Behavioural Brain Research 414 (2021) 113487

Contents lists available at ScienceDirect

Behavioural Brain Research

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

Transcranial Direct Current Stimulation (tDCS) over the Frontopolar Cortex (FPC) Alters the Demand for Precommitment

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ARTICLE INFO

Keywords:
intertemporal choice
frontopolar cortex
transcranial Direct Current Stimulation
precommitment
willpower
delay discounting

ABSTRACT

Caving into temptation leads to deviation from the planned path, which reduces our performance, adds trouble to our daily life, and can even bring about psychiatric disorders. Precommitment is an effective way to remedy the failure of willpower by removing the tempting short-term option. This paper aims to test the neural mechanisms of precommitment through a monetary task that excluded the interference of heterogeneous individual preferences and complements present researches. We examined whether transcranial direct current stimulation (tDCS) over the frontopolar cortex (FPC) could affect the demand for precommitment. The participants were required to make a decision regarding whether they were willing to precommit to binding later-lar ger rewards and remove the sooner-smaller rewards. Three conditions, including no precommitment, loose precommitment and strict precommitment, were established to perform a comprehensive investigation. We found that tDCS over the FPC altered the demand for precommitment in the condition involving loose precommitment with the control of delay discounting, specifically, anodal stimulation led to more precommitment, whereas cathodal stimulation reduced the demand for precommitment. Our findings established a causal correlation between the FPC and willingness to precommit and suggested a feasible method to enhance self-control in addition to exercising willpower.

1. Introduction

Many economic decisions require people to make trade-off between different rewards or losses across the different time points that are involved. “Consumption/savings decisions” are the most common intertemporal choices in our lives. To obtain savings in the next month, people need to restrain their consumption this month, which refers to the choice of whether to consume immediately or to save in the future. However, due to the limited ability to resist appealing immediate rewards, it is difficult to control consumption impulsivity.

Giving in to tempting short-term choices not only hampers following a planned course of action [1,2,53] but also leads to negative emotions such as regret, guilt and self-blame [3,4]. Hence, resisting temptation is essential for the implementation of the optimal choice. Come back to the consumption/savings decisions, for the purpose of ensuring the success of the saving plan, we may choose to deposit the money into a fixed account in addition to controlling consumption impulsivity by willpower [5,6]. Imposing such voluntary restrictions on one’s future choice options to avoid anticipated willpower failures is referred to as “precommitment” [7].

The efficiency of this response has been verified in many behavioral experiments [2,8–12]. Despite extensive research into precommitment by behavioral experiments and theoretical considerations, its neural mechanisms were not clear until a functional magnetic resonance imaging (fMRI) study [13]. This research identified regions that may play a main role in precommitment. In contrast to responses when no precommitment option was possible, precommitment choices activated the frontopolar cortex (FPC). The authors concluded that the FPC might be involved in monitoring the expected value of precommitment.

The frontopolar cortex lies at the top of the hierarchy of a prefrontal control network and is thought to play a key role in motivation [14,15]. Activation of the FPC correlates with individual measures of motivation

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https://doi.org/10.1016/j.bbr.2021.113487
Received 8 February 2021; Received in revised form 24 May 2021; Accepted 17 July 2021
Available online 21 July 2021

and with successful performance in incentivized tasks requiring high cognitive effort [16–18]. Downa and Daskalakis [19] found that the FPC could be a target region for modulating depression and cognitive abilities. Using transcranial direct current stimulation (tDCS), Soutschek et al. [7] demonstrated the causal role of the FPC in the implementation of precommitment through a task that involved watching erotic images. Soutschek et al. [18] also found a causal role of the FPC in overcoming costs to obtain greater goods.

Prior work has put much effort into research on the effects of tDCS over the FPC on demand for precommitment using a variety of consumption goods as rewards or losses [7,18]. However, research in the monetary domain is also indispensable, as monetary decisions are continuous events where marginal changes could be quite important [11], while the consumption domain usually involves discrete events. Moreover, using monetary rewards can avoid the interference of heterogeneous preferences in participants' willingness to precommit, further influencing the effects of tDCS over the FPC.

This paper carried out an experiment where monetary rewards were offered and paid with an actual time delay, and participants had the opportunity to precommit to the binding larger-later rewards. According to the conclusion that the FPC biases the decision to precommit as a function of the expected value of the precommitment [13], we predicted that tDCS over the FPC could alter participants' demand for precommitment. To be specific, it was predicted that anodal stimulation over the FPC could enhance the willingness to precommit, whereas cathodal stimulation over the FPC could reduce the demand for precommitment. To take a comprehensive look at this issue, we established three conditions, including a no precommitment condition where participants completed the intertemporal decisions depending only on the willpower, a loose precommitment condition where no cost was required for withdrawing from the precommitment and a strict precommitment condition where the opportunity to withdraw from the precommitment was excluded.

