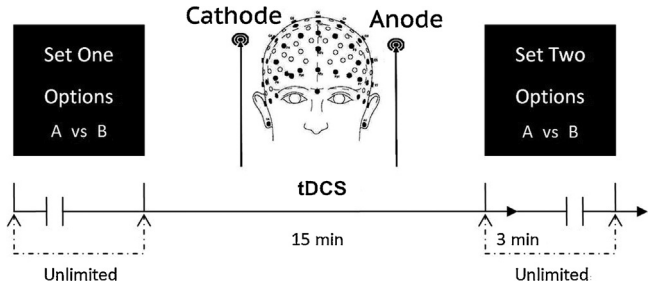

Fig. 2. Schematic representation of the experimental design. After 15 min of stimulation, each participant was then asked to complete the second task with the stimulation being delivered for another 3 min.

The critical value a^* describes the participant's degree of risk aversion as reflected by the choice if he/she chooses the safe option. We normalise a^* to obtain the weight of each choice

$$\text{Weight}_i = \frac{a_i^*}{\sum_{i=1}^{16} a_i^*}$$

The weighted value of the choices (denoted as the weighted risk aversion, WRA) appears to be a reasonable index of the participant's degree of risk aversion.

The task was run using the experimental software z-Tree [11]. The choices of the two frames (gain and loss) were mixed up in random order and presented one by one. The computer had a random program that calculated the rewards and penalties of the participant according to his/her choices.

The participants were required to complete choices before receiving tDCS. After 15 min of stimulation, they were required to complete another set of choices. Actually, the two sets of choices had exactly the same content but different orders. However, we did not offer this information to the participants. After they finished the choices, they were asked to complete a questionnaire before finally receiving their payment.

2.4. Data analysis

We first focused on comparing the WRA of participants before and after the stimulation. Because the two sets of choices had exactly the same content, if the two values of WRA were significantly different from each other, we might conclude that the stimulation had changed the participant's degree of risk aversion. To distinguish time and learning effects from the treatment effect, we further compared the right anodal/left cathodal and left anodal/right cathodal treatments to the sham treatment. Statistical analyses were performed using SPSS statistical software (version 20).

3. Results

There was no significant difference in the participants' WRA before the stimulation (ANOVA; WRA of gain frame, $p = 0.223$; WRA of loss frame, $p = 0.81$). This result indicated that the participants' degree of risk aversion did not differ across treatments.

We first tested the prior hypothesis from previous findings by Fecteau et al. [2], which postulated that participants who received anodal tDCS to the right DLPFC coupled with cathodal tDCS to the

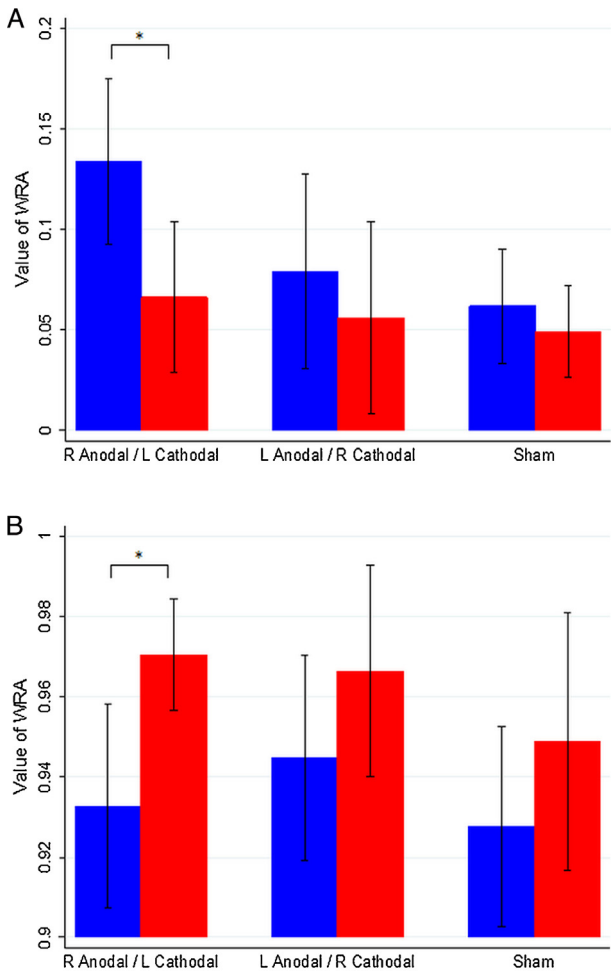

Fig. 3. Values of WRA in the gain frame (a) and loss frame (b) before and after stimulation across treatments. After right anodal/left cathodal tDCS, the participants' WRA values were significantly lower in the gain frame and significantly higher in the loss frame. There was no significant difference in other treatments. Blue columns, pre-tDCS; red columns, post-tDCS. Error bars indicate SEM.

