Brain Research 1648 (2016) 325–332

Contents lists available at ScienceDirect

Brain Research

journal homepage: www.elsevier.com/locate/brainres

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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ARTICLE INFO

Article history:
Received 14 December 2015
Received in revised form
27 July 2016
Accepted 5 August 2016
Available online 6 August 2016

Keywords:
Dorsolateral prefrontal cortex
Gain frame
Loss frame
Risk preference
Unilateral transcranial direct current stimulation

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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http://dx.doi.org/10.1016/j.brainres.2016.08.007
0006-8993/

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