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Research article

Transcranial direct current stimulation over prefrontal cortex diminishes degree of risk aversion

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HIGHLIGHTS

- Modulation of DLPFC by tDCS changed degree of risk aversion.
- A risk-measurement table was designed for testing risk preference.
- A within-subject design was adopted for boosting statistical power.
- Sham stimulation was highly influenced by wealth effect.
- Gender differences were found in risk averse response style.

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ABSTRACT

Previous studies have established that transcranial direct current stimulation (tDCS) is a powerful technique for manipulating the activity of the human cerebral cortex. Many studies have found that weighing the risks and benefits in decision-making involves a complex neural network that includes the dorsolateral prefrontal cortex (DLPFC). We studied whether participants change the balance of risky and safe responses after receiving tDCS applied over the right and left prefrontal cortex. A total of 60 healthy volunteers performed a risk task while they received either anodal tDCS over the right prefrontal cortex, with cathodal over the left; anodal tDCS over the left prefrontal cortex, with cathodal over the right; or sham stimulation. The participants tended to choose less risky options after receiving sham stimulation, demonstrating that the task might be highly influenced by the "wealth effect". There was no statistically significant change after either right anodal/left cathodal or left anodal/right cathodal tDCS, indicating that both types of tDCS impact the participants' degrees of risk aversion, and therefore, counteract the wealth effect. We also found gender differences in the participants' choices. These findings extend the notion that DLPFC activity is critical for risk decision-making. Application of tDCS to the right/left DLPFC may impact a person's attitude to taking risks.

1. Introduction

Human risk taking is characterized by substantial individual heterogeneity. Many decisions, such as whether to invest in the stock market or to accept a new job, involve the possibility of gaining or losing relative to the status quo. When faced with such decisions, most people are markedly risk averse. For instance, people typically reject gambles that offer a 50/50 chance of gaining or losing money, unless the amount that could be gained is at least twice the amount that could be lost, such as with a 50/50 chance of either gaining $100 or losing $50 [1]. Prospect theory, the classical behavioral model of decision-making under risk and uncertainty, can be used to explain the risk aversion of the participant to gambles that mix gain and loss. People are more sensitive to the possibility of losing objects or money than they are to the possibility of gaining the same objects or amounts of money. Therefore, people typically require a potential gain of at least $100 to make up for exposure to a potential loss of $50 because the subjective impact of losses is roughly twice that of gains [2].

Neuroimaging studies have shown evidence of a relationship between risk aversion and the prefrontal cortex [1,3]. Transcranial magnetic stimulation (TMS) and transcranial direct current

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stimulation (tDCS) have also been used to investigate the neurological process of risk decision making in healthy participants. They found that participants receiving stimulation over the DLPFC change their risk averse response style [4–7].

In the current study, we investigated the effect of tDCS over the right and left prefrontal cortex of subjects performing a risk task, which showed their attitude to the gains and losses. Using different tDCS polarities, we aimed to explore the role of DLPFC on complex decision-making. We designed a risk measurement table, which was highly susceptible to the influence of the wealth effect (participants tended to be more conservative when they expected that they had got positive experiment benefits) to test the risk attitude of participants and compare the difference of the same participant's performance before and after the stimulation. Particularly, when facing situations such as lotteries or gambling, people carefully weigh the gains and losses to decide whether or not to participate, and this is indicative of their risk attitude. Through these choices, we can identify participants' risk preference. In addition, survey data and experimental evidence in economics suggest that women may be more risk averse than men towards gamble tasks [8–10]. In this paper, we also found that gender differences influenced the conclusion of risk preference. The importance of this study is to further explore the different regions of the prefrontal that impact the risk decision, especially the role the right/left DLPFC play in this process, which supplements previous research.

2. Materials and methods

2.1. Subjects

We recruited 60 healthy college students (36 females; mean age 21.3 years, ranging from 17 to 28 years) to participate in our experiment. All participants were right-handed and naïve to tDCS and risk tasks, and they lacked a 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 30 RMB yuan (approximately 4.83 US dollars) plus the gains and losses from the tasks. The participants received 41.2 RMB yuan (approximately 6.64 US dollars) on average, which fluctuated according to their performance. Participants gave written informed consent before entering the study, which was approved by the Zhejiang University ethics committee. No participants reported any adverse side effects about pain on the scalp or headaches after the experiment.

2.2. Transcranial direct current stimulation (tDCS)

Transcranial direct current stimulation (tDCS) involves the application of 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 (Multichannel noninvasive wireless tDCS neurostimulator, Starlab, Barcelona, Spain), which was controlled through a Bluetooth signal. It was adjusted to induce cortical excitability of the target area without causing any physiological damage to the participants. Various orientations of the current had various effects on the cortical excitability. Generally speaking, anodal stimulation enhances the cortical excitability, whereas cathodal stimulation restrains it [11].

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. For sham stimulation, the procedures were the same, but the current only lasted 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 is reliable [12]. The current was constant and had an intensity of 2 mA with 15 s of ramp up and down, the safety and efficiency of which has been shown in previous studies. After the participant finished the first of two tasks, the laboratory assistant placed 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 without stimulation. We chose a bifrontal electrode montage to provide stimulation that could enhance the activity of one side of the DLPFC, while simultaneously diminishing the other side.

Table 1
The menu of paired lottery choices.

Row no.	Option A	Option B	
		B_1 Prob.1/2	B_2 Prob.1/2
1	0	−5	20
2	0	−6	20
3	0	−7	20
4	0	−8	20
5	0	−9	20
6	0	−10	20
7	0	−11	20
8	0	−12	20
9	0	−13	20
10	0	−14	20
11	0	−15	20
12	0	−16	20
13	0	−17	20
14	0	−18	20
15	0	−19	20
16	0	−20	20
17	0	−21	20
18	0	−22	20
19	0	−23	20
20	0	−24	20

2.3. Task and procedure

The experiment was based on a menu of paired lottery choices that aims to provide a simple and direct measure of the participants' degrees of risk aversion with little requirement for strategy or working memory. This menu consists of 20 choices (Table 1). In each choice, participants choose between two options. Each option has a constant realization of zero or two different realizations (B_1 or B_2) with the same probability of 1/2 over the 20 rows. Option A is safe and has no risk at all. Option B is risky and has an expected value in most cases above zero while occasionally below zero. For example, if the participant chose option A in the first choice, there was neither gain nor loss. If he/she chose option B, he/she would lose 5 RMB yuan or gain 20 RMB yuan at the same probability. Both gains and losses were included in the final payoff, encouraging the participants to earn as much as possible.

The task was run using the experimental software z-Tree [13]. The choices were presented one by one in random order. We used a computerized, random generator program that calculated the gains and losses of the participant according to his/her choices.

The participants were required to make choices before receiving tDCS. After 15 min of stimulation, they were required to select another menu of paired lottery choices (Fig. 1). The two menus had the same content with different orders, which was not informed to the participants. After they finished making their choices, the participants were asked to complete a questionnaire before finally receiving their payment. The questionnaire contained questions about personal information such as gender, age, income, consump-

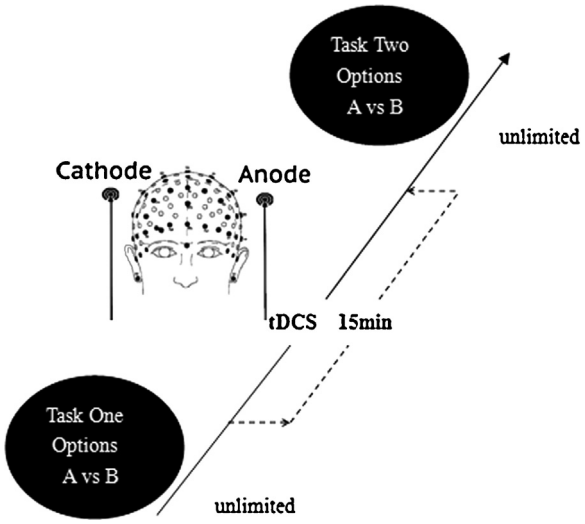

Fig. 1. Schematic representation of the experimental design. Each participant started to perform the risk task after receiving 15 min of stimulation.

tion expenditure and self-assessment of risk preference as well as questions about the experiment process.

2.4. Data analysis

For each choice, the participant displayed a higher degree of risk aversion if he/she chose option A (the safe option) rather than option B (the risky option). We calculated the number of safe options the participant chose and regarded it as a reasonable index for the participant's degree of risk aversion.

To distinguish the different risk preference between female participants and male participants, we processed three subject groups: the group of females ($n = 36$, denoted as female), the group of males ($n = 24$, denoted as male) and the group of both genders ($n = 60$, denoted as whole). We first compared the numbers of safe options before and after right anodal/left cathodal stimulation, left anodal/right cathodal stimulation and sham treatment; then, we compared the changes in the numbers of safe options after the stimulation across the three treatments. Because the sham treatment contained no real stimulation, the changes in the numbers of safe options could be attributed to the wealth effect. This means that participants appear to be conservative in their choices for the latter menu because of the expected benefits from the first menu. If the changes in the numbers of safe options were significantly different from the active treatments, we might conclude that the active stimulations have changed the participants' degrees of risk aversion. Statistical analyses were performed using SPSS 20 (SPSS Inc., Chicago, Illinois, USA).

3. Results

There was no significant difference in the participants' numbers of safe options before the stimulation (ANOVA; female, $F_{2,33} = 0.916$, $p = 0.410$; male, $F_{2,21} = 0.293$, $p = 0.749$; whole, $F_{2,57} = 0.743$, $p = 0.480$). This indicated that the participants' degrees of risk aversion were not different across the treatments.

We first tested whether the participants' numbers of safe options were significantly different before and after the stimulation. In the right anodal/left cathodal and left anodal/right cathodal stimulation treatments, there were no significant differences in the participants' numbers of safe options before and after the stimulation, whether in regard to the female group (right anodal/left cathodal, $t_{10} = -0.690$, $p = 0.506$; left anodal/right cathodal, $t_{13} = 0.563$, $p = 0.583$), the male group (right anodal/left cathodal, $t_8 = 0.870$, $p = 0.410$; left anodal/right cathodal, $t_5 = -0.255$, $p = 0.809$) or the whole group (right anodal/left cathodal, $t_{19} = 0.301$, $p = 0.767$; left anodal/right cathodal, $t_{19} = 0.195$, $p = 0.847$). However, there was a significant difference in the sham treatment in regard to the female group ($t_{10} = -2.429$, $p = 0.036$) and the whole group ($t_{19} = -3.059$, $p = 0.006$). The male group displayed the same tendency but was not significant enough ($t_8 = -1.765$, $p = 0.116$). As a result, the participants tended to choose more safe options because of the wealth effect (this was much more obvious in female participants), while the treatment effect probably counteracted this effect in the active treatments.

To further test the treatment effect, we also calculated the changes in the safe options after the stimulation compared with the safe options chosen before the stimulation (after minus before). A significant difference was observed across the three treatments in regard to the female group (ANOVA, $F_{2,33} = 3.916$, $p = 0.030$) and the whole group ($F_{2,57} = 5.071$, $p = 0.009$), but not in regard to the male group ($F_{2,21} = 1.978$, $p = 0.163$). Post hoc analyses showed that the changes in the safe options of participants receiving anodal tDCS to the right DLPFC coupled with cathodal tDCS to the left DLPFC were significantly less than those receiving sham treatment (Fisher's LSD; female, $p = 0.063$; male, $p = 0.061$; whole, $p = 0.006$). Participants receiving anodal tDCS to the left DLPFC coupled with cathodal tDCS to the right DLPFC also displayed the same significant tendency except for the male group (Fisher's LSD; female, $p = 0.010$; male, $p = 0.319$; whole, $p = 0.010$). The participants' choices of the three groups see Fig. 2.

