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Research report

Activation of the prefrontal cortex by unilateral transcranial direct current stimulation leads to an asymmetrical effect on risk preference in frames of gain and loss

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ABSTRACT

Previous brain imaging and brain stimulation studies have suggested that the dorsolateral prefrontal cortex may be critical in regulating risk-taking behavior, although its specific causal effect on people's risk preference remains controversial. This paper studied the independent modulation of the activity of the right and left dorsolateral prefrontal cortex using various configurations of transcranial direct current stimulation. We designed a risk-measurement table and adopted a within-subject design to compare the same participant's risk preference before and after unilateral stimulation when presented with different frames of gain and loss. The results confirmed a hemispheric asymmetry and indicated that the right dorsolateral prefrontal cortex has an asymmetric effect on risk preference regarding frames of gain and loss. Enhancing the activity of the right dorsolateral prefrontal cortex significantly decreased the participants' degree of risk aversion in the gain frame, whereas it increased the participants' degree of risk aversion in the loss frame. Our findings provide important information regarding the impact of transcranial direct current stimulation on the risk preference of healthy participants. The effects observed in our experiment compared with those of previous studies provide further evidence of the effects of hemispheric and frame-dependent asymmetry. These findings may be helpful in understanding the neural basis of risk preference in humans, especially when faced with decisions involving possible gain or loss relative to the status quo.

1. Introduction

Risk decision making is an important part of our daily lives, involving a delicate evaluation between benefits and possible risks. A remarkable feature in risky choices indicated by psychological studies is that people are inclined to be risk-averse in the gain frame while risk-seeking in the loss frame (Lichtenstein and Slovic, 1971; Kahneman and Tversky, 1979, 1984; Tversky and Kahneman, 1991). For example, people prefer gaining 10 dollars with certainty to gaining 20 dollars with a probability of 50%, but at the same time they prefer losing 20 dollars with a probability of 50% to losing 10 dollars with certainty. This reversal of risk preference seems irrational because peoples' preferences should be consistent regardless of the frames, thus it attracts great attention in social science such as economics and psychology (Brickman et al., 1978; Chew and MacCrimmon, 1979; Thaler, 1985; Loomes and Sugden, 1986; Gul, 1991; Starmer, 2000).

Cognitive neuroscientific studies have also paid much attention to the neural basis of risk decision making. Studies using functional magnetic resonance imaging, functional near-infrared spectroscopy and positron emission tomography have revealed evidence of a relationship between risk preference and dorsolateral prefrontal cortex (DLPFC) activity (Ernst et al., 2001; Bolla et al., 2005; Rao et al., 2008; Cazzell et al., 2012; Bembich et al., 2014; Lin et al., 2014). The activation is lateralized on the right side of DLPFC, associated with choice risk level and peoples' degree of risk aversion (Rao et al., 2008; Bembich et al., 2014; Holper et al. 2014). Clinically, patients with right DLPFC lesions have bad performance in risk decision making tasks (Manes et al., 2002; Clark et al., 2003; Fellows and Farah, 2005). Related studies indicated that the right DLPFC specializes in response suppression or inhibition in the context of risk decision making (Verfaellie and Heilman, 1987; De Zubicaray et al., 2000; Ersche et al., 2005; Schonberg et al., 2012; Yamamoto et al., 2015), which is believed to be one of the cognitive functions of right DLPFC used to mediate

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between different alternatives in risk decision making (Ernst et al., 2001; Bembich et al., 2014; Yamamoto et al., 2015).

However, these technologies cannot demonstrate a direct causal association between the DLPFC and risk decision making. If the right DLPFC is associated with response inhibition and alternative mediation, then altering the activity of this region may probably affect peoples' behaviors in risk decision making. Studies using brain stimulation technologies, such as transcranial magnetic stimulation and transcranial direct current stimulation (tDCS), provide the opportunity to modulate activity in the DLPFC to detect its causal effect on risk preference in control experiments. Unfortunately, these studies obtained various results. For example, Knoch et al. (2006), using transcranial magnetic stimulation, found that participants receiving stimulation over the right DLPFC changed their risk-averse response style and displayed significantly riskier decision making. Fecteau et al. (2007a) revealed that participants receiving right anodal/left cathodal tDCS adopted a risk-averse response style. Fecteau et al. (2007b) indicated that tDCS applied over the bilateral DLPFC led to more risk-averse behavior compared with unilateral and sham stimulations. Weber et al. (2014) found that enhancing the activity of either right or left DLPFC using tDCS did not change participants' risk preferences.

These varying results may be related to the various psychological or economic tasks, such as Rogers' Risk Task (Rogers et al., 1999), the Balloon Analogue Risk Task and the Columbia Card Task (Figner et al., 2009). Different frames of the risk tasks may cause ambiguity, and different patterns of brain activity may be associated with these processes. In addition, most experiments that have analyzed risk preference adopted a between-subject design, which requires a large sample to overcome the heterogeneity of the participants. However, the methodological constrains of brain stimulation technologies make it difficult to afford large sample sizes, which may reduce the statistical power of the corresponding results. More importantly, these studies do not distinguish between the gain frame and the loss frame. People may have different understandings of the tasks and attribute them into different frames, thus leading to different or even reversal behaviors and making the results much more complicated to be explained. Furthermore, most previous studies do not distinguish the effect of unilateral DLPFC stimulation from that of bilateral DLPFC stimulation, leaving the question as to whether the impact on risk decision making is solely attributable to the modulation of activity in the unilateral DLPFC or an altered balance of activity across both DLPFCs.

In this study, we designed a risk-measurement table with two frames of gain and loss. The risk-measurement table consists of 35 choices in each frame and is modified from Holt and Laury (2002) and Ye et al. (2015), which provided a simple and direct measure of the participants' risk preferences without requiring strategy or working memory. In each choice of the table, the participants should choose between a safe option and a risky option. It is supposed that the more safe options the participant chose, the more risk-averse he/she is. We recruited a total of 100 healthy college students to participate in our experiment and adopted the within-subject design. The participants were required to complete a set of choices (the first task) before receiving tDCS and another set of equivalent choices (the second task) after the stimulation. As hemispherical asymmetry of DLPFC is observed in previous findings, we applied a unilateral stimulation montage to distinguish the impact of the right or left DLPFC from that of changing the balance of activity across both DLPFCs. The participants were randomly assigned to one of five single-blind tDCS conditions, which were defined as right anodal tDCS, right cathodal tDCS, left anodal tDCS, left cathodal tDCS and sham stimulation.

By comparing the participants' degree of risk aversion before and after different kinds of tDCS, we aimed to find out how modulating the activity of unilateral DLPFC will affect the participants' risk preference when faced with frames of gain and loss. Based on previous studies indicating that activation is lateralized on the right side of DLPFC in risk decision making tasks, we anticipated a hemispherical asymmetry of DLPFC, and stimulation over the right DLPFC has more effect in changing the participants' behaviors than that over the left DLPFC. We also anticipated a frame-dependent asymmetry, meaning that stimulation over DLPFC had different effects in frames of gain and loss. The behavioral feature indicated by psychological studies that people are inclined to be risk-averse in the gain frame while risk-seeking in the loss frame may be derived from the long evolutionary history of human being and has been rooted in human psychology as instinctive impulses. Thus the anodal tDCS over the right DLPFC may have inhibitive effect on these impulses, leading the participants being more risk-seeking in the gain frame while more risk-averse in the loss frame. Similarly, the cathodal tDCS over the right DLPFC may have an opposite effect, leading the participants being more risk-averse in the gain frame while more risk-seeking in the loss frame. Furthermore, we explored the influence of gender on participants' risk decision making and anticipated a difference between males and females.

2. Results

2.1. Main results

For each choice of the risk-measurement table, the participants were required to choose between the safe option and the risky option. The participant was considered to have a higher degree of risk aversion if he/she chose the safe option rather than the risky option. Generally speaking, the more safe options the participant chose, the more risk-averse he/she was. As a result, we calculated the number of safe options the participant chose and regarded it as a reasonable index for the participant's risk preference.

We analyzed the number of safe options the participant chose using repeated measures ANOVA with Frame (gain vs. loss) and Time (before vs. after stimulation) as within-subjects factors and Stimulation type (right anodal, right cathodal, left anodal, left cathodal or sham) as a between-subject factor. There was a significant effect of Frame ($F_{1,95}=11.590$, $p=0.001$), indicating that in the gain frame, the participants tended to choose more safe options than in the loss frame (gain frame: mean=22.885; loss frame: mean=19.535). We also found a significant interaction of Frame and Time ($F_{1,95}=25.833$, $p<0.001$). Tests of simple main effect showed that in the gain frame, the participants chose less safe options after the stimulation ($p<0.001$), while in the loss frame they chose more safe options after the stimulation ($p=0.012$). As for comparisons between the gain frame and the loss frame, we found significant differences both before and after the stimulation (before: gain frame=23.540, loss frame=19.160, $p<0.001$; after: gain frame=22.230, loss frame=19.910, $p=0.021$).

Crucially, a three-way interaction of Frame, Time and Stimulation type was found significant ($F_{4,95}=3.607$, $p=0.009$). After receiving right anodal stimulation, the participants were likely to choose less safe options in the gain frame (before: mean=24.800; after: mean=22.150; $p<0.001$) while more safe options in the loss frame (before: mean=17.300; after: mean=19.650; $p=0.001$). After receiving left cathodal stimulation, the participants were likely to choose less safe options in the gain frame (before: mean=25.000; after: mean=23.650; $p=0.037$), but no contrary tendency was found in the loss frame.

In addition, neither in the gain frame nor in the loss frame had

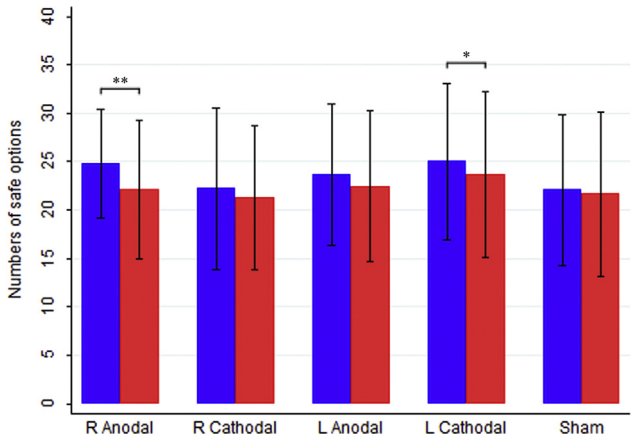

Fig. 1. Numbers of safe options in the gain frame before and after stimulation across conditions. Blue columns, pre-tDCS; red columns, after-tDCS. Error bars indicate standard errors. Asterisks indicate statistical significance of difference within subjects (**: $p < 0.01$, *: $p < 0.05$).

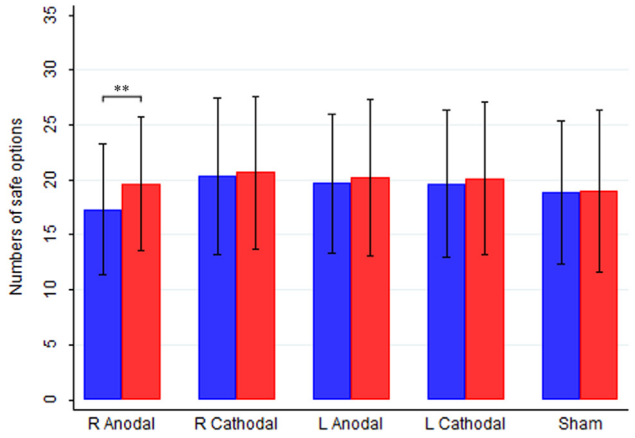

Fig. 2. Numbers of safe options in the loss frame before and after stimulation across conditions. Blue columns, pre-tDCS; red columns, after-tDCS. Error bars indicate standard errors. Asterisks indicate statistical significance of difference within subjects (**: $p < 0.01$, *: $p < 0.05$).

significant difference been observed between the four active tDCS conditions and the sham condition before the stimulation (in all conditions: $p = 1.000$), which may indicate that the participants were randomly assigned to these conditions. However, there was also no significant difference between these active conditions and the sham condition after the stimulation (in all conditions: $p = 1.000$). The participants' choices for the different conditions are summarised in Fig. 1 and Fig. 2.