2. Materials and Methods

2.1. Experimental design

The participants performed a decision-making task requiring them to choose between smaller-sooner (SS) monetary rewards and larger-later (LL) monetary rewards, and the pairs of reward amounts were compared at present value. The completion process of this task was referred to as the delay phase. Our delay phase was designed based on the delay discounting questionnaire of Kirby et al. (1996) that included 21 choice trials. Each choice trial consisted of one SS monetary reward and one LL monetary reward; the SS reward could be obtained in 1 day, and the LL reward could be obtained in 10-39 days. We provided two future income options rather than one "instant income" option and one future income option, which avoids the potential problem of the subject facing extra transactions costs with the future income option, we hold these transactions costs constant by having both options entail future income (Harrison et al., 2002). All 21 choice trials fell into 7 hyperbolic discounting rate parameter scales (from 0.0038416 to 0.0875) and 3 groups of small (10-19 days), medium (20-29 days), and large (31-39 days) delay lengths. The trials were presented in the same randomized order on all questionnaires. The choice trials and their associated discounting parameter values are displayed in Table 1. After the decisions were made, the computer randomly drew a pair of alternatives, and actual money was transferred by Ali pay (a popular mobile application for money transfers in China) after the actual delay in days based on the participants' actual choices, which encouraged the participants to give true responses.[1]

Table 1
Choice trials and their associated discounting parameter values.

Order	Choice Trail	Hyperbolic Discounting Parameter Values
4	29 yuan in 1 day or 30 yuan in 10 days	0.0038416
15	37 yuan in 1 day or 40 yuan in 22 days	0.00407056
7	54 yuan in 1 day or 60 yuan in 30 days	0.00384615
20	23 yuan in 1 day or 25 yuan in 14 days	0.00722892
9	35 yuan in 1 day or 40 yuan in 21 days	0.00719424
12	49 yuan in 1 day or 59 yuan in 30 days	0.00732601
8	24 yuan in 1 day or 28 yuan in 19 days	0.00934579
16	37 yuan in 1 day or 45 yuan in 25 days	0.00986193
14	45 yuan in 1 day or 58 yuan in 32 days	0.00909091
10	25 yuan in 1 day or 30 yuan in 12 days	0.01851852
3	32 yuan in 1 day or 45 yuan in 24 days	0.01775956
18	38 yuan in 1 day or 58 yuan in 30 days	0.01848429
11	20 yuan in 1 day or 31 yuan in 15 days	0.04089219
2	22 yuan in 1 day or 40 yuan in 22 days	0.04054054
19	25 yuan in 1 day or 55 yuan in 33 days	0.04155844
21	15 yuan in 1 day or 29 yuan in 17 days	0.0619469
6	18 yuan in 1 day or 40 yuan in 23 days	0.05882353
17	20 yuan in 1 day or 55 yuan in 32 days	0.05982906
5	15 yuan in 1 day or 30 yuan in 13 days	0.09090909
13	16 yuan in 1 day or 40 yuan in 20 days	0.08571429
1	18 yuan in 1 day or 60 yuan in 30 days	0.0875

Before the decision-making task, there was a pre-delay phase: the participants were asked to decide whether to retain the free choices between SS rewards and LL rewards or to precommit to a binding choice that removed the SS options from the delay phase allowing only choosing the LL options. The participants who wanted to ensure obtaining the cognitively better LL rewards would choose to precommit to the binding choice.

The decision-making task had three conditions: willpower condition, opt-out condition and precommitment condition. The willpower condition did not include the pre-delay phase, and the participants started with the delay phase in the willpower condition. This condition specifically assessed when the participants were exerting willpower, the participants needed to resist the temptation of obtaining smaller rewards immediately to obtain the larger rewards in the future. Thus, we could test the efficiency of the offer of precommitment by comparing the frequency of LL choices between the willpower condition and the opt-out, precommitment condition.

The opt-out condition started with a pre-delay phase: the participants decided whether to keep a free choice between the SS and LL

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[1] See Azrieli et al. [54] for the incentive compatibility of the random binary choice (RBC) mechanism. Truth telling is a dominant strategy for this mechanism.

options or to precommit to the binding LL options during the subsequent delay phase. Notably, the participants always had the option to quit from the precommitment contract, and the participants who precommited to the binding choices could revert to the SS options, which meant that the SS options were also available for selection during the delay phase. The participants were aware of the above information before the experiment.

In the precommitment condition, if the participants decided to precommit to the LL options, the SS options would be removed from the delay phase, which meant that the SS options would not be available during the delay phase, and all the choices would be for the binding LL options. We provided the above information to the participants before the beginning of the experiment.

Table 2 shows the characteristics of the three conditions. In this design, the opt-out condition and precommitment condition represented two precommitment mechanisms: one was extremely loose where participants who requested the precommitment mechanism could withdraw from it without cost, and the other was totally strict where there was no possibility to withdrawing from it. This paper tested how stimulation over the FPC affected participants' demand for precommitment in cases where it was loose and strict.

2.2. Task and Procedure

Our experiment consisted of three conditions: willpower, opt-out, and precommitment. Responses in these conditions were tested in three groups: the sham group, anodal group and cathodal group. The stimulation type was tested in a between-participants design, which allowed us to test the effects of stimulation over FPC on the demand for precommitment. The calculated hyperbolic discounting rate parameters in the delay phase helped us control the potential effects of impulsivity.

Fig. 1 shows the entire experimental process. After all of the participants received tDCS for 20 min (single-blinded, sham-controlled), they were required to complete the practice phase before executing the decision-making task. The practice phase consisted of a table with 10 choice sets, which also included one SS reward and one LL reward. The rewards were not monetary rewards but consumption rewards, such as cinema tickets, milk tea, coupons and so on. In this phase, all the rewards were imaginary. The practice phase deepened the participants' understanding of the characteristics of intertemporal choice, and the use of consumption rewards avoided potential interference with the participants' monetary preferences. The next phase was either the delay phase in the willpower condition, or the pre-delay phase in the opt-out and precommitment conditions, which involved whether the participants engaged in the precommitment mechanism. The subsequent delay phase varied across conditions. In the opt-out conditions, the participants always had the free choice between the SS rewards and LL rewards regardless of whether or not they chose to precommit in the pre-delay phase. In the precommitment conditions, the participants could only choose the LL rewards if they chose to precommit in the pre-delay phase.

Finally, we collected the demographic information of the participants by a questionnaire. The entire experimental process was carried out on the computer through ztree 3.5.1 [20].

Table 2
The willpower condition excluded the pre-delay phase, while the opt-out and precommitment condition included both the pre-delay and delay phase. Moreover, the opt-out condition allowed participants to quit from the precommitment contract, while the precommitment condition did not.

Experimental condition	Pre-delay phase	Delay phase	Quit from precommitment
Willpower condition		√	
Opt-out condition	√	√	√
Precommitment condition	√	√	

2.3. Participants

We recruited 270 right-handed healthy participants (mean age 19.55 years; ranging from 17 to 26 years, 135 females) with no history of neurological or psychiatric problems in the Zhejiang University of Finance and Economics. All the participants had normal or corrected-to-normal vision, and provided their written informed consent, which was approved by the Zhejiang University ethics committee. The entire experiment lasted approximately 40 min, and each participant received a payment of 46.14 RMB Yuan (approximately 7.10 US dollars) upon completion of their tasks. None of the participants reported any adverse side effects concerning pain on the scalp or headaches after the experiment.

2.4. Transcranial Direct Current Stimulation

For tDCS, a weak direct current was applied to the scalp via two saline-soaked surface sponge electrodes (5 cm × 7 cm; 35 cm^2). The current was constant and was delivered by a battery-driven stimulator (NeuroConn, Germany). 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. In general, anodal stimulation would enhance cortical excitability, whereas cathodal stimulation would restrain it [21].

Participants were randomly and averagely assigned to 9 sessions, which were sham-willpower session, sham-opt-out session, sham-precommitment session, anodal-willpower session, anodal-opt-out session, anodal-precommitment session, cathodal-willpower session, cathodal-opt-out session and cathodal-precommitment session. The target areas were localized according to Waveguard Duke 128 channels cap. Fig. 2 is the schematic diagram. Fig. 3 illustrates electrode positioning and the modeled current density for the stimulation. For the anodal tDCS over FPC ($n = 90$, 45 females), the anodal electrode was placed over the electrode position LL1 on the 128 channels cap, while the return electrode was placed over the electrode position Z7 [7]. For the cathodal stimulation ($n = 90$, 45 females), the polarity was reversed, where the cathodal electrode was placed over LL1, whereas the return electrode was placed over Z7. The current was constant and of 1.5 mA in intensity, with a 30 s ramp up and down; the safety and efficiency of this stimulation has been demonstrated in previous studies [22]. For sham stimulation ($n = 90$, 45 females), the placement of anodal electrode was either over electrode position Z7 or LL1, and the return electrode was placed over LL1 or Z7 accordingly, but the current lasted for only 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 [23]. 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 experimental tasks.

2.5. Data analysis

2.5.1. Eliciting of participants' hyperbolic discounting rate parameter

For the 21 pairs of alternatives, indifference between two options indicated the following hyperbolic discount parameter k [24,25]:

$$k = \frac{future(\$) - tomorrow(\$)}{delay(indays) * tomorrow(\$) - future(\$)}$$

For example, the participant who was indifferent between 29 yuan in 1 day and 30 yuan in 10 days discounts future reward with a hyperbolic rate parameter of 0.0038416. Choices revealed where one began to prefer LL rewards, individual discount parameters were computed as the geometric mean of the k-values bounding this preference switch [26]. Because participants' choices were not always perfectly consistent with any single parameter value, the parameter assignments could not be

