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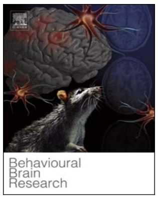

Modulating the activity of the dorsolateral prefrontal cortex by tDCS alters distributive decisions behind the veil of ignorance via risk preference

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ABSTRACT

Distributive justice concerns how individuals and societies distribute income in a just or equal manner. Previous studies from behavioural experiments have revealed that participants' distributive decisions vary according to the contexts of income distribution. Despite the long history of work on distributive behaviour, however, its psychological and neural underpinnings remain poorly understood. There many debates on whether and how the "weights" that are assigned to the individual payoffs (self-interest or risk aversion) and the payoff distribution of the others (social preference or fairness) in participants' objective functions, especially behind the veil of ignorance. In the present study, we aimed to separately analyse the effects of risk aversion and impartial social preferences in a veil of ignorance setting and to test the roles of social welfare and self-interest in behavioural distributive justice. We thus provide evidence of a causal link between the neural and behavioural results through the application of bilateral transcranial direct current stimulation (tDCS) over the dorsolateral prefrontal cortex (DLPFC) of our participants. The participants were found to distribute more income to the lowest income stratum and to make fairer distributions under the veil after receiving right anodal/less cathodal tDCS over DLPFC. In contrast, the participants distributed less income to the lowest income stratum and made more unfair distribution under the veil after receiving right cathodal/left anodal tDCS over DLPFC. Simultaneously, we elicited the participants' risk preferences and found that the participants who received right anodal/left cathodal tDCS over DLPFC were more conservative than the participants who received sham stimulation, whereas participants who received right cathodal/left anodal tDCS over DLPFC were more risky than the participants who received sham stimulation. These findings are fully consistent with a stimulation effect of the participants' distributive decisions under the veil of ignorance, and the participants' distributive proportions to the lowest income stratum under the veil of ignorance were strongly related to their risk preference. Therefore, the present study demonstrated that modulating the excitability of the DLPFC using tDCS altered the distributive decisions of the participants under the veil of ignorance, and this effect might be attributable to a change in the individuals' risk pReferences

1. Introduction

The formulation of public policy is significantly affected by the concepts of fairness and distributive justice. The issues surrounding distributive justice arise in the context of allocation problems and focus on the normative question of how the allocation should be performed. More generally, distributive justice concerns how individuals and societies allocate benefits or burdens in a just or moral manner, and it is central to social choice theory, moral psychology, and welfare economics. There are many empirical studies of issues that concern how a society or group allocates benefits or burdens in a just or moral manner through the use of three different approaches.

The veil of ignorance approach describes a decision making environment in which hypothetical rational individuals make decisions from an "original position" prior to entering society, without any knowledge of what their position in society might be or what individual attributes or circumstances they will face [1–3]. Therefore, choices made in the "original position" behind a "veil of ignorance" are made in a state of uncertainty. The goal of using the "veil" of imperfect information is to strip away any prejudices from history, status quo property rights, and institutions so that impartial decisions based on the formal principle of distributive justice can be made.

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The social-planner approach assumes that some outside judge or observer, a social planner, or some impersonal social welfare function, evaluates the equity of income distribution. The social welfare function lacks any personal involvement because the social-planner does not become a member of the society [4–7]. This procedure required him or her to genuinely behave as an umpire for income distribution. The social-planner compiled their orderings of income sets without having any stakes in the outcomes. The umpire himself or herself was excluded from any chance of receiving a payoff.

The known position approach sets an authority, leader, or member of the highest income stratum to make decisions for income distribution. He or she knows their prominent roles in this society before they make decisions. They had to determine both their own payoffs and the payoffs of their society members. He or she was called to the forefront and became visible to all other members to strengthen his or her social responsibility in the face of the whole public [8,9]. This approach establishes that a person's fairness motive in terms of maximizing a social welfare function of the payoff distribution is mixed with his or her selfish motive in terms of maximizing his or her own payoff.

In the veil of ignorance approach, income distributions share a striking similarity with lotteries [10,11]. However, for the evaluation of income distribution, it is often argued that individuals develop social responsibility and would thus, in contrast to lotteries, exhibit both a risk component and an altruism component in their behaviour [12]. The social-planner approach assumes that the planner maximizes the social welfare of an external society, and the lack of personal involvement within this context appears to induce a moderate degree of inequality aversion [6]. Within the known position approach, the authority's preferences determined the choice of the prevailing income distribution. The utility of a person is assumed to depend not only on his or her own monetary payoff but also on a specific social welfare function of the payoff distribution. Hence, results that were obtained on the known position approach support recent experimental evidence on social preferences [13–15].

Most of the above studies used non-incentivized questionnaires that ask participants to choose between lotteries representing different income distributions from the perspective of an uninvolved outside observer, i.e., from behind the veil of ignorance and a purely individual risk perspective [16,17]. In this study, we elicit preferences over income distribution in an incentive compatible manner and test how such preferences relate to some simple notions of income justice. We focused on "fixed pie" type problems in which the initial endowment of items is to be distributed into three different social stratums, and the participants are required to have a size order for the distributive income across different stratums.

To separately analyse the effects of risk aversion and impartial social preferences in a veil of ignorance setting, while test the roles of social welfare and self-interest in behavioural distributive justice, we utilized a controlled laboratory setting with three different distributive contexts that included behind a veil of ignorance, as a social-planner and with a known position.

In the first distributive context, the participants do not know which future position in society he (as well as other individuals) will be assigned to when deciding how to distribute the initial endowment across the different stratums. In the second distributive context, participants will not be assigned a future position in society and will receive a fixed payoff as a social-planner when deciding how to distribute the initial endowment across the different stratums. In the third distributive contexts, the participants know they will be assigned to the richest stratum in society when they decide how to distribute the initial endowment across the different stratums. In addition, we added a risk-measurement table to measure participants' risk preference in the experiment.

Despite the long history of work on distributive behaviour, its psychological and neural underpinnings remain poorly understood, are much of the work has centered on the intentions of decisions. The previous studies include many debates on whether and how the "weights" that are assigned to the individual payoffs (self-interest or risk aversion) and the payoff distributions of the others (social preference or fairness) in the participants' objective functions.

Essentially, there are obvious distinctions between the two different distributive intentions in neural substrates. A wide variety of decision-making studies indicate nearby paralimbic regions, especially the septal-subgenual area, in altruism and social attachment [18,19]. Additionally, the insular cortex is likely involved in the encoding of inequity, as recent work has demonstrated the important role of the insular cortex in fairness and empathy [20–22]. Another brain region that has also been repeatedly and reliably found to be implicated in tasks requiring the ability to represent and understand others' perspectives is the temporoparietal junction (TPJ) [23–25].

In contrast, clinical and neuroimaging studies have revealed the involvement of a distributed bihemispheric, corticosubcortical network in decision making [26,27]. The dorsolateral prefrontal cortex (DLPFC) is an important part of this network [28,29] and appears to be particularly involved in decision making when choices are ambiguous [27]. This connection is of particular relevance in light of the growing evidence that the DLPFC is involved in risky decisions and risk perception [30,31]. Studies of brain imaging explicitly indicate that risk decision making is associated with activity of the DLPFC [32,33].

Neuroimaging studies are useful for establishing correlations between brain activations and risk-taking processes, but they do not provide information regarding whether a given region is necessary to the resulting behaviour. Noninvasive brain stimulation techniques, such as repetitive transcranial magnetic stimulation (rTMS), Transcranial direct current stimulation (tDCS), allow for the study of the behavioural consequences of an externally induced brain activation or inactivation in healthy participants and thus enable the establishment of a causal relationship between the DLPFC and risk decision-making [34–37].

The main objective of the present paper is to provide neural evidence for intrinsic preference in different contexts of income distribution, and to test whether distributive decisions behind the veil of ignorance are driven by only social preferences or also by risk attitudes. We performed an income distribution experiment to investigate whether bilateral stimulation of the DLPFC (anodal stimulation of the right and cathodal stimulation of the left DLPFC or vice versa) would alter distributive decisions in different contexts, especially behind the veil of ignorance. By comparing the values of risk aversion in the risk-measurement table between different tDCS stimulations, a causal relationship between the excitability of the DLPFC and risk preference might be observed. Based on these results, we can infer that modulating the activity of DLPFC might alter the distributive decisions behind the veil of ignorance through their main driving force, i.e., individual risk attitude.

2. Materials and methods

2.1. Subjects

We recruited 75 healthy college students (37 females; mean age 19.8 years, ranging from 17 to 25 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 = 25, 12 females), right cathodal/left anodal tDCS (n = 25, 13 females) or sham stimulation (n = 25, 12 females). The final payoff was a fixed show-up fee of 20 RMB Yuan (approximately 3 US dollars) plus the reward gained from the distributive tasks. The participants received 51.9 RMB Yuan (approximately 7.8 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 concern-

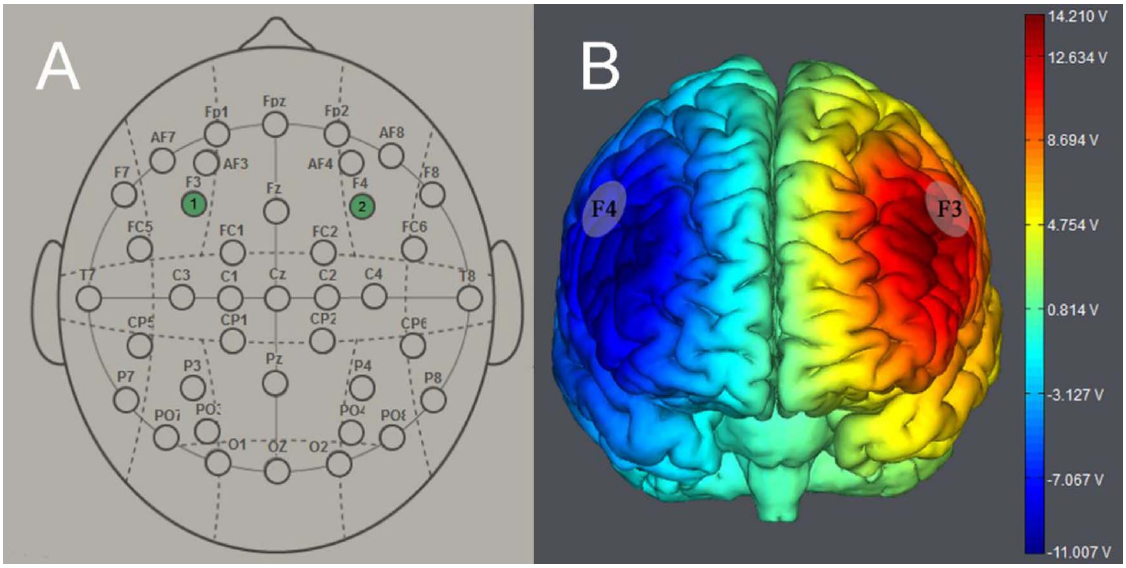


Fig. 1. Schematic drawing of electrode positions suited for tDCS of the dorsolateral prefrontal cortex. (A) Stimulation of the respective cortices according to the 10–20 system. (B) The electrode placement of right cathodal/left anodal stimulation. The anodal electrode was placed over F3 and the cathodal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

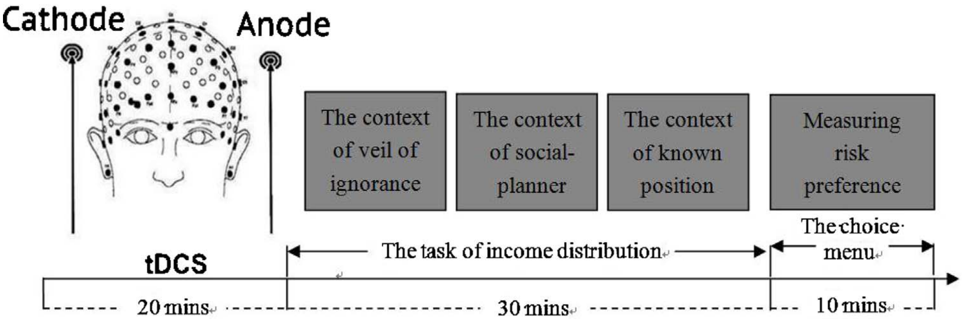


Fig. 2. Schematic representation of the experimental design. After 20 min of stimulation, each participant was then asked to complete the distribution task in the three types of distributive context and the choice menu.

ing 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 [38].

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 right cathodal/left anodal stimulation the placement was reversed. The anodal electrode was placed over F3 and the cathodal electrode was placed over F4 (Fig. 1A, 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 [39]. 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 [40].