2.2. Gender differences

To take a close look at the influence of gender on participants' behavior, we included Gender as a between-subject factor to the repeated measures ANOVA in 2.1. Once again we found significant effects of Frame ($F_{1,90} = 6.140$, $p = 0.015$), the interaction of Frame and Time ($F_{1,90} = 22.005$, $p < 0.001$) and the three-way interaction of Frame, Time and Stimulation type ($F_{4,90} = 4.233$, $p = 0.003$). More importantly, we found a significant interaction of Frame and Gender ($F_{1,90} = 7.218$, $p = 0.009$). Tests of simple main effect showed that in the gain frame, the male participants chose less safe options than the female participants (male: mean = 20.917; female: mean = 24.162; $p = 0.045$), while no similar tendency was found in the loss frame.

Furthermore, we applied the same tests in 2.1 to the male and female participants separately. For the male participants, we found no significant effect of Frame but a significant interaction of Frame and Time ($F1,31 = 8.058$, $p = 0.008$). Simple main effect tests showed that in the gain frame, the participants chose less safe options after the stimulation (before: mean = 21.433; after: mean = 20.401; $p = 0.009$). The three-way interaction of Frame, Time and Stimulation type was also found significant ($F4,31 = 4.930$, $p = 0.003$). Analyses showed that after receiving right anodal stimulation, the male participants were likely to choose less safe options in the gain frame (before: mean = 22.500; after: mean = 20.000; $p = 0.003$) while more safe options in the loss frame (before: mean = 17.250; after: mean = 21.250; $p < 0.001$).

For the female participants, on the other hand, we found a significant effect of Frame ($F_{1,59} = 22.508$, $p < 0.001$). This means that in the gain frame, the female participants tended to choose more safe options than in the loss frame (gain frame: mean = 24.162; loss frame: mean = 18.868). There was also a significant interaction of Frame and Time ($F_{1,59} = 17.785$, $p < 0.001$). Simple main effect tests showed that in the gain frame, the participants chose less safe options after the stimulation (before: mean = 24.909; after: mean = 23.414; $p < 0.001$). As for comparisons between the gain frame and the loss frame, we found significant differences both before ($p < 0.001$) and after ($p < 0.001$) the stimulation. Furthermore, the female participants were likely to choose less safe options in the gain frame after receiving right anodal stimulation (before: mean = 22.500; after: mean = 20.000; $p = 0.003$) and to choose less safe options in the gain frame after receiving left cathodal stimulation (before: mean = 25.133; after: mean = 23.600; $p = 0.068$), while no significant changes were found in the loss frame.

2.3. Awareness of risk preference

After finishing the second task, the participants were asked to complete a questionnaire containing questions about personal information and the participants' self-assessment of risk preference. The participants were asked how they evaluated their risk preferences according to their behaviors in the experiment, given a scale from 1 to 6 with 1 meaning “very risk averse” and 6 meaning “very risk-seeking”. This was a supplementary test aiming to check whether the participants had realized that their risk preferences were changed. However, there was no significant difference in self-assessment of risk preference between the five different tDCS conditions (one-way ANOVA, $p = 0.662$). As the questionnaire was completed after the stimulation, this may indicate that participants receiving right anodal tDCS were unaware that their risk preferences had been changed.

3. Discussion

This paper studied the independent modulation of the activity of the right and left DLPFC using various configurations of tDCS. We designed a risk-measurement table and adopted a within-subject design to compare the same participant's risk preference before and after unilateral stimulation when presented with different frames of gain and loss. Our results indicated both a hemispheric asymmetry and a frame-dependent asymmetry. Enhancing the activity of the right DLPFC decreased the participants' degree of risk aversion in the gain frame, whereas it increased the participants' degree of risk aversion in the loss frame. Left cathodal tDCS also decreased the participants' degree of risk aversion in the gain frame, but no contrary effect was found in the loss frame.

Compared to previous studies about risk preference and DLPFC using brain stimulation technologies, this study may have improvements in some aspects. We extended the sample to 100

participants and adopted the within-subject design to prevent interference due to the heterogeneity of the participants. We designed a risk-measurement table based on Holt and Laury (2002) and Ye et al. (2015). The risk-measurement table proposed by Ye et al. (2015) consists of 16 choices. For each choice, participants must choose between a safe option and a risky option. However, for some of the choices, the risky option has a much higher expected value than the safe option but is only slightly riskier. As a result, most participants will choose the risky option both before and after the tDCS of limited intensity. These choices minimally contribute to interference in the participants' risk preferences and may influence the significance of the difference before and after the stimulation. Therefore, we modified the risk-measurement table, adjusting the expected values of the two options to be equal or nearly equal to capture mild changes in participants' risk preferences. This modification also allowed for a simpler measurement of the participants' risk preferences without the use of an assumed utility function or an index of weighted risk aversion. In addition, we extended the choice quantity to 35 choices not only to enhance the statistical power but also to reduce the learning effect, which may be mixed with the stimulation effect. The questionnaire revealed that the participants were not aware of the homogeneity of the two tasks, and the participants reported that they would reconsider the choices without recalling previous ones.

More importantly, we distinguished between the effect of the unilateral DLPFC and the effect due to changing the balance of activity across both DLPFCs. Neuroscientific studies have suggested that the right DLPFC is engaged in response inhibition, especially the inhibitory cognitive control of affective impulses (Ernst et al., 2001; Schonberg et al., 2012; Pripfl et al., 2013), and the right side of DLPFC is much more intensively activated during risk decision making tasks (Rao et al., 2008; Bembich et al., 2014; Holper et al. 2014). As a result, it is crucial to independently test the effect of unilateral DLPFC in risk decision making. This montage of unilateral stimulation is widely used in tDCS studies (Fecteau et al., 2007a; Jacobson et al., 2011; Hasan et al., 2013; Sellaro et al., 2015). We chose the parietal cortex to place the return electrode so as to complete the current circuit because of its reasonable spatial and functional distance from the DLPFC, thus decreasing the possibility of stimulation or task interferences. The parietal cortex is believed to be related with attention (including visual, auditory and haptic attention), the development of human language as well as calculation abilities (Pugh et al., 1996; Burton et al., 1999; Colby and Goldberg, 1999; Kanwisher and Wojciulik, 2000; Culham and Kanwisher, 2001; Simon et al., 2002). In addition, all the four active tDCS conditions have used the parietal cortex to place the return electrode. If the significant effect of right anodal (left cathodal) on the participants' behaviors was due to the effect of parietal cortex, there should be significant difference in condition of right cathodal (left anodal) as well, but we didn't find any significant difference in the latter condition. Nevertheless, it's still possible that this montage may have some effects on risk decision making. This is a trade off as we aimed to distinguish between the effect of the unilateral DLPFC and that of changing the balance of activity across both DLPFCs.

Furthermore, we distinguished between gain and loss frames in the risk decision making task. Psychological studies indicated that people are inclined to be risk-averse in the gain frame while risk-seeking in the loss frame (Lichtenstein and Slovic, 1971; Kahneman and Tversky, 1979, 1984; Tversky and Kahneman, 1991). This behavioral feature may be derived from the long evolutionary history of human being and has been rooted in human psychology as instinctive impulses (McFarlane and Pliner, 1997; Wilkinson and Klaes, 2012). Moreover, previous studies indicated that the right DLPFC appears to be involved in impulsive choice inhibition during decision making (Ersche et al., 2005; Schonberg et al., 2012; Yamamoto et al., 2015). In our experiment, the anodal tDCS over the right DLPFC may have increased the inhibition of the participants' instinctive affective impulses for being risk-averse in the gain frame while being relatively risk-seeking in the loss frame. As a result, the primal instinct may be partly inhibited, thus leading the participants to be less risk-averse in the gain frame while less risk-seeking in the loss frame. However, we didn't find an opposite effect of right cathodal tDCS on risk behavior. Most previous studies about the effect of tDCS on risk behavior also didn't find significant effects of cathodal stimulations over the right DLPFC, and the anodal-excitation and cathodal-inhibition effect was found to occur rarely in cognitive studies (Jacobson et al., 2012). These phenomena were supposed to be related with the initial neuronal activation state, the susceptibility of the cognitive task or the effect of contralateral compensation (Silvanto et al., 2008; Fox et al., 2006; Jacobson et al., 2012).

We also found significant effect of left cathodal tDCS. Participants receiving left cathodal tDCS turned more risk-seeking in the gain frame, but no contrary effect was found in the loss frame. Literature has shown the involvement of left DLPFC in response inhibition, self control and working memory in some other cognitive domains (Menon et al., 2001; Shafritz et al., 2006; Andrews et al., 2011; Hollmann et al., 2012; Steinbeis et al., 2012). However, it is hard to conclude whether left DLPFC had a real effect on participants' risk preferences because no significant effect was found in left anodal tDCS condition and the effect found in left cathodal tDCS condition was only slightly significant in the gain frame. Investigating the effect of tDCS via a cognitive task is highly susceptible to external noise (Jacobson et al., 2012), and the slight significance may be attributed to the effect of contralateral compensation or the participants' heterogeneities. In this context, further studies are needed to reveal the real effect of left DLPFC on risk decision making.

Gender also played a role in the participants' decisions in our experiment. The right anodal tDCS significantly changed the male participants' risk preferences in the loss frame but not the female ones'. Although it is believed that prefrontal cortex maturity occurs earlier in females than males (Powell, 2006; Cazzell et al., 2012), gender difference are rarely reported in neuroscientific studies due to small sample sizes. Cazzell et al. (2012) conducted strong bilateral brain activations on DLPFC in both gain and loss frames for female subjects and in gain frame for male subjects, while Lin et al. (2014) found that brain behaved similarly for both genders in risk decision making and Fecteau et al. (2007a) found no significant impact of gender on risk decision making after tDCS. It is hard to conclude whether the gender difference observed in this study is attributed to the heterogeneity of participants or some cognitive neural differences between the male and the female, which undoubtedly deserves further studies.

In our study, we found significant differences in right anodal and left cathodal tDCS conditions before and after the stimulation while no significant difference in the sham condition. However, there was no significant difference between right anodal or left cathodal tDCS condition and the sham condition either before or after the stimulation. This may be attributed to the fact that although the effect of tDCS significantly changed the participants' behaviors in a single condition, it was not strong enough to cause significant differences across conditions given the heterogeneity of participants. Nevertheless, the reliability of the results obtained in our study was toned down a bit in the context of this point and further evidences are needed to confirm these findings. Moreover, the clinical features of the participants were only requested as a self-declaration, which was insufficient for excluding any pathological profile of the sample. These should be the limitations of our study.

To conclude, our findings provide important information regarding the impact of tDCS on the risk preferences of healthy participants. The effects observed in our experiments compared with those of previous studies provide increased evidence of hemispheric and frame-dependent asymmetric effects. These findings may be helpful in elucidating the neural basis of risk preference in humans, especially regarding decisions making that may lead to gain or loss relative to the status quo. Future studies are needed to explore the neural changes associated with these neuromodulations using neuroimaging technologies.

4. Experimental procedures

4.1. Subjects

We recruited 100 healthy college students (64 females; mean age 21.3 years, ranging from 18 to 27 years) to participate in our experiment. All participants were right-handed and naïve to both tDCS and risk tasks. No history of psychiatric illness, neurological disorders or clinical impairments was reported by the participants. The participants were randomly assigned to one of five different tDCS conditions, which were defined as right anodal tDCS (n=20, 12 females), right cathodal tDCS (n=20, 11 females), left anodal tDCS (n=20, 13 females), left cathodal tDCS (n=20, 15 females) and sham stimulation (n=20, 13 females). The final payoff was a fixed show-up fee of 50 RMB Yuan (approximately 7.99 US dollars) plus the reward (or penalty) gained from the tasks. On average, the participants received 52.82 RMB Yuan (approximately 8.44 US dollars). Participants gave informed written consent before entering the experiment, which was approved by the Zhejiang University ethics committee. No participants reported adverse side effects related to pain on the scalp or headaches after the experiment.

4.2. Transcranial direct current stimulation (tDCS)

Transcranial direct current stimulation (tDCS) applied a weak direct current to the scalp via two rounded, saline-soaked surface sponge electrodes (35 cm^2). The current was constant, delivered using a battery-driven stimulator (Multichannel non-invasive wireless tDCS neurostimulator, Starlab, Barcelona, Spain), and controlled via a Bluetooth signal. It was adjusted to induce cortical excitability of the target area without causing any physiological damage to the participants. Various configurations of the current induced various effects on cortical excitability. Generally speaking, anodal stimulation enhances cortical excitability and cathodal stimulation inhibits cortical excitability (Nitsche and Paulus, 2000).

Participants were randomly assigned to one of the five single-blind tDCS conditions. The target site was the right DLPFC or the left DLPFC, and the control site was the parietal cortex because of its reasonable spatial and functional distance from the DLPFC, thus decreasing the possibility of stimulation or task interferences. For the right anodal stimulation, the anodal electrode was centered over the right F4 according to the international EEG 10–20 system, and the cathodal electrode was centered over the Pz. For the left anodal stimulation, the anodal electrode was centered over the left F3, and the cathodal electrode was also centered over the Pz (Fig. 3). For the right cathodal or left cathodal stimulation, the placements were reversed. The anodal electrode was centered over the Pz, and the cathodal electrode was centered over the F4 or F3 (Fig. 4). For the sham stimulation, the placements were chosen randomly from the above four modes. Table 1 provides the detailed description of each stimulation condition.

In the sham stimulation, the current stimulation duration was only 30 s. No current was delivered for the rest of the stimulation period, although the participants may have felt the initial itching and believed that they were receiving the stimulation. This method of sham stimulation is wildly used and has been shown to be reliable (Gandiga et al., 2006). The current was a constant 2 mA intensity with a 15-s of ramp up and down. The safety and efficiency of these stimulation parameters have been shown in previous studies.

4.3. Task and procedure

The risk-measurement table consisted of 35 choices (Table 2).

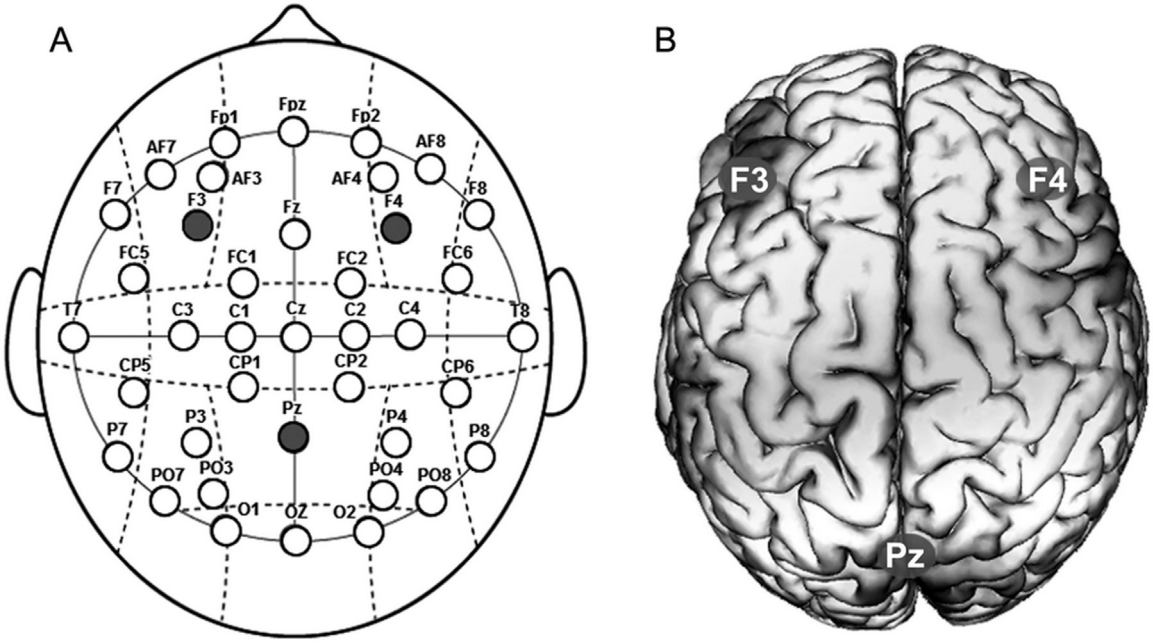

Fig. 3. Schematic of the electrode positions based on the EEG 10–20 system (A) and locations of the dorsolateral prefrontal cortex and the parietal cortex of the human brain (B).

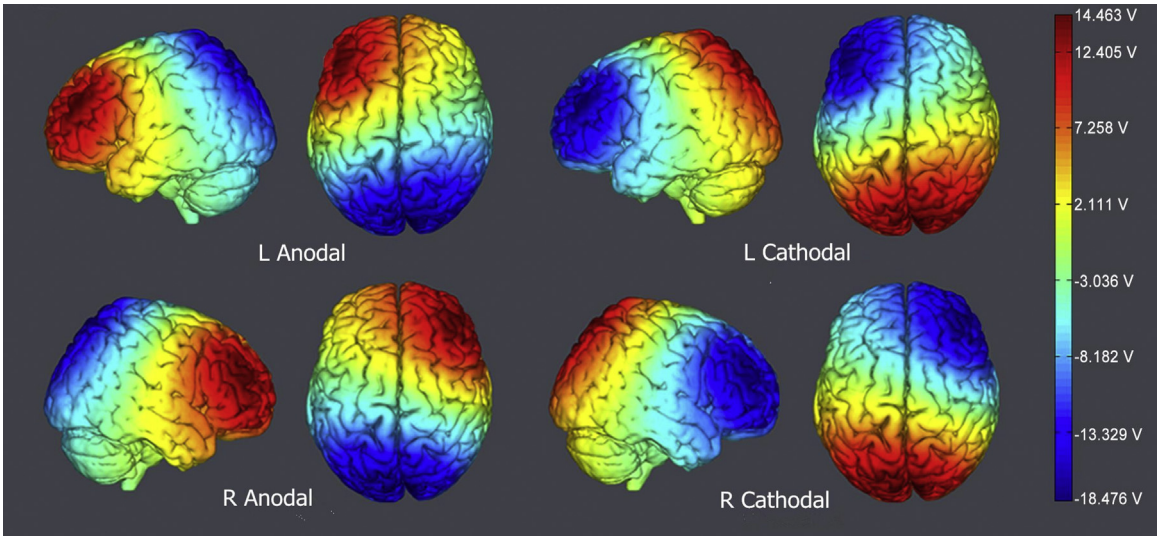

Fig. 4. The simulational activated patterns of human brain for the four active stimulations. The axis represents the range of voltage from −18.476 V to 14.463 V.

Table 1
The detailed description of each stimulation condition.

Stimulation condition	Sample size	Position of anodal electrode	Position of cathodal electrode
right anodal tDCS	n=20, 12 females	right F4	Pz
right cathodal tDCS	n=20, 11 females	Pz	right F4
left anodal tDCS	n=20, 13 females	left F3	Pz
left cathodal tDCS	n=20, 15 females	Pz	left F3
sham stimulation	n=20, 13 females	randomly chosen from the four configurations	

Table 2
The risk-measurement table.

Row No.	Option A			Option B		
	A_1	A_2	expected value	B_1	B_2	expected value
	Prob. 1/2	Prob. 1/2		Prob. 1/2	Prob. 1/2	
1	6	14	10	5	15	10
2	7	13	10	5	14	9.5
3	7	13	10	5	15	10
4	7	13	10	6	14	10
5	7	13	10	6	15	10.5
6	8	12	10	5	14	9.5
7	8	12	10	5	15	10
8	8	12	10	5	16	10.5
9	8	12	10	6	13	9.5
10	8	12	10	6	14	10
11	8	12	10	6	15	10.5
12	8	12	10	7	13	10
13	8	12	10	7	14	10.5
14	9	11	10	5	14	9.5
15	9	11	10	5	15	10
16	9	11	10	5	16	10.5
17	9	11	10	6	13	9.5
18	9	11	10	6	14	10
19	9	11	10	6	15	10.5
20	9	11	10	7	12	9.5
21	9	11	10	7	13	10
22	9	11	10	7	14	10.5
23	9	11	10	8	12	10
24	10	10	10	5	14	9.5
25	10	10	10	5	15	10
26	10	10	10	5	16	10.5
27	10	10	10	6	13	9.5
28	10	10	10	6	14	10
29	10	10	10	6	15	10.5
30	10	10	10	7	12	9.5
31	10	10	10	7	13	10
32	10	10	10	8	11	9.5
33	10	10	10	8	12	10
34	10	10	10	9	11	10
35	10	10	10	9	12	10.5

In each choice, participants chose between two options. Each option could have two realisations (A_1 or A_2 and B_1 or B_2) with an equal probability of 1/2. The expected values of the two options are the same or nearly the same over the 35 choices with different degrees of risk, which was designed to capture any mild change of the participants' risk preferences. Option A is safer (denoted as the "safe" option) with a constant expected value, whereas option B is riskier (denoted as the "risky" option) with expected values equal or close to Option A. The table was applied in two frames, gain and loss, thus there were a total of 70 choices in a task. For example, in the gain frame, if the participant chose option A in the first choice, then he/she was rewarded 6 or 14 RMB Yuan at a probability of 1/2. If he/she chose option B, then he/she was rewarded 5 or 15 RMB 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, so the participants were encouraged to earn as much as possible.

The task was run using the experimental software z-Tree (Fischbacher, 2007). The 70 choices of the two frames (gain and loss) were randomized and presented one by one. The computer calculated the rewards and penalties of the participant using a random program according to his/her choices. The experiment involved two tasks. After the participant finished the first task, the laboratory assistant placed a tDCS device on his/her head for stimulation and told him/her to rest and remain calm. After 15 min of stimulation, the participant was asked to complete the second task while the stimulation was continued for another 3 min (Fig. 5). Stimulation applied for 9–13 min is able to produce lasting effect for about an hour (Nitsche et al., 2008). However, as our task lasts for about 20–30 min, we started the tDCS before the task and performed it during the task like previous studies in order to insure the intensity and stability of the stimulation effect (Fecteau et al., 2007a, 2007b; Boggio et al., 2010).

The two tasks were made up of equivalent content, but the order of the choices was altered, and the positions of the two

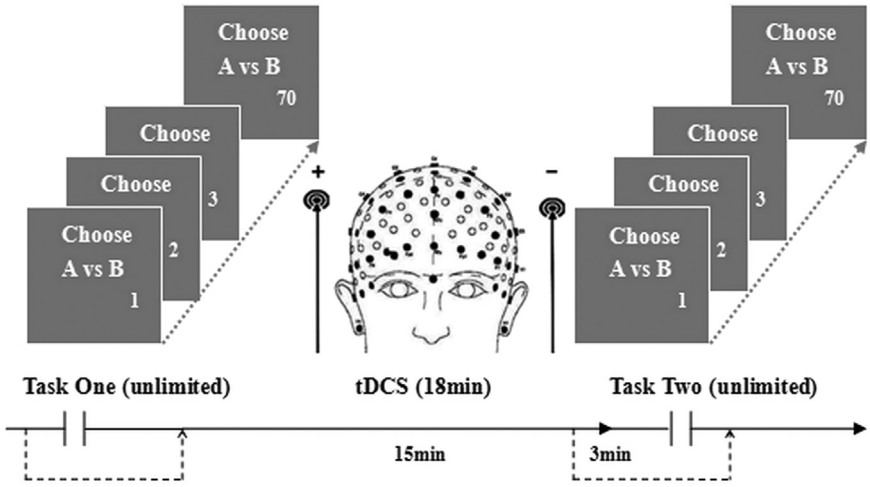

Fig. 5. Schematic representation of the experimental design. After 15 min of stimulation, each participant was asked to complete the second task while the stimulation was continued for another 3 min.

options were exchanged for some of the choices. After completing the second task, the participants were asked to complete a questionnaire before receiving their payment.

4.4. Data analysis

We used repeated measures ANOVA to analyze the number of safe options the participant chose and one-way ANOVA to analyze the self-assessment of risk preference of the participants. Post hoc tests were adjusted by Bonferroni correction. The critical level of significance was set at $p < 0.05$. All statistical tests were performed using SPSS 20 (SPSS Inc., Chicago, Illinois, USA).

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References

Andrews, S.C., Hoy, K.E., Enticott, P.G., Daskalakis, Z.J., Fitzgerald, P.B., 2011. Improving working memory: the effect of combining cognitive activity and anodal transcranial direct current stimulation to the left dorsolateral prefrontal cortex. Brain Stimul. 4 (2), 84–89.

Bembich, S., Clarici, A., Vecchiet, C., Baldassi, G., Cont, G., Demarini, S., 2014. Differences in time course activation of dorsolateral prefrontal cortex associated with low or high risk choices in a gambling task. Front. Hum. Neurosci. 8 (464), 10–3389.

Boggio, P.S., Campanhã, C., Valasek, C.A., Fecteau, S., Pascual-Leone, A., Fregni, F., 2010. Modulation of decision-making in a gambling task in older adults with transcranial direct current stimulation. Eur. J. Neurosci. 31 (3), 593–597.

Bolla, K.I., Eldreth, D.A., Matochik, J.A., Cadet, J.L., 2005. Neural substrates of faulty decision-making in abstinent marijuana users. Neuroimage 26 (2), 480–492.

Brickman, P., Coates, D., Janoff-Bulman, R., 1978. Lottery winners and accident victims: is happiness relative? J. Personal. Soc. Psychol. 36 (8), 917.

Burton, H., Abend, N.S., MacLeod, A.M., Sinclair, R.J., Snyder, A.Z., Raichle, M.E., 1999. Tactile attention tasks enhance activation in somatosensory regions of parietal cortex: a positron emission tomography study. Cereb. Cortex 9 (7), 662–674.

Cazzell, M., Li, L., Lin, Z.J., Patel, S.J., Liu, H., 2012. Comparison of neural correlates of risk decision making between genders: an exploratory fNIRS study of the Balloon Analogue Risk Task (BART). Neuroimage 62 (3), 1896–1911.

Chew, S.H., MacCrimmon, K.R., 1979. Alpha-nu Choice Theory: A Generalization of Expected Utility Theory. University of British Columbia, Vancouver, Canada.

Clark, L., Manes, F., Antoun, N., Sahakian, B.J., Robbins, T.W., 2003. The contributions of lesion laterality and lesion volume to decision-making impairment following frontal lobe damage. Neuropsychologia 41 (11), 1474–1483.

Colby, C.L., Goldberg, M.E., 1999. Space and attention in parietal cortex. Annu. Rev. Neurosci. 22 (1), 319–349.

Culham, J.C., Kanwisher, N.G., 2001. Neuroimaging of cognitive functions in human parietal cortex. Curr. Opin. Neurobiol. 11 (2), 157–163.

De Zubicaray, G.I., Andrew, C., Zelaya, F.O., Williams, S.C.R., Dumanoir, C., 2000. Motor response suppression and the prepotent tendency to respond: a parametric fMRI study. Neuropsychologia 38 (9), 1280–1291.

Ernst, M., Bolla, K., Mouratidis, M., Contoreggi, C., Matochik, J.A., Kurian, V., Cadet, J., Kimes, S.A., London, E.D., 2001. Decision-making in a risk-taking task: a PET study. Neuropsychopharmacology 26, 682–691.

Ersche, K.D., Fletcher, P.C., Lewis, S.J.G., Clark, L., Stocks-Gee, G., London, M., Deakin, J.B., Robbins, T.W., Sahakian, B.J., 2005. Abnormal frontal activations related to decision-making in current and former amphetamine and opiate dependent individuals. Psychopharmacology 180 (4), 612–623.

Fecteau, S., Knoch, D., Fregni, F., Sultani, N., Boggio, P., Pascual-Leone, A., 2007a. Diminishing risk-taking behavior by modulating activity in the prefrontal cortex: a direct current stimulation study. J. Neurosci. 27 (46), 12500–12505.

Fecteau, S., Pascual-Leone, A., Zald, D.H., Liguori, P., Théoret, H., Boggio, P.S., Fregni, F., 2007b. Activation of prefrontal cortex by transcranial direct current stimulation reduces appetite for risk during ambiguous decision making. J. Neurosci. 27 (23), 6212–6218.

Fellows, L.K., Farah, M.J., 2005. Different underlying impairments in decision-making following ventromedial and dorsolateral frontal lobe damage in humans. Cereb. Cortex 15 (1), 58–63.

Figner, B., Mackinlay, R.J., Wilkening, F., Weber, E.U., 2009. Affective and deliberative processes in risky choice: age differences in risk taking in the Columbia Card Task. J. Exp. Psychol. Learn. Mem. Cogn. 35 (3), 709.

Fischbacher, U., 2007. z-Tree: Zurich toolbox for ready-made economic experiments. Exp. Econ. 10 (2), 171–178.

Fox, P.T., Narayana, S., Tandon, N., Fox, S.P., Sandoval, H., Kochunov, P., Capaday, C., Lancaster, L., 2006. Intensity modulation of TMS induced cortical excitation: primary motor cortex. Hum. Brain Mapp. 27, 478–487.

Gandiga, P.C., Hummel, F.C., Cohen, L.G., 2006. Transcranial DC stimulation (tDCS): a tool for double-blind sham-controlled clinical studies in brain stimulation. Clin. Neurophysiol. 117 (4), 845–850.

Gul, F., 1991. A theory of disappointment aversion. Économ. J. Econom. Soc., 667–686.

Hasan, A., Misewitsch, K., Nitsche, M.A., Gruber, O., Padberg, F., Falkai, P., Wobrock, T., 2013. Impaired motor cortex responses in non-psychotic first-degree relatives of schizophrenia patients: a cathodal tDCS pilot study. Brain Stimul. 6 (5), 821–829.

Hollmann, M., Hellrung, L., Pleger, B., Schlögl, H., Kabisch, S., Stumvoll, M., Villringer, A., Horstmann, A., 2012. Neural correlates of the volitional regulation of the desire for food. Int. J. Obes. 36 (5), 648–655.

Holper, L., Wolf, M., Tobler, P.N., 2014. Comparison of functional near-infrared spectroscopy and electrodermal activity in assessing objective versus subjective risk during risky financial decisions. NeuroImage 84, 833–842.

Holt, C.A., Laury, S.K., 2002. Risk aversion and incentive effects. Am. Econ. Rev. 92 (5), 1644–1655.

Jacobson, L., Javitt, D.C., Lavidor, M., 2011. Activation of inhibition: diminishing impulsive behavior by direct current stimulation over the inferior frontal gyrus. J. Cogn. Neurosci. 23 (11), 3380–3387.

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

Kahneman, D., Tversky, A., 1979. Prospect theory: an analysis of decision under risk. Économ. J. Econom. Soc., 263–291.

Kahneman, D., Tversky, A., 1984. Choices, values, and frames. Am. Psychol. 39 (4), 341.