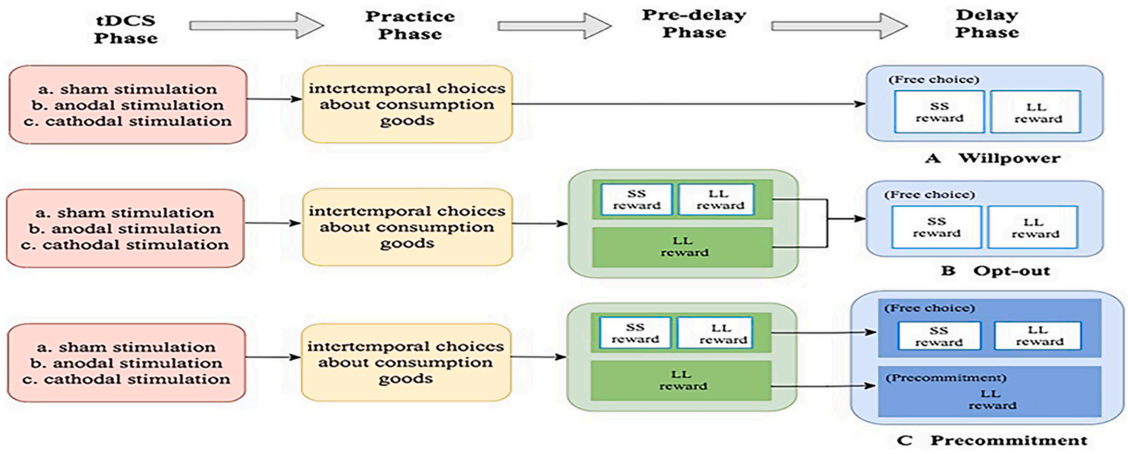

Fig. 1. Flowchart of the entire experiment.

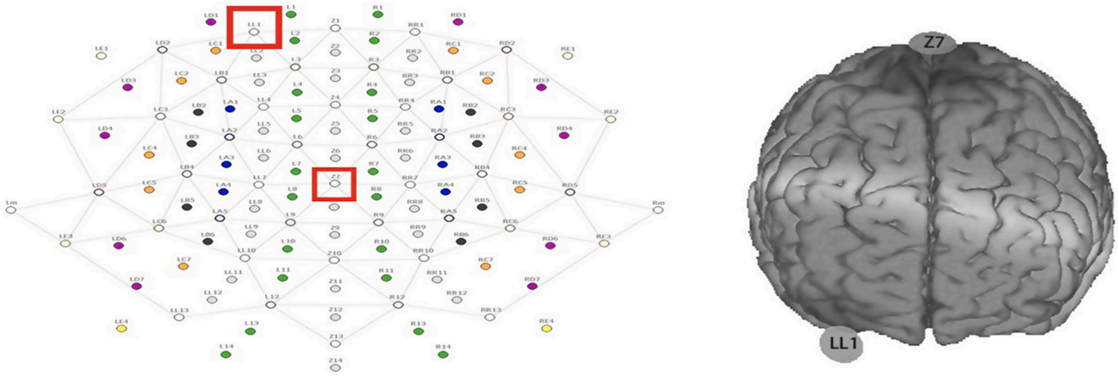

Fig. 2. Schematic and locations of the electrode positions. (A) Schematic of the electrode positions Z7 and LL1 based on the Waveguard Duke 128 channels cap. (B) Locations of Z7 and LL1 of the human brain.

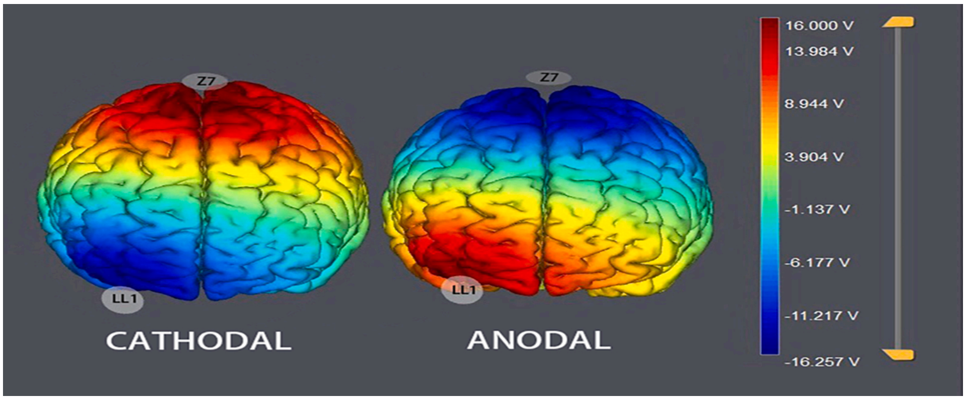

Fig. 3. The stimulation modes of tDCS treatments. Electric field simulations were performed with the Neuroelectrics Instrument Controller software (version 1.3, Spain). Simulated field intensity is indicated by the color bar. The axis represents the range of input voltage from −16.257 to 16.000 V.

made by simply looking for a switch from the immediate to the delayed rewards. Instead, participants were assigned to the range that yielded the highest consistency. Participants who always chose delayed rewards or immediate rewards could not be assigned to a bounded range of parameter values, these data (totally 46, proportion = 17.04%) would be dropped from our analysis. Calculated individual discount parameters in this paper eliminated the potential confounds for the specificity of the stimulation effects over FPC.