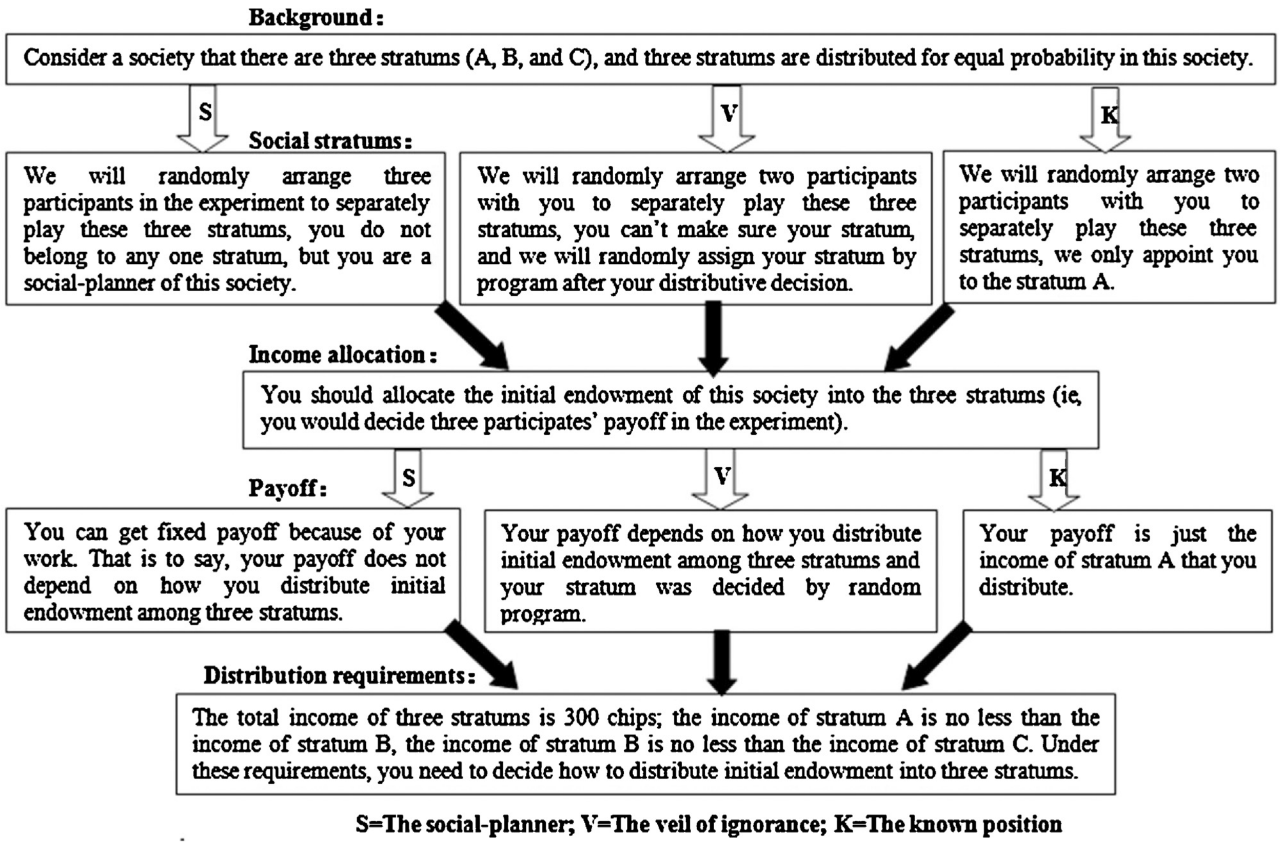
Before the decision making tasks, the laboratory assistant put a tDCS device on the participant's head for stimulation. After 20 min of stimulation, the tDCS device was taken off and the participant was then asked to complete distributive decision and risk-measurement table. The reason we chose a bifrontal electrode montage was to provide stimulation able to enhance the activity of one side of the DLPFC while simultaneously diminishing the other side.

2.3. Task and procedure

After the participants received tDCS stimulation for 20 min (bilateral stimulation, single-blinded, sham-controlled), they completed an income distributive task (the computer program for this task was written in visual C#).

The task consists of 30 stories, and each story includes a distributive context and a question about how to distribute an initial endowment among three stratums (Fig. 2). These stories involve three types of distributive context (social-planner, the veil of ignorance and known position) with ten levels of initial endowments (30, 60, 90, 120, 150, 180, 210, 240, 270, 300 chips), and 50 chips = 1 RMB Yuan. The participants could choose freely which amounts to give each of the three stratums in this task.

To avoid the order effect and income effect, we assigned three fixed orders (pseudo-random order) in which all stories were presented on the screen, and we balanced the numbers of people, participants' genders, and stimulation group across the three orders. The presentation order of the three different distributive contexts was also counterbalanced in the three orders among the participants receiving the three



Consider a society that there are three stratums (A, B, and C), and three stratums are distributed for equal probability in this society.

We will randomly arrange three participants in the experiment to separately play these three stratums, you do not belong to any one stratum, but you are a social-planner of this society.

We will randomly arrange two participants with you to separately play these three stratums, you can't make sure your stratum, and we will randomly assign your stratum by program after your distributive decision.

We will randomly arrange two participants with you to separately play these three stratums, we only appoint you to the stratum A.

You should allocate the initial endowment of this society into the three stratums (ie, you would decide three participates' payoff in the experiment).

You can get fixed payoff because of your work. That is to say, your payoff does not depend on how you distribute initial endowment among three stratums.

Your payoff depends on how you distribute initial endowment among three stratums and your stratum was decided by random program.

Your payoff is just the income of stratum A that you distribute.

The total income of three stratums is 300 chips; the income of stratum A is no less than the income of stratum B, the income of stratum B is no less than the income of stratum C. Under these requirements, you need to decide how to distribute initial endowment into three stratums.

Fig. 3. A story within the context of social-planner, veil of ignorance and known position presenting on the computer screen.

different stimulations. The trails were shown in fixed sequence to insure that the behaviors of the participants receiving different stimulations were completely comparable. However, within each pseudo-random order, the sequence of the contexts and the chips were counter-balanced with no obvious rules which may influence the expectations or behaviors of the participants. These stories were presented one by one, and participants made distributive decisions by computers (Fig. 3).

The participants were given 30 min to complete the task of income distribution. After the participants completed the distributive task, they were asked to complete a choice menu in 10 min and a questionnaire before finally receiving their payment.

We used the risk-measurement table 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 [41], consists of 16 choices (Table 1). In each choice, participants 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:

Table 1
The risk-measurement table.

Row No.	Option A		Option B		a^*	Risk Aversion
	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

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

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:

Table 2
The mean and SD of distributive amounts across contexts and chips in the sham group.

Chips	Contexts	The veil of ignorance			The social-planner			The known position		
	Stratums	A	B	C	A	B	C	A	B	C
30	Mean	12	10	8	12.8	10	7.2	22	4.8	3.2
	SD	4.08	0	4.08	4.58	0	4.58	9.13	5.10	4.76
60	Mean	26.8	19.2	14	24.4	20	15.6	45.2	9.2	5.6
	SD	7.48	2.77	6.45	5.07	0	5.07	14.47	8.62	7.12
90	Mean	36.4	29.6	24	36	29.6	24.4	56.4	19.2	14.4
	SD	7.57	2	7.07	9.13	2	8.21	20.99	11.87	10.03
120	Mean	51.2	39.6	29.2	48.4	39.2	32.4	84.4	21.6	14
	SD	9.71	2	8.62	11.79	4.93	9.26	28.59	17	12.91
150	Mean	60	48.8	41.2	60	50.4	39.6	110.4	22.4	17.2
	SD	12.25	3.32	10.13	11.18	4.55	11.36	38.24	21.27	17.68
180	Mean	71.2	58.4	50.4	69.2	59.6	51.2	131.2	27.2	21.6
	SD	13.64	3.74	10.98	13.52	2	12.36	47.20	25.90	21.92
210	Mean	82.4	68	59.6	81.2	68	60.8	147.2	36	26.8
	SD	17.39	5	13.38	15.09	5	11.15	49.88	28.43	22.68
240	Mean	97.6	80.4	62	92.8	79.2	68	170	40	30
	SD	15.08	4.55	15.55	18.82	6.40	15	58.24	32.91	26.46
270	Mean	106	88.4	75.6	107.2	88	74.8	198.8	40	31.2
	SD	16.33	5.54	14.17	26.85	8.66	21.63	70.79	39.48	32.32
300	Mean	117.2	98.4	84.4	115.6	99.6	84.8	221.2	43.6	35.2
	SD	21.51	4.73	18.73	23.47	4.55	20.64	78.97	43.67	36.41
Total	Mean	66.08	54.08	44.84	64.76	54.36	45.88	118.7	26.4	19.92
	SD	35.12	29.90	25.94	34.81	29.84	26.22	67.00	13.38	10.90

$$Weight_i = \frac{a_i^*}{\sum_{i=1}^{16} a_i^*}$$

The weighted value of the choices appears to be a reasonable index of the participant's degree of risk aversion.

2.4. Data analysis

We first focused on comparing the distributive decisions of the participants across the different distributive contexts in the sham group, and we hoped for the result that the participants' distributive decisions depended on the distributive context. To test the causal relationship between the activity of DLPFC and participants' distributive decisions, we investigated the distributive decisions across the three contexts in the different stimulation group, especially behind the veil of ignorance. We further measured the participants' risk preferences in the different stimulation group and analyzed the correlation between the participants' risk preferences and their distributive decisions to the stratum of the lowest income under the veil of ignorance to demonstrate the role of the participants' risk attitudes in distributive decisions under the veil of ignorance. Finally, we also studied the time of participants taking in distributive decisions across the three contexts in the different stimulation group. Additionally, we used the participants' distributive incomes to the three stratums and the Gini coefficient (a method measuring distributive fairness in economics) as data to represent the participants' distributive decisions. The higher the value of Gene coefficient is, the more unfair our society is.

The Gini coefficient is usually defined mathematically based on the Lorenz curve, which plots the proportion of the total income of the population (y axis) that is cumulatively earned by the bottom x% of the population. An alternative approach would be to consider the Gini coefficient as half of the relative mean absolute difference, which is a mathematical equivalence [42]. The mean absolute difference is the average absolute difference of all pairs of items of the population, and the relative mean absolute difference is the mean absolute difference divided by the average, to normalise for scale. If x_i is the wealth or income of person *i*, and there are n persons, then the Gini coefficient *G* is given by:

$$G = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} |x_i - x_j|}{2\sum_{i=1}^{n} \sum_{j=1}^{n} x_j}$$

Statistical analyses were performed using SPSS statistical software (version 20).

3. Results

3.1. The sham group

First, we tested whether there was any significant difference in participants' distributive decisions across contexts in the sham group. The distributive amounts to stratum C (the lowest income stratum) across three contexts in the sham group were analyzed with analyses of variance (ANOVAs) with contexts (the social-planner, the veil of ignorance contexts vs. the known position) as a between-subjects factor. There was a significant main effect of context ($F_{(1,748)} = 492.072$, $p < 0.001$, $\eta_p^2 = 0.307$). Post-hoc analyses (Bonferroni) revealed that the participants' distributive incomes to stratum C with the context of known position was significantly lower than those obtained for the context of social-planner ($t_{(499)} = -17.039$, $p < 0.01$, Cohen's $d = 1.500$) and the context of veil of ignorance ($t_{(499)} = -17.664$, $p < 0.01$, Cohen's $d = 1.463$). No significant difference between the context of social-planner and the context of veil of ignorance was observed ($t_{(499)} = -0.625$, $p = 0.5642$, Cohen's $d = 0.056$). We have shown the mean and SD of distributive amounts across contexts and chips in the sham group (Table 2).

In addition, we also were analyzed the Gini coefficients across three contexts in the sham group by ANOVAs with contexts (the social-planner, the veil of ignorance contexts vs. the known position) as a between-subjects factor. There was a significant main effect of context ($F_{(1,748)} = 733.602$, $p < 0.001$, $\eta_p^2 = 0.398$). Post-hoc analyses (Bonferroni) revealed that the Gini coefficients of participants' distributive decisions with the context of known position was significantly higher than those obtained for the context of social-planner ($t_{(499)} = -19.868$, $p < 0.01$, Cohen's $d = -1.893$) and the context of veil of ignorance ($t_{(499)} =$ -18.001, $p < 0.01$, Cohen's $d = -1.829$). No significant difference between the context of social-planner and the context of veil of ignorance was observed ($t_{(499)} = 2.128$, $p < 0.01$, Cohen's $d = 0.164$).

These results clearly indicated that the participants' distributive decisions depended on the given context, and self-interest was an important factor in the distributions the participants knew their positions.

3.2. The stimulation effect

We then performed two-way ANOVA for distributive proportions to stratum C with the stimulation type (right anodal/left cathodal tDCS, right cathodal/left anodal tDCS, sham stimulation) as a between-subject factor and the context (social-planner, veil of ignorance, known position) as a within-subject factor. There were significant main effects of stimulation type ($F_{(2,747)} = 23.156$, $p < 0.01$, $\eta_p^2 = 0.320$) and context ($F_{(2,747)} = 504.564$, $p = 0.016$, $\eta_p^2 = 0.510$). More importantly, we found a significant interactive effect of type and context ($F_{(4,745)} = 2.614$, $p = 0.016$, $\eta_p^2 = 0.246$). Post hoc analyses (Bonferroni) showed that the participants' distributive proportion to stratum C under the veil of ignorance after receiving right cathodal/left anodal tDCS over DLPFC was lower than that after receiving sham stimulation ($t_{(499)} = -4.877$, $p < 0.01$, Cohen's $d = 0.436$). This finding indicates that restraining the activity of the right DLPFC and enhancing the activity of left DLFPC made the participants riskier and made them less worried about being in the lowest income stratum under the veil of ignorance.

To further study participants' distributive decisions across different stimulation groups under the veil of ignorance, we ran a repeated measures ANOVA on the participants' distributive proportion to stratum C under the veil of ignorance, with the initial endowments (30, 60, 90, 120, 150, 180, 210, 240, 270, 300 chips) as a within-subject factor and the stimulation type (right anodal/left cathodal tDCS, right cathodal/left anodal tDCS or sham stimulation) as a between-subject factor. We found significant effects of the initial endowments ($F_{(2,747)} = 7.987$, $p < 0.01$, $\eta_p^2 = 0.512$) and stimulation type ($F_{(2,747)} = 9.266$, $p < 0.01$, $\eta_p^2 = 0.587$). Moreover, some significant results were observed by comparing the participants' distributive proportions to stratum C in the active stimulation and sham stimulation conditions across various initial endowments. The participants' distributive proportion to stratum C under the veil of ignorance after receiving right cathodal/left anodal tDCS over DLPFC was lower than that after the receiving sham stimulation when the initial endowments were 30 chips ($t_{(49)} = -2.155$, $p = 0.035$, Cohen's $d = -0.610$), 60 chips ($t_{(49)} = -2.621$, $p = 0.011$, Cohen's $d = -0.741$), 90 chips ($t_{(49)} = -2.826$, $p = 0.006$, Cohen's $d = -0.800$), and 180 chips ($t_{(49)} = -2.319$, $p = 0.023$, Cohen's $d = -0.656$). On the other hand, the distributive proportion of participants who receiving right anodal/left cathodal tDCS over DLPFC was higher than that after receiving sham stimulation when the initial endowments were 270 chips ($t_{(49)} = 2.043$, $p = 0.045$, Cohen's $d = 0.578$) and 300 chips ($t_{(49)} = 2.201$, $p = 0.031$, Cohen's $d = 0.623$). These results revealed that the effect of active stimulation on distributive decisions depended on the initial endowment (Fig. 4). The participants were riskier and distributed less income to the lowest income stratum under the veil after receiving right cathodal/left anodal tDCS over DLPFC when the initial endowment was relatively low. In contrast, the participants were more conservative and distributed more income to the lowest income stratum under the veil after receiving right anodal/less cathodal tDCS over DLPFC when the initial endowment was relatively high.

In addition to the distributive proportion to the lowest income stratum, we also used the Gini coefficient to examine the participants' equity-efficiency trade-offs in the income distributions (Table 3).

Repeated measures ANOVA on the Gini coefficient of income distribution was executed, with the initial endowments (30, 60, 90, 120, 150, 180, 210, 240, 270, 300 chips) as a within-subject factor and the stimulation type (right anodal/left cathodal tDCS, right cathodal/left anodal tDCS or sham stimulation) as a between-subject factor. A significant influence of initial endowments was observed ($F_{(2,747)} = 6.967$, $p = 0.002$, $\eta_p^2 = 0.403$). There was also a significant main effect of tDCS stimulation ($F_{(2,747)} = 5.957$, $p = 0.004$, $\eta_p^2 = 0.342$). There was no significant interactive effect on the Gini coefficient between the initial endowment and the stimulation type in the contexts of social-planner ($F_{(4,245)} = 1.110$, $p = 0.357$, $\eta_p^2 = 0.086$) and known position ($F_{(4,245)} = 0.871$, $p = 0.536$, $\eta_p^2 = 0.035$). No significant difference between the active stimulation and sham stimulation conditions in these two contexts across the various initial endowments was found. However, the interaction of the initial endowment and the stimulation type within the context of veil had a significant effect ($F_{(4,245)} = 2.837$, $p = 0.01$, $\eta_p^2 = 0.289$) on the Gini coefficient. Post hoc analyses (Bonferroni) showed that the value of Gini coefficient under the veil of ignorance in the right anodal/left cathodal tDCS were significantly lower than those obtained in the sham group ($t_{(49)} = -2.501$, $p = 0.006$, Cohen's $d = -0.707$) and the value of Gini coefficient under the veil of ignorance in the right cathodal/left anodal tDCS were significantly higher than those obtained in the sham group ($t_{(49)} = 5.232$, $p = 0.003$, Cohen's $d = 1.480$) (Fig. 5).

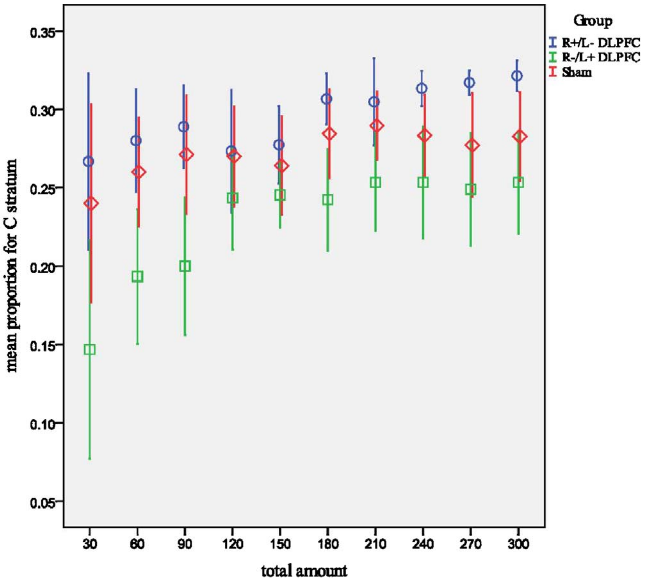


Fig. 4. Mean proportions for the stratum C under the veil of ignorance across the three stimulation group and various initial endowments.

3.3. The participants' risk preference

We introduced participants' risk preferences to analyse the distributive decisions. We found that the participants' distributive proportions to stratum C within the contexts of social planner and known position were not related to their risk preferences (Spearman test: the social-planner, $r_{(73)} = 0.1562$, $p = 0.3578$, Cohen's $d = 0.3162$; the known position, $r_{(73)} = 0.0425$, $p = 0.6321$, Cohen's $d = 0.0850$). However, the participants' distributive proportions to stratum C under the veil of ignorance was strongly related to their risk preferences, which were measured with the choice menu (Spearman test: right anodal/left cathodal, $r_{(23)} = 0.4296$, $p < 0.01$, Cohen's $d = 0.9514$; right cathodal/left anodal, $r_{(23)} = 0.3387$, $p < 0.01$, Cohen's $d = 0.7199$; sham, $r_{(23)} = 0.4384$, $p < 0.01$, Cohen's $d = 0.9755$).

The result revealed that the participants who allocated more income to stratum C tended to exhibit more risk aversion under the veil of ignorance and such an observation was robust in all of the three tDCS groups (Fig. 6A). There is a flatter increasing trend of distributive proportions to stratum C with the increase of risk aversion in the line of best fit for right anodal/left cathodal and right cathodal/left anodal

Table 3
The mean and SD of Gini coefficient across contexts and stimulation types.

Context	R Anodal/L Cathodal		R Cathodal/L Anodal		Sham	
	Mean	SD	Mean	SD	Mean	SD
The veil of ignorance	0.2459	0.05684	0.2970	0.08230	0.2651	0.06227
The social-planner	0.2625	0.05565	0.2790	0.06860	0.2704	0.05952
The known position	0.4573	0.1656	0.4531	0.1664	0.4676	0.1683

groups comparing to those for sham group (see Fig. 6 for scatter plots and line of best fits). The quadratic curve of best fits may indicate that the relationship between distributive proportions to stratum C and risk aversion seems tighter among participants with higher risk aversion in the sham group than those in the right anodal/left cathodal and right cathodal/left anodal groups (Fig. 6B).

We also compared the participants' risk preference between the active stimulation and sham stimulation conditions. The risk coefficient of the participants who received right anodal/left cathodal tDCS over DLPFC was lower than that of the participants who received sham stimulation (Mann-Whitney test: $z_{(48)} = -2.995$, $t = 0.0027$, $\eta^2 = 0.179$), and the risk coefficient of participants who received right cathodal/left anodal tDCS over DLPFC was higher than participants who received sham stimulation (Mann-Whitney test: $z_{(48)} = 2.540$, $t = 0.0111$, $\eta^2 = 0.129$). These results indicated that tDCS to the DLPFC altered the risk preferences of the participants (i.e., the participants were more conservative after receiving right anodal/left cathodal tDCS, and participants were riskier after receiving right cathodal/left anodal tDCS) and led to relative changes in their distributive decisions under the veil of ignorance.

3.4. The decision time data

Last, we also examined the decision time. The times the participants required to make distributive decisions across the three contexts in the sham group were investigated. The time that the participants required to make distributive decisions under the veil of ignorance was found to be longer than the times in the other two contexts (ANOVA, LSD post hoc test: social-planner, $t_{(499)} = 7.356$, $p < 0.01$, Cohen's $d = 0.623$; known position, $t_{(499)} = 5.214$, $p = 0.007$, Cohen's $d = 0.389$). A two-way ANOVA was applied to the times the participants required to make distributive decisions with stimulation type (right anodal/left cathodal tDCS, right cathodal/left anodal tDCS, sham stimulation) and context (social-planner, veil of ignorance, known position) as factors. Significant main effects of stimulation ($F_{(2,747)} = 12.537$, $p < 0.01$, $\eta_p^2 = 0.713$) and context ($F_{(2,747)} = 16.3$, $p < 0.01$, $\eta_p^2 = 0.846$) and

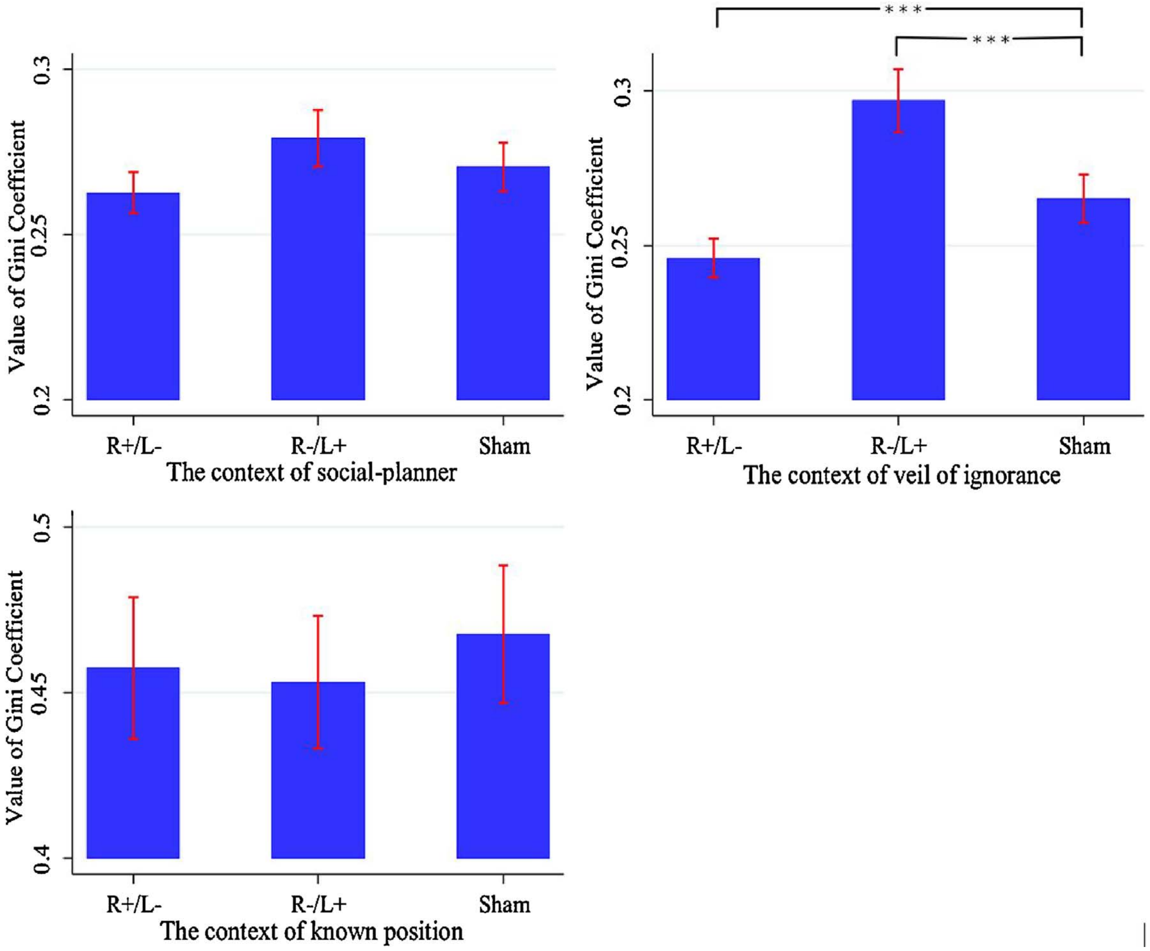


Fig. 5. Mean Gini coefficients of participants' distribution across different contexts and stimulation types over DLPFC. Error bars indicate 95% confidence intervals. Asterisks indicate statistical significance of difference between treatments.

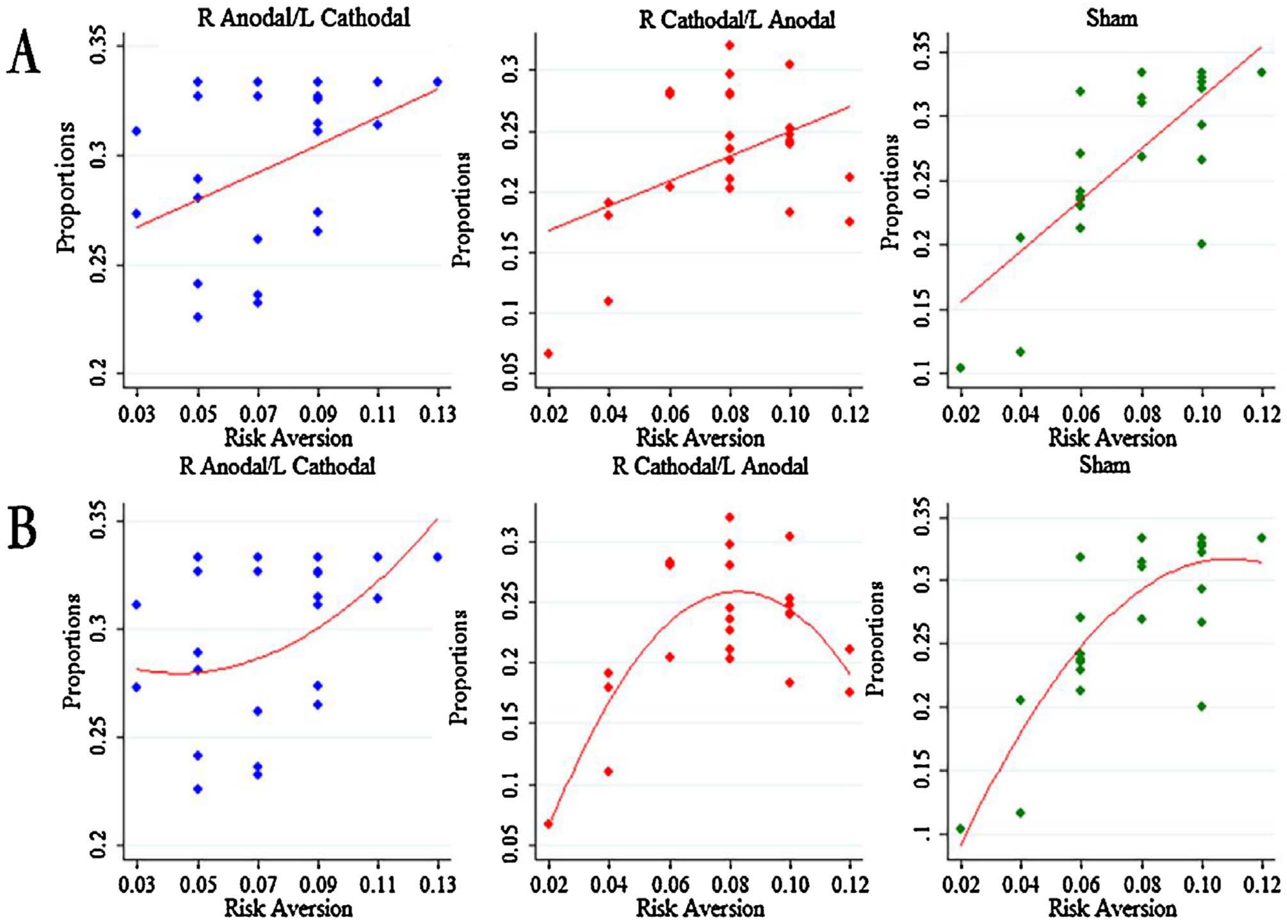


Fig. 6. Scatter plots of participants under the veil of ignorance. The horizontal axis represents the participants' risk aversion and the vertical axis represents the distributive proportions to stratum C. (A) The line of best fits for scatter plots of participants receiving different stimulations. (B) The quadratic curve of best fits for scatter plots of participants receiving different stimulations.

an interactive effect ($F_{(4,745)} = 7.227$, $p < 0.01$, $\eta_p^2 = 0.486$) were found. Analysis indicated that, under the veil of ignorance, the participants in the right anodal/left cathodal stimulation group required less time than those in the sham stimulation group ($t_{(499)} = -3.448$, $p < 0.01$, Cohen's $d = -0.308$), and the participants in the right cathodal/left anodal stimulation group required more time than those in the sham stimulation group ($t_{(499)} = 2.050$, $p = 0.040$, Cohen's $d = 0.183$).

4. Discussion

Many previous studies from different fields have discussed the issues of income distribution justice and the factors that influence individuals' distributive decisions [2,5,7]. These studies focused on how people solve equity-efficiency trade-offs in income distribution [3,6]. Such redistribution choices might be governed by self-interest (risk aversion) or social preference (inequality aversion) [8,9]). However, evidence is lacking in neuroscience regarding the link between distributive behaviour and the regions of the brain that are possibly related to preference.

The present research complements these studies with tDCS by providing a causal relationship between distributive decisions across various social contexts and the activities of the DLPFC. In addition to the brain stimulation results, we also investigated the participants' behavioural data and the time required to make distributive decisions in this distributive experiment to present a comprehensive theory about the roles of risk attitudes and social preference in distributive decisions in three different distributive contexts, especially behind the veil of ignorance.

According to the behavioural data from the participants in the sham group across the three contexts, we found a context dependence of the distributive decisions, i.e., the participants distributive income to the highest income stratum in the known position context was significantly greater than those in the other two contexts, and participants' distributive income to the midst and lowest income stratum in the known position context is significant lower than those in the other two contexts. Additionally, the Gini coefficients for the distribution incomes in the social-planner and veil of ignorance contexts were both lower than that of the context of known position. However, there was no significant difference in the participants' distributive decisions (including the participants' distributive income to the three income stratums and the Gini coefficients) between the contexts of social-planner and the veil of ignorance.

Consistent with prior distributive justice studies, these results demonstrated that the individuals displayed remarkable self-interest, and these decisions may be viewed as a posteriori rationalizations when the positions were known [43]. In the social-planner and the veil of ignorance contexts, the individuals tended to make more equal distributions among the three social stratums. The participants in the social-planner context decided on only the other participants' payoffs without being paid themselves [7]. Hence, our experimental results revealed the subjects' social preferences for the equal income distribution. Our results also demonstrated that the participants under the veil of ignorance preferred the distribution that maximized the well-being of the least well-off [44]. However, the behavioural data were still unable to confirm whether participants' equal distribution decisions in this context were the result of risk aversion or impartial social pReferences

Based on the above behavioural results, we provided further neural evidence regarding distributive decisions behind the veil of ignorance. First, we found that the participants allocated less income to the lowest income stratum under the veil when the activity of right DLFPC was restrained and the activity of left DLFPC was improved. Regarding the effect of the initial endowment, we acquired more detailed findings in that the participants allocated less income to the lowest income stratum under the veil after receiving right cathodal/left anodal tDCS over DLPFC when the initial endowment was relatively low. On the contrary, participants allocated more income to the lowest income stratum under the veil after receiving right anodal/less cathodal tDCS over DLPFC when the initial endowment was relatively high.

Functional magnetic resonance imaging studies and functional near-infrared spectroscopy of the brain have revealed evidence of a relationship between risk preference and DLPFC activity [33,45]. Using brain stimulation technologies, researchers particularly found that participants with right anodal/left cathodal stimulation over DLPFC chose low-risk prospects more often compared with participants with sham stimulation [36,37], and participants receiving right cathodal/left anodal tDCS chose high-risk prospects more often compared with participants receiving sham stimulation [22,25].

Together, the findings of these previous studies and our findings about the distributive decisions of participants receiving tDCS seem to indicate that the alterations of the risk preferences of the participants after the receipt of tDCS to DLPFC led to alter their distributive decisions under the veil of ignorance. Specifically, the participants were be riskier after receiving right cathodal/left anodal tDCS over DLPFC, which made them less concerned that they would be in the lowest income stratum under the veil of ignorance. However, the participants were be more conservative after receiving right anodal/left cathodal tDCS over DLPFC, which made them more concerned that they would be in the lowest income stratum under the veil of ignorance.

Additionally, we also observed an asymmetric effect of bilateral stimulation over the DLPFC on the participants' distributive income to the lowest income stratum under the veil of ignorance in terms of the value of the initial endowments. Enhancing the activity of the right DLPFC and restraining the activity of left DLPFC significantly increased the distributive income to the lowest stratum compared with the sham stimulation when the initial endowment was relatively high, whereas restraining the activity of the right DLPFC and enhancing the activity of left DLPFC decreased the distributive income to the lowest stratum when the initial endowment was relatively low.

The asymmetric results of the bilateral stimulation might be associated with the incentive effect of risk aversion. Previous experimental studies have reported that risk attitudes are affected by large changes in payoffs, typically decreasing absolute risk aversion over this range of payoffs from several dollars to several hundred dollars [41,46]. Based on these studies, we inferred that the participants tended to be more conservative when the initial endowment was relatively high and were thus less risky in distributive decision and therefore significantly increased the distributive income to the lowest stratum under the veil after receiving right anodal/less cathodal tDCS over DLPFC. In contrast, the participants tended to be more risky when the initial endowment was relatively low and were less conservative in distributive decision; therefore, they significantly decreased the distributive income to the lowest stratum under the veil after receiving right cathodal/left anodal tDCS over DLPFC.

We also provided more evidence about stimulation effect on Gini coefficients. We found that the value of Gini coefficient under the veil of ignorance in the right anodal/left cathodal tDCS were significantly lower than those obtained in the sham group and the value of Gini coefficient under the veil of ignorance in the right cathodal/left anodal tDCS were significantly higher than those obtained in the sham group. These findings means that the participants made more equal distribution under the veil of ignorance after receiving the right anodal/left cathodal tDCS and the participants made less equal distribution under the veil of ignorance after receiving the right cathodal/left anodal tDCS. However, previous neuroscience studies have demonstrated that septal-subgenual area, insular cortex and TPJ activations are associated with social preference, including altruism and fairness, and the TPJ is particularly recruited when subjects face trade-offs between economic self-interest and other people's interests [24,47]. According to these studies, individuals' social preference should not have been changed after receiving tDCS over the DLPFC. Therefore, we might rule out the role of social preference and restate the important role of risk attitude in distributive decision behind the veil of ignorance.

We directly elicited participants' risk preference with a risk-measurement table to further verify the role of risk attitude in distributive decisions behind the veil of ignorance. Powerful evidence indicated that the participants' distributive proportions to the lowest income stratum under the veil of ignorance were strongly related to their risk preferences. This finding suggests that the participants' equal distributions under the veil of ignorance were derived from their risk preference. More importantly, we observed a significant stimulation effect on risk preferences of the participants. The participants who received right anodal/left cathodal tDCS over DLPFC were more conservative than the participants who received sham stimulation, and participants who received right cathodal/left anodal tDCS over DLPFC were riskier than the participants who received sham stimulation. These findings are fully consistent with the stimulation effect on the participants' distributive decisions under the veil of ignorance. Therefore, the present study demonstrated that modulating the excitability of the DLPFC might alter participants' distributive decisions under the veil of ignorance through the main driving force of these decisions, i.e., risk preference.

The data regarding the distributive decision times provides us with some supplementary evidence supporting the main conclusions. The time the participants required to make the distributive decisions under the veil of ignorance was the longest among the three contexts. Compared with the other two contexts, the context of the veil involved more trade-offs of equity-efficiency in income distributions because of the risk factor being considered by the participants and thus made the distributive decisions in the veil of ignorance context more difficult. We also found that right anodal/left cathodal stimulation to DLPFC decreased the time required for the distributive decisions under the veil of ignorance, whereas right cathodal/left anodal to DLPFC increased the time required for the distributive decisions under the veil of ignorance. It was expected that the participants receiving right anodal/left cathodal stimulation to DLPFC would be more conservative and would thus more easily chose the equal income distribution. On the contrast, the participants receiving right cathodal/left anodal stimulation to DLPFC were riskier, and thus experienced more conflict between the equal distribution and risky distribution.

In this study, we provided causal evidence regarding the function of the DLPFC in income distributive decisions across various contexts and revealed that activating this neural region can alter the participants' distributive decisions under the veil of ignorance, but no significant influence on the participants' distributive decisions in the social-planner and known position contexts were found. Our observations also indicate that participants' risk preference is closely correlated with their distributive decisions under the veil of ignorance; thus, modulating the activity of the DLPFC can change participants' distributive decisions by altering their risk pReferences

One limitation of the current study is that although our findings regarding the effect of stimulation over the DLPFC on risk preference were consistent with previous findings, the potential neural mechanism by which the specific brain area influences distributive decisions by altering risk preference remains to be revealed and discussed. Further brain imaging studies may focus on the dynamic activation of the DLPFC while participants make distributive decisions across various contexts. Another option is to modulate the activities of other relative brain regions (e.g. TPJ) to explore whether participants' distributive decisions are changed, which would provide more information about intrinsic preferences related to distributive decisions across different contexts. A deficiency of our study is that we cannot determine if the impact on distributive decisions and risk preference are 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. There have been numerous studies showing that the role of dlPFC laterality in depression and anxiety [48,49]. It might be interesting to study whether the current findings can be interpreted in the light of this affective model of DLPFC laterality.

5. Conclusion

To conclude, our experiment demonstrated that modulating the excitability of the DLPFC using tDCS altered the distributive decisions of the participants under the veil of ignorance, and this effect might be attributable to a change in the individuals' risk pReferences

Declaration of interest

The authors report no conflict of interest. The authors alone are responsible for the content and writing of this paper.

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