left DLPFC would display risk-averse behaviour in a risk task. To address this hypothesis, we tested whether the values of WRA differ significantly before and after stimulation in frames of both gain and loss. The results revealed that after right anodal/left cathodal tDCS, the participants' WRA values were significantly lower in the gain frame (ANOVA, $p = 0.002$). However, the WRA values in the loss frame were significantly higher after the stimulation (ANOVA, $p = 0.025$). No significant differences were found for the other treatments (Fig. 3). This result indicates that the participants tended to choose more risky options in the gain frame and more safe options in the loss frame after right anodal/left cathodal tDCS.

We then performed two-way ANOVA with treatment (right anodal/left cathodal tDCS, sham) as a between-subject factor and turn (before/after tDCS) as a within-subject factor. In the gain frame, we found a main effect of treatment ($F = 6.512$, $p = 0.013$) and of turn ($F = 3.165$, $p = 0.08$). However, there was no treatment × turn interaction ($p = 0.228$). In the loss frame, there was no significant treatment effect ($p = 0.43$), turn effect ($p = 0.114$) or treatment × turn interaction ($p = 0.652$). Two-way ANOVA with left anodal/right cathodal tDCS treatment and sham treatment showed no significant difference.

To further test the treatment effect, we also calculated the changes in WRA before and after stimulation. In the gain frame, there was a significant effect of treatment ($F = 2.899$, $p = 0.063$). Post hoc analyses showed that the WRA changes of participants receiving right anodal/left cathodal were significantly larger than those of participants receiving sham treatment (Bonferroni correction, $p = 0.081$). This result means that right anodal/left cathodal tDCS significantly decreased WRA values compared with sham treatment. There was no significant difference in the loss frame. Additionally, left anodal/right cathodal tDCS showed no significant difference compared with sham stimulation.

Finally, we tested for a possible impact of the demographic characteristics of the participants on WRA. There was a significant difference in gender across the three treatments (ANOVA; WRA of gain frame, $p = 0.002$; WRA of loss frame, $p = 0.045$). Additionally, the self-assessment of risk preference from the questionnaire was significantly associated with WRA (ANOVA; WRA of gain frame, $p = 0.008$; WRA of loss frame, $p = 0.002$), indicating that WRA may be a reasonable measurement of the degree of risk aversion in participants.

4. Discussion

Functional magnetic resonance imaging studies have suggested that the prefrontal cortex may be particularly critical for the regulation of risk-taking behaviour [5,12,13], and other functional near-infrared spectroscopy studies have reached similar conclusions [14–16]. However, these studies have not provided a direct causal link between brain structures and human behaviour. In the present study, we found that the modulation of activity in the right DLPFC using tDCS can influence decision-making behaviour in healthy individuals, supporting previous work showing that right anodal/left cathodal stimulation appears to have a greater effect on behavioural changes than does sham stimulation or left anodal/right cathodal stimulation.

However, existing tDCS studies of risk decision-making have not distinguished between the frames of gain and loss. Psychological studies have shown that one of the basic phenomena of choice under both risk and uncertainty is that losses loom larger than gains [6,7]. This asymmetry leads to psychological and behavioural differences between the frames of gain and loss, which can also be understood intuitively from the evolutionary perspective. People are much more risk-averse in the "gain frame" when outcomes are expressed in terms of the probability of living (survival) than in the "loss frame" when outcomes are expressed in terms of the probability of dying (mortality). Several findings have proven quite robust experimentally, including the transfer of the concepts of risk attitude and loss aversion, meaning that losses hurt more than equivalent gains please. As evolutionary psychologists note, a hungry animal should be more motivated to find food, and thus more prone to taking risks, than is a full one. Considering this distinction, we treated gain and loss as two distinct frames, measuring the risk preference of the participants separately for each frame. We found that in the gain frame, participants tended to choose more risky options after receiving right anodal/left cathodal tDCS, whereas in the loss frame, participants tended to choose more safe options.

In previous studies, the specific effects of tDCS on the right or bilateral DLPFC have been controversial. Fecteau et al. [2] revealed that participants with right anodal/left cathodal stimulation chose low-risk prospects more often compared with participants with sham stimulation and those with left anodal/right cathodal stimulation. Moreover, there was no difference between groups receiving left anodal/right cathodal and sham stimulation. Fecteau et al. [3] found that participants who received bilateral DLPFC tDCS with an anodal electrode over the right or the left DLPFC displayed a more conservative risk-averse response style than did those with sham stimulation. Boggio et al. [4] found that older adults receiving left anodal/right cathodal tDCS chose high-risk prospects more often

compared with participants receiving sham stimulation or those receiving right anodal/left cathodal stimulation.

These varying results of the above studies might be task related (risk task vs. BART). Some decision-making tasks involve risk, whereas others involve ambiguity [17], and differential patterns of brain activity have been associated with these processes [18]. However, the same experimental methodology used in the previous studies had an opposite effect here. This opposite effect might be induced by variations in the ages of the participants. A possible explanation involves the hemispheric asymmetry reduction in the old adults model, which proposes that frontal activity has a tendency to be less lateralised in older than in younger adults during cognitive demands [19,20]. This model indicates that the cognitive pattern of older adults might be quite different from that of younger adults in risk tasks. The risk-measurement table we proposed here, however, provides a more specific alternative, leading to less ambiguity in cognition. This risk-measurement table was derived from Holt and Laury [10], in which a menu of paired lottery choices is structured so that the crossover point to the high-risk lottery can be used to infer the degree of risk aversion. We made several modifications to this table to make it suitable for a tDCS experiment. First, we simplified the values of the options and probabilities to encourage intuitive choosing rather than calculating. Second, we designed the values of the options based on the utility function to facilitate the measurement of risk preference with various benefits and risks. Finally, as mentioned above, we extended the table to two types corresponding to the two frames of gain and loss to specify the type of cognition.

The tDCS experiments considering risk preference had all adopted a between-subjects design. However, the corresponding results lack statistical power because of the heterogeneity of the participants, especially when confronted with small samples. Our experiment adopted a within-subject design to avoid interference from heterogeneity among participants. As long as the multiple exposures are independent, these designs make it possible for causal estimates to be obtained by examining how individual behaviour changed when the stimulation changed.

The most challenging aspect of within-subject design is to reduce learning effect, which may be mixed with the stimulation's effect. Here, we increased the choice quantity, randomising the order and the presentation of these choices. The experimental results indicated that the learning effect might be well reduced, for there was a significant difference between the right anodal/left cathodal tDCS and sham stimulation but not between the left anodal/right cathodal tDCS and sham stimulation. Moreover, the questionnaire also showed that the participants were not aware that the two sets of choices were completely the same and reported that they would reconsider the options without recalling previous choices.

In conclusion, our findings provide important information about the impact of tDCS on healthy participants. The various behavioural effects observed in our experiment compared with those of previous studies can be regarded as further evidence of the effects of hemispheric asymmetry. These findings might be helpful to elucidate decision-making under uncertainty, for example, whether to invest in the stock market or to accept a new job, involving the possibility of gaining or losing relative to the status quo.

A limitation of the present study is that we cannot determine if the impact on risk decision-making is solely attributable to modulation of activity in the right DLPFC or if the behavioural effects are the result of changing the balance of activity across both DLPFCs. Future studies may include neuroimaging measures to explore the neural changes associated with neuromodulation leading to behavioural effects and also to explore other paradigms of stimulation, such as unilateral stimulation.

5. Conclusion

To conclude, our experiment demonstrated that the modulation of activity in the right DLPFC using tDCS can influence decision-making behaviour in healthy individuals. What's more, we found an asymmetric role of the right DLPFC in the gain frame vs. the loss frame of risk decision-making. In the gain frame, participants tended to choose more risky options after receiving right anodal/left cathodal tDCS, whereas in the loss frame, participants tended to choose more safe options.

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