2.5.2. *Binary logistic regression model*

We used the Binary logistic regression model as implemented in IBM SPSS Statistics 25.0 to analyze subjects' decisions in the opt-out and precommitment condition. The main variable in our research, the choice of whether to precommit to the LL options, is a categorical variable, therefore we could not carry out a multiple linear regression as many of the assumptions of this technique will not be met. Instead, we would carry out a logistic regression analysis. Logistic regression may be thought of as an approach that is similar to that of multiple linear regression, but takes into account the fact that the dependent variable is categorical. Specifically, we analyzed the effects of tDCS on choices in the pre-delay phase, we predicted participants' propensity to precommit to the LL options in the precommitment and opt-out condition using stimulation predictors for active, i.e., anodal and cathodal, tDCS. The stimulation predictors were dummy variables that were set to 1 if a participant received anodal or cathodal stimulation, otherwise their value was set to 0. Hence, anodal or cathodal effects compared to baseline performance in the sham group could be tested. Besides, we included predictors for delay lengths (10–19, 20–29, or 30–39 days) and interactions between delay length and anodal or cathodal tDCS.

3. Results

3.1. Baseline measures

Because delay discounting varies across the lifespan [27], sham group, anodal group and cathodal group were well balanced with respect to age (One-way ANOVA, $F_{(2,267)} = 0.256$, $p = 0.775$, $\eta_p^2 = 0.002$), which eliminated effects of age on intertemporal preference. In addition, because the demand for precommitment is not independent on individual differences in delay discounting [13,28–30], we performed One-way ANOVA on delay discounting as a factor to test the main effects of stimulation, delay discounting was measured using the delay discounting questionnaire of Kirby et al. (1996). The results suggested the stimulation over the FPC did not alter participants' delay discounting. For willpower condition, $F_{(2,74)} = 0.167$, $p = 0.847$, $\eta_p^2 = 0.004$; for opt-out condition, $F_{(2,74)} = 0.044$, $p = 0.957$, $\eta_p^2 = 0.001$; for precommitment condition, $F_{(2,67)} = 0.355$, $p = 0.702$, $\eta_p^2 = 0.01$, which showed the control of potential tDCS effects on participants' delay discounting.[2]

3.2. Analysis of sham group

Firstly, we tested the efficiency of precommitment as a self-control mechanism through comparing the consumption of LL rewards in the willpower condition with the opt-out and precommitment condition. In the willpower condition, participants' mean frequency to make LL choices (percentage of LL choices relative to all choices) was 59% (SEM = 5%), while in the opt-out condition, all the participants had the chance to precommit unconstrainedly, their mean frequency to make LL choices was 70% (SEM = 4%), the increase was significant (t-test, $t(58) = -1.798, p = 0.077$). As to the precommitment condition, in which participants could choose to make binding choices, it also led to more LL choices (mean = 74%, SEM = 4%) than that in the willpower condition (t-test, $t(58) = -2.293$, $p = 0.025$). Thus, the offering of precommitment was efficient in enhancing participants' LL choices. Notably, our results indicated that no matter the precommitment was strict or loose, as long as it was offered, it was efficient in strengthening participants' preference for LL rewards.

Next, we tested how the delay length affected reward preference. We found that there was a clear increasing trend in the willpower, opt-out, and precommitment condition (Fig. 4), which means the discounted value of LL rewards increases with the delay length. We further performed One-way ANOVA on percentage of LL choices as a factor showed the main effects of delay length. The results were significant in the opt-out condition ($F_{(2,87)} = 6.218$, $p = 0.003$, $\eta_p^2 = 0.125$), the *Post hoc* analyses (Bonferroni) revealed that choices of LL rewards in 10-19 days group (mean = 60%, SEM = 4%) were significantly lower than those in 30-39 days group (mean = 80%, SEM = 3%, $p = 0.003$), no other significant effects were observed among 10-19 days, 20-20 days, and 30-39 days group (all $p > 0.1$). In the precommitment condition, the results were also significant ($F_{(2,87)} = 3.424, p = 0.037, \eta_p^2 = 0.073$), the *Post hoc* analyses (Bonferroni) showed that choices of LL rewards in the 10-19 days group (mean = 68%, SEM = 5%) were significantly lower than those in 30-39 days group (mean = 84%, SEM = 4%, $p = 0.034$), no other significant effects were observed (all $p > 0.1$). In addition, the tendency was not significant in the willpower condition ($F_{(2,87)} = 1.754$, $p = 0.179, \eta_p^2 = 0.039$).

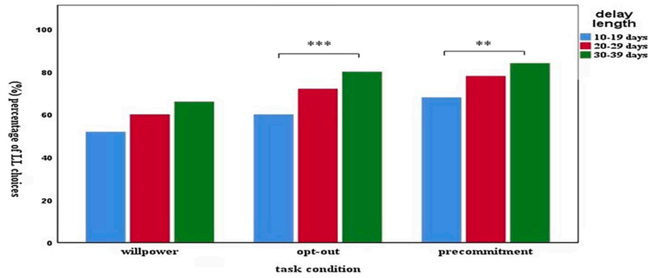

Fig. 4. The preference for the LL rewards increases as a function of delay length. Error bars indicate 95% confidence intervals. The asterisks (**) indicate a significant effect at a threshold of p < 0.05, the asterisks (***) indicate a significant effect at a threshold of p < 0.01. One or more error bar graph calculations yielded infinite results, these error bars have been removed from the chart.

3.3. Anodal tDCS over the FPC promotes precommitment in the opt-out condition

Testing whether the stimulation over the FPC alters the demand for precommitment is the main goal of this research. To achieve it, we performed a Binary Logistic regression that predicted the participants' propensity to engage in precommitment using dummy variables for the effects of anodal and cathodal tDCS relative to sham tDCS in both opt-out condition and precommitment condition. In the opt-out condition, the results revealed that the stimulation over the FPC had significant effects on participants' demand for precommitment ($\chi^2 = 11.761, p = 0.003$). Specifically, the anodal stimulation could significantly enhance participants' demand for precommitment, participants in anodal group were 4 times more likely to engage in precommitment than those in sham group (OR = 4.261, 95% CI: 0.806-22.532, $p = 0.088$), whereas the cathodal stimulation could significantly reduce the demand for precommitment, participants in cathodal group were 11 times less likely to demand precommitment than those in sham group (OR = 10.706, 95% CI: 2.148-53.348, $p = 0.004$). In the precommitment condition, we found that neither anodal stimulation ($p = 0.681$) nor cathodal stimulation ($p = 0.837$) affects participants' demand for precommitment (Fig. 5). This result shows the stimulation effect on the decision to precommit, it also indicates the FPC stimulation works only in the context of loose precommitment.

To investigate the specificity more stringently, we examined whether the effects of FPC stimulation were significantly stronger in the opt-out condition than precommitment condition when the regression includes task condition predictor. For this purpose, we further conducted a Binary Logistic Regression including predictors for anodal tDCS, cathodal tDCS, task condition (a dummy-coded predictor that was 0 for the precommitment condition and 1 for the opt-out conditon), and the interactions between these factors. The results showed that both anodal tDCS × opt-out condition interaction (OR = 3.824, 95% CI: 0.8-18.278, $p = 0.093$) and cathodal tDCS × opt-out condition interaction (OR = 0.126, 95% CI: 0.018-0.879, $p = 0.037$) were significant, confirming

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[2] Since 17.04% of the sample was dropped, we used the interval regression [55] to re-test the data in the willpower and opt-out condition, the results showed that there is no significant effect of the tDCS type (i.e. sham, anodal, cathodal) for delay discounting ($N = 180$, all $p > 0.3$), which is consistent with the One-way ANOVA analysis. As to the precommitment condition, the strict precommitment device tortured participants' preference between SS rewards and LL rewards, so we believe that dropping the choices that selected all LL rewards is more suitable for the calculation of individual delay discounting.

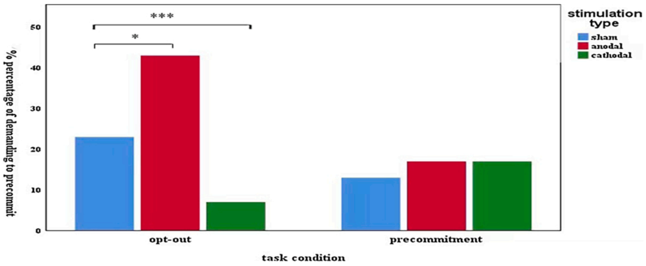

Fig. 5. Effects of anodal and cathodal tDCS relative to sham stimulation on demand for precommitment in the opt-out and precommitment conditions. Relative to sham tDCS, anodal FPC stimulation increases the number of precommitment decisions in the opt-out condition but showes no effects in the precommitment condition. There are no significant effects of cathodal tDCS on task performance. The asterisk (*) indicates a significant effect at a threshold of $p < 0.1$, the asterisks (***) indicate a significant effect at a threshold of $p < 0.01$. One or more error bar graph calculations yielded infinite results, these error bars have been removed from the chart.

that stimulation effects were significantly stronger in the opt-out condition than in the precommitment condition. These data provided evidence in the monetary domain for how tDCS over the FPC affected participants' willingness to precommit, suggesting that stimulation over the FPC had little effect on demand for precommitment when the precommitment was strict, which was different from the observation of Soutschek et al. [7] in the consumption domain. This difference indicated the effects of tDCS over the FPC was related to the application domain.

In addition, we tested whether tDCS over the FPC affected the influence of delay length on participants' preference for LL rewards. We observed the similar increasing tendency in the anodal group and cathodal group as the sham group in the willpower (Fig. 6), opt-out (Fig. 7) and precommitment (Fig. 8) condition. To test it more stringently, we computed the Multiple Linear Regression including predictors for delay length, stimulation type, delay discounting and their interactions. No significant result about tDCS predictors was observed either in the willpower, opt-out or precommitment condition (all $p > 0.3$), which indicated that effects of delay length on participants' choices of LL rewards weren't influenced by the stimulation over the FPC.

4. Discussion

This paper revealed that stimulation over the FPC could alter the demand for precommitment, which supported the neuroimaging-inspired hypothesis of a causal role of the FPC in precommitment [13]. Notably, according to the results of our monetary experiment, tDCS over the FPC worked only in the context with no quitting cost, i.e., when the precommitment was loose. These results were similar to what Soutschek et al. [7] observed; they also found facilitation of precommitment with anodal tDCS over the FPC. The difference was that their experimental task was unrelated to the monetary incentive, and their results only supported the positive role of anodal tDCS over the FPC in choosing strict precommitment.

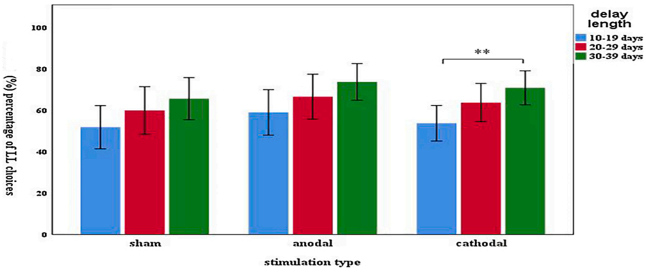

Fig. 6. In the willpower condition, the preference for the LL reward increases as a function of delay length in sham group, anodal group and cathodal group. Error bars indicate 95% confidence intervals. The asterisks (**) indicate a significant effect at a threshold of $p < 0.05$.

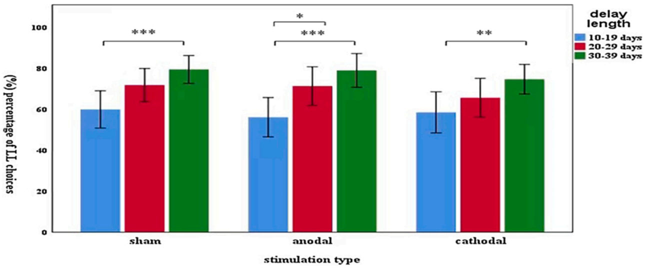

Fig. 7. In the opt-out condition, the preference for the LL reward increases as a function of delay length in sham group, anodal group and cathodal group. Error bars indicate 95% confidence intervals. The asterisk (*) indicates a significant effect at a threshold of $p < 0.1$, the asterisks (**) indicate a significant effect at a threshold of $p < 0.05$, the asterisks (***) indicate a significant effect at a threshold of $p < 0.01$.

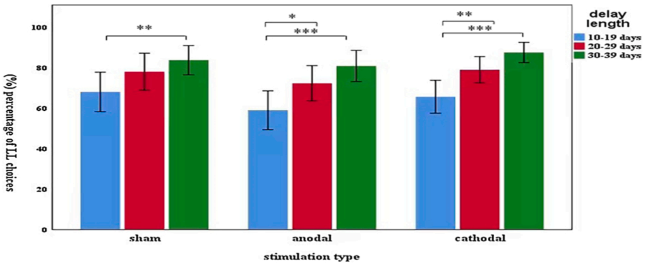

Fig. 8. In the precommitment condition, the preference for the LL reward increased as a function of delay length in sham group, anodal group and cathodal group. Error bars indicate 95% confidence intervals. The asterisk (*) indicates a significant effect at a threshold of $p < 0.1$, the asterisks (**) indicate a significant effect at a threshold of $p < 0.05$, the asterisks (***) indicate a significant effect at a threshold of $p < 0.01$.

Actually, the activation of the FPC relates highly to motivation and cognitive effort activities [16–18]. According to previous studies relating the FPC to metacognitive functions, the expected value of precommitment is the main basis upon which the FPC decides whether to choose precommitment [31,32]. Thus, anodal tDCS over the FPC works by increasing the FPC's sensitivity to an individual's measure of the expected value of precommitment, whereas cathodal stimulation works by decreasing the sensitivity.

As to the difference between our result and what Soutschek et al. [7] observed, it could be attributed to the discrepancy in experimental tasks. Based on the framework of a neural model of precommitment whereby the ventromedial prefrontal cortex (vmPFC) evaluates the expected value of precommitment and relays this information to FPC, which then implements those decisions via the DLPFC and PPC [13], we consider that the different results in different experimental tasks could be attributed to the different degree of the participation of the FPC in the process of deciding whether to choose precommitment.

Intertemporal choices in our lives could be divided into two types: monetary decision-making, which involves continuous events, and decisions using consumption goods as incentives, such as losing weight and procrastination, which are usually discrete events (Augenblick et al., 2015). For the discrete events, the reward and cost of performing the activity in any given period are unaffected by whether and when the agent previously performed the activity, which means that past behavior does not influence payoffs from the current behavior; in contrast, the opposite is true for continuous events, which means marginal changes could be quite important [11]. It indicated that monetary intertemporal decision-making needs higher evaluation skills of expected value, where vmPFC plays a crucial role [33–36]. Therefore, when participants are faced with monetary tasks, more activities in the vmFPC are involved with the process of deciding whether to precommit. For this reason, we can see that, when participants are faced with monetary tasks, they did not significantly increase their precommitment choices under tDCS over the FPC in the precommitment condition, however, the increase is significant when they are faced with consumption tasks. Similarly, due to the no-cost quit mechanism, lower evaluation skills are required, which means the FPC has a higher degree of participation, the participants did not significantly increase their precommitment choices in the precommitment condition, however, the increase is significant in the opt-out condition.

Experimental tasks that use money or use consumption goods as incentives each have their own advantages. Monetary tasks eliminate interference by individual preferences, consumption tasks exclude the smoothing problem, they complement each other, which makes them two indispensable perspectives to investigate the research goal. Our results complement what Soutschek et al. [7] observed and provide evidence from a perspective based on monetary tasks.

It is also important to note that the current data revealed no effects of tDCS over the FPC on impulse control. On the one hand, the willingness to precommit was not independent of individual differences in delay discounting [13,28–30,37], therefore, the well-balanced distribution of delay discounting in the sham group, anodal group and cathodal group excluded potential confounds. On the other hand, individual delay discounting levels are related to lateral prefrontal cortex (DLPFC) activity [32,38–40], and the consistency in individual delay discounting in the sham group, anodal group and cathodal group indicated that tDCS exerted its effects by modulating neural activity in the FPC rather than in other brain regions that were not activated by the current task.

We further noticed the results show that whether it is in the sham group, anodal group, or cathodal group, whether it is in the willpower condition, opt-out condition, or precommitment condition, the preference for LL rewards increased with delay length. This result is consistent with previous classics of behavioral economics [41–44]. It confirms the characteristics of the hyperbolic discounting pattern, that is, people's impatience diminishes over time, which is an important content of the hyperbolic discounting theory [45,46].

Finally, we turn to the results from the analysis of the sham group. We found that the participants resorted to more precommitment when it was loose, and we verified the efficiency of the loose precommitment by the enhancement of the frequency of LL choices in the opt-out condition relative to the willpower condition. These data indicated the advantages of loose precommitment, which is in line with our life experiences. For example, we could easily find that many restaurant vouchers sold online can be returned for free; this loose precommitment increased the number of vouchers purchased (attracted more demand for precommitment relative to the precommitment condition) and further improved the dining rate (achieved more LL choices relative to the willpower condition).

The precommitment strategy has been widely used in the correction of procrastinating tendencies, smoking cessation, drug abuse, and so forth. The finding that precommitment can be facilitated with brain stimulation may be of relevance for the treatment of psychiatric disorders involving self-control problems [47–49]. Therefore, anodal tDCS over the FPC to improve the willingness to precommit could be a feasible method for enhancing our self-control abilities. Furthermore, our results emphasized that in regard to monetary tradeoffs, a loose precommitment mechanism is more likely to be engaged with and thereby result in better performance. This may have broad application prospects in wealth management, resolution of poverty problems and other monetary-related issues.

5. Limitations

One limitation of this study is that we did not use a questionnaire to inquiry about the feeling of tDCS. Based on the fact that no participant reported discomfort to us during the experiment, if the questionnaire could reflect the difference in perception of stimulation between the sham group and the tDCS group, i.e., anodal and cathodal group, it will provide stronger support for the results.

In addition, the neural model of precommitment [13] is the main theoretical basis of the experiment, in which evaluating the expected value of precommitment is an important part. Therefore, confirming the relationship between the expected value of precommitment and the decision to precommit could be a powerful support for the model. Self-report is a potentially cost effective and efficient way for the measurement of the expected value of precommitment. Based on the fact that evaluating the expected value of precommitment is a kind of metacognitive functioning [29,30], the questionnaires could be designed by the lights of the literature on the measurement of metacognitive skills [50–52], which could be further explored in future research.

6. Conclusion

In summary, we designed a monetary experiment to provide important information regarding the effects of tDCS over the FPC in healthy participants' willingness to precommit with the control of delay discounting. Activating the FPC can enhance the demand for precommitment, whereas inhibiting the FPC decreases the willingness to precommit, but only in conditions involving loose precommitment.

Declaration of Competing Interest

This study was carried out in accordance with the recommendations of the guideline of tDCS experiment, Zhejiang University ethics committee with written informed consent from all subjects. All subjects gave written informed consent in accordance with the Declaration of Helsinki. The protocol was approved by the Zhejiang University ethics committee.

Funding

This work was supported by the the China's National Natural Science program (Grant number: 72073117), the Key projects of Zhejiang Province Soft Science research program (Grant number: 2021C25041), and Zhejiang University Academic Award for Outstanding Doctoral Candidates (Grant number: 188310+194412105/009/002).

CRediT authorship contribution statement

Jinjin Wang: Conceptualization, Software, Formal analysis, Writing - original draft. **Yuzhen Li:** Data curation, Writing - review & editing. **Siqi Wang:** Validation, Writing - review & editing. **Wenmin Guo:** Validation, Writing - review & editing. **Hang Ye:** Funding acquisition, Writing - review & editing. **Jinchuan Shi:** Writing - review & editing. **Jun Luo:** Conceptualization, Project administration, Writing - review & editing.

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