Finally, we focused on the whole group and tested the possible impact of the demographic characteristics of the participants on the numbers of safe options. We performed factorial ANOVA with treatment (right anodal/left cathodal, left anodal/right cathodal, sham) as a between-subject factor, turn (before/after tDCS) as a within-subject factor, and the personal information gained from the questionnaires as covariates. Apart from significant effects of treatment ($F_{2,109} = 4.47$, $p = 0.014$) and gender ($F_{1,109} = 17.646$, $p = 0.000$), we also found a significant effect of consumption expenditure ($F_{1,109} = 3.234$, $p = 0.075$). This meant that participants who consumed more tended to be more risk averse. Additionally, the self-assessment of risk preference was also significantly associated with the numbers of safe options ($F_{1,109} = 11.033$, $p = 0.001$), which indicated that the numbers of safe options might be a reasonable measurement of the participants' degrees of risk aversion.

4. Discussion

In the present study, we found that participants receiving bilateral DLPFC tDCS with an anodal electrode over the right or left DLPFC (with a cathodal electrode over the homologous area of the contralateral hemisphere) had decreased degrees of risk aversion and chose more the risky options compared with participants with sham stimulation, whereas there was no significant difference between the two groups receiving active stimulation (bilateral DLPFC anodal right or bilateral DLPFC anodal left) in terms of the number of risky options selected. These results supported the suggestion from some neuroimaging studies that the prefrontal cortex (PFC) appears to be critical in the decision-making process [14–18]. Our findings are also consistent with previous work showing that tDCS over the DLPFC impacts risk decision-making [5–7].

The above tDCS studies provide a direct causal link between the DLPFC and risk decision-making. However, they used nearly the same methodology in their experiments, including the same risk task (Rogers' Risk Task or BART) and same experimental design (between subjects design). The aim of the present study was to demonstrate the robustness of the results that neuromodulation of

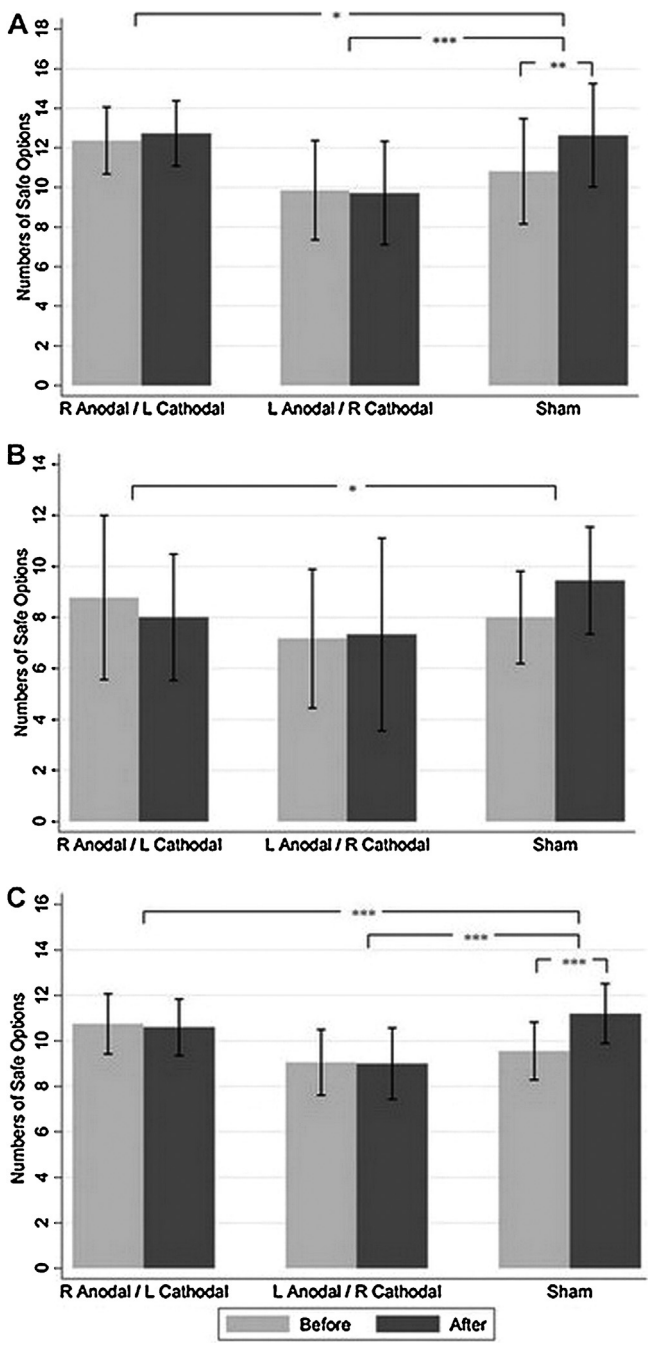

Fig. 2. Numbers of safe options before and after the stimulation of the three groups across treatments. (A) The female group. (B) The male group. (C) The whole group.

the DLPFC can lead to behavioral changes in risk taking that are not related to the risk task or experimental design.

In the present study, we used a different paradigm that provides a more specific and direct measure of the participants' risk preference. The risk-measurement table was derived from Fehr and Goette [19], in which a menu of paired lottery choices is structured so that the number of the safe options the participant chooses can be used to infer the degree of risk aversion.

With respect to the experimental design, although these studies tried to avoid the question about the internal validity of the between subjects design by random assignment, the results still lack statistical power because of the heterogeneity of the participants, especially with their small sample size. We adopted a within-subject design to substantially boost the statistical power for testing the stimulation effect. However, the challenges to within analyses are essentially some confounding in the identification that may be introduced because of the necessity to expose each subject to multiple treatments (before and after stimulation). To reduce these confounds, such as the learning effect [20], we randomized the order of the presentation of these choices. The questionnaire after experiment results showed that the learning effect might have been reduced with this design; the participants were not aware that the two menus of choices were the same, and they reported that they would reconsider the options without recalling previous choices.

In addition to the learning effect, the wealth effect is another important confounder to identification. In our menu of paired lottery choices, participants have an evaluation for positive benefits after completing the first menu for the reason that the aggregated expected value of option B is above zero. As a result, they have a tendency with low risk in doing the second task because of a kind of "myopic risk aversion", which has been widely found in experimental economics studies about risk preference [21]. It is revealed that the more frequently returns are evaluated, the more risk averse investors [22]. Such phenomenon is called the "wealth effect" [23].

Moreover, a previously published tDCS study also found that participants receiving sham stimulation had a conservative tendency to choose significantly more safe options as the task is repeated [6]. Similar results had been revealed that participants receiving sham stimulation chose significantly more safe options in the second menu compared with the first menu. Participants were randomly assigned to three different stimulation treatments, and they were required to separately accomplish two menus of choices before and after stimulation in the present study. Therefore, we can combine the advantages of both the within subject design and between subject design, comparing whether the changes of safe options of the participants receiving active stimulation differ from those receiving sham stimulation and verifying the causal effect of DLPFC on risk decision making.

Furthermore, it has been revealed in our experiment that the results depended on the gender of participants. The female participants tended to be more conservative after the sham stimulation compared with before the stimulation because of the wealth effect. However, there was no significant difference in regard to the male participants before and after sham stimulation. All the participants receiving anodal tDCS to the right DLPFC coupled with cathodal tDCS to the left DLPFC chose significantly fewer safe options than those receiving sham treatment. It indicated that the gender factor had an impact on results for risk preference without influencing the stimulation effect. Female participants tended to be more risk averse in the second menu of lottery choices because of their expectation of positive benefits after completing the first menu. On the contrary, male participants are riskier than female participants [10,24], who may probably be less susceptible to be conservative in the second menu of choices.

In conclusion, our findings provide important information about the impact of tDCS applied in healthy participants, which might especially be helpful to research on risk decision making, such as whether to invest in the stock market or accept a new job, which involve the possibility of gaining or losing relative to the status quo. The limitation of the present study is that we cannot determine whether the impact on the degree of risk aversion is solely attributable to the modulation of activity in the right/left DLPFC or whether the behavioral effects are the result of changing the balance of activity across both DLPFCs. Future studies may include neuroimaging measures to explore the neural changes that are associated with neuromodulation leading to behavioral effects and also explore other paradigms of stimulation such as that using unilateral stimulation [6].

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