Kanwisher, N., Wojciulik, E., 2000. Visual attention: insights from brain imaging. Nat. Rev. Neurosci. 1 (2), 91–100.

Knoch, D., Gianotti, L.R., Pascual-Leone, A., Treyer, V., Regard, M., Hohmann, M., Brugger, P., 2006. Disruption of right prefrontal cortex by low-frequency

repetitive transcranial magnetic stimulation induces risk-taking behavior. J. Neurosci. 26 (24), 6469–6472.
Lichtenstein, S., Slovic, P., 1971. Reversals of preference between bids and choices in gambling decisions. J. Exp. Psychol. 89 (1), 46.
Lin, Z.J., Li, L., Cazzell, M., Liu, H., 2014. Atlas-guided volumetric diffuse optical tomography enhanced by generalized linear model analysis to image risk decision-making responses in young adults. Hum. Brain Mapp. 35 (8), 4249–4266.
Loomes, G., Sugden, R., 1986. Disappointment and dynamic consistency in choice under uncertainty. Rev. Econ. Stud. 53 (2), 271–282.
Manes, F., Sahakian, B., Clark, L., Rogers, R., Antoun, N., Aitken, M., Robbins, T., 2002. Decision-making processes following damage to the prefrontal cortex. Brain 125 (3), 624–639.
McFarlane, T., Pliner, P., 1997. Increasing willingness to taste novel foods: effects of nutrition and taste information. Appetite 28 (3), 227–238.
Menon, V., Adleman, N.E., White, C.D., Glover, G.H., Reiss, A.L., 2001. Error-related brain activation during a Go/NoGo response inhibition task. Hum. Brain Mapp. 12 (3), 131–143.
Nitsche, M.A., Paulus, W., 2000. Excitability changes induced in the human motor cortex by weak transcranial direct current stimulation. J. Physiol. 527 (3), 633–639.
Nitsche, M.A., Cohen, L.G., Wassermann, E.M., Priori, A., Lang, N., Antal, A., Pascual-Leone, A., 2008. Transcranial direct current stimulation: state of the art 2008. Brain Stimul. 1 (3), 206–223.
Powell, K., 2006. Neurodevelopment: how does the teenage brain work? Nature 442 (7105), 865–867.
Pripfl, J., Neumann, R., Köhler, U., Lamm, C., 2013. Effects of transcranial direct current stimulation on risky decision making are mediated by 'hot' and 'cold' decisions, personality, and hemisphere. Eur. J. Neurosci. 38 (12), 3778–3785.
Pugh, K.R., Shaywitz, B.A., Shaywitz, S.E., Fulbright, R.K., Byrd, D., Skudlarski, P., Lacadie, C., 1996. Auditory selective attention: an fMRI investigation. Neuroimage 4 (3), 159–173.
Rao, H., Korczykowski, M., Pluta, J., Hoang, A., Detre, J.A., 2008. Neural correlates of voluntary and involuntary risk taking in the human brain: an fMRI study of the Balloon Analog Risk Task (BART). Neuroimage 42 (2), 902–910.
Rogers, R.D., Owen, A.M., Middleton, H.C., Williams, E.J., Pickard, J.D., Sahakian, B.J., Robbins, T.W., 1999. Choosing between small, likely rewards and large, unlikely rewards activates inferior and orbital prefrontal cortex. J. Neurosci. 19 (20), 9029–9038.
Sellaro, R., Güroğlu, B., Nitsche, M.A., van den Wildenberg, W.P., Massaro, V., Durieux, J., Colzato, L.S., 2015. Increasing the role of belief information in moral judgments by stimulating the right temporoparietal junction. Neuropsychologia 77, 400–408.
Schonberg, T., Fox, C.R., Mumford, J.A., Congdon, E., Trepel, C., Poldrack, R.A., 2012. Decreasing ventromedial prefrontal cortex activity during sequential risk-taking: an fMRI investigation of the balloon analog risk task. Front. Neurosci. 6, 80.
Shafritz, K.M., Collins, S.H., Blumberg, H.P., 2006. The interaction of emotional and cognitive neural systems in emotionally guided response inhibition. Neuroimage 31 (1), 468–475.
Silvanto, J., Muggleton, N., Walsh, V., 2008. State-dependency in brain stimulation studies of perception and cognition. Trends Cogn. Sci. 12 (12), 447–454.
Simon, O., Mangin, J.F., Cohen, L., Le Bihan, D., Dehaene, S., 2002. Topographical layout of hand, eye, calculation, and language-related areas in the human parietal lobe. Neuron 33 (3), 475–487.
Starmer, C., 2000. Developments in non-expected utility theory: The hunt for a descriptive theory of choice under risk. J. Econ. Lit. 38 (2), 332–382.
Steinbeis, N., Bernhardt, B.C., Singer, T., 2012. Impulse control and underlying functions of the left DLPFC mediate age-related and age-independent individual differences in strategic social behavior. Neuron 73 (5), 1040–1051.
Thaler, R., 1985. Mental accounting and consumer choice. Mark. Sci. 4 (3), 199–214.
Tversky, A., Kahneman, D., 1991. Loss aversion in riskless choice: a reference-dependent model. Q. J. Econ., 1039–1061.
Verfaellie, M., Heilman, K.M., 1987. Response preparation and response inhibition after lesions of the medial frontal lobe. Arch. Neurol. 44 (12), 1265–1271.
Weber, M.J., Messing, S.B., Rao, H., Detre, J.A., Thompson-Schill, S.L., 2014. Prefrontal transcranial direct current stimulation alters activation and connectivity in cortical and subcortical reward systems: a tDCS-fMRI study. Hum. Brain Mapp. 35 (8), 3673–3686.
Wilkinson, N., Klaes, M., 2012. An Introduction to Behavioral Economics. Palgrave Macmillan, London, United Kingdom.
Yamamoto, D.J., Woo, C.W., Wager, T.D., Regner, M.F., Tanabe, J., 2015. Influence of dorsolateral prefrontal cortex and ventral striatum on risk avoidance in addiction: a mediation analysis. Drug Alcohol Depend. 149, 10–17.
Ye, H., Chen, S., Huang, D., Wang, S., Luo, J., 2015. Modulating activity in the prefrontal cortex changes decision-making for risky gains and losses: a transcranial direct current stimulation study. Behav. Brain Res. 286, 17–21.