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The brain stimulation of DLPFC regulates choice preference in intertemporal choice self-other differences

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A R T I C L E I N F O

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A B S T R A C T

Intertemporal choice requires to make decision by evaluating the value of two options consisting of different times and benefits. The dorsolateral prefrontal cortex (DLPFC) is a key brain region for modulating intertemporal choice. The aim of this study is to investigate the effect of non-invasive brain stimulation over DLPFC on intertemporal choice behavior for self and others. We used transcranial direct current stimulation (tDCS) and continuous theta burst stimulation (cTBS) to stimulate bilateral DLPFC in two experiments respectively. After stimulation, subjects made a choice between a Smaller-Sooner (SS) reward and a Larger-Later (LL) reward in intertemporal choice task. The results showed that cTBS stimulation on the left DLPFC reduced the choice preference for SS reward when individuals made choices for themselves. The cTBS stimulation caused preference difference between choosing for self and parents. But tDCS stimulation had no effect on regulating choice preference. In addition, subjects preferred SS reward for self than strangers. Time-types and monetary difference of rewards affected the choice preference. The presence of immediate time increased the choice preference of SS reward. As the monetary difference increased, the choice proportion of SS reward decreased. Our study demonstrates that brain stimulation on the left DLPFC can regulate choice preference behavior in intertemporal choice.

1. Introduction

In investment and saving economic activities, individuals need to make economic decisions to get maximum benefits, considering diverse factors, such as time and risk [1,2]. Intertemporal choice requires to make decision by evaluating the value of two options consisting of different times and benefits [3,4]. It is usually necessary to make choice between a Smaller-Sooner (SS) reward and a Larger-Later (LL) reward. For example, we need to make choice between a reward of $100 today or a reward of $200 in two weeks. Studies found that individuals were more inclined to choose future gains (i.e. Larger-Later rewards), resulting in the discount of the value of current gains, which is known as delay discounting [3]. Individuals with addictive behaviors (smoking, drug abuse, and gambling) and patients with attention deficit hyperactivity disorder had steeper delay discounting than healthy persons [5-7]. Intertemporal choice was used to measure impulsivity and self-control, which involve neural representations of future reward value [8].

The dorsolateral prefrontal cortex (DLPFC) plays a role in regulating intertemporal choice which is involved in planning and goal control [9,10]. When individuals chose the LL rewards, the lateral prefrontal cortex (LPFC) was activated [11]. The valuation stage of intertemporal choice was modulated by ventral striatum and ventromedial prefrontal cortex, and the choosing stage was modulated by the activities of DLPFC and inferior frontal gyrus [12]. When value difference between the SS and LL rewards was small, it was difficult to make a choice, and “hard choice” revealed significant effect on the DLPFC [13,14]. When time interval and monetary magnitude difference of two rewards were large, DLPFC engaged in the magnitude and time sensitivity [15].

We make choices not only for ourselves, but also choosing for others. There was difference between making choices for ourself and others, which was the decision-maker role effect [16]. Studies had confirmed that there was a difference between choosing for oneself and others [17-19]. When subjects faced with risky options, they were more inclined to take a risk for friends rather than themselves [17]. There were

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self-other differences in intertemporal choice both in terms of behavior and brain activity. Individuals preferred SS reward for themselves but not strangers [20]. For the emotion reward, brain regions(ventral striatum, anterior cingulate gyrus, and medial prefrontal cortex) were more activated for themselves than others [21]. Wang used Inclusion of Other in the Self Scale (IOS) to measure mental distance between self and others (intimate friends or complete strangers), and found that individuals had greater preference for LL reward when choosing for themselves or an intimate friend, than choosing for a complete stranger [16].

The transcranial direct current stimulation (tDCS) and transcranial magnetic stimulation (TMS) are non-invasive neuromodulation techniques. The tDCS could modulate cortex activity with constant and low-intensity direct current stimulation. It induced neural activity changes in resting potential hyperpolarization or depolarization depending on the polarity of stimulation [22]. The tDCS stimulation on decision-making brain regions altered decision-making behavior [23,24]. Compared with sham stimulation, anodal stimulation over left DLPFC and cathodal stimulation over right DLPFC made individuals more inclined to choose SS reward [25]. Anodal stimulation over left DLPFC with high-definition tDCS (HD-tDCS) reduced impulsivity, so subjects were more inclined to choose LL reward [26,27]. In contrast, cathodal stimulation over left DLPFC increased impulsivity, so that individuals were more inclined to choose SS rewards. However, the tDCS stimulation over right DLPFC didn't change decision-making behavior [27]. TMS stimulation induced currents through the skull to modulate neural activity with transient magnetic fields. Previous studies had shown that off-line effect of TMS can last for 30 min by stimulation specific frequency [28,29]. Different frequency of TMS stimulation regulates decision-making behavior differently. Low frequency TMS stimulation over left LPFC significantly increased the choice preference of SS reward [30]. High frequency TMS stimulation over left DLPFC lasted for more than 20 min made anorexia nervosa patients tend to choose LL reward [31]. The continuous theta burst stimulation (cTBS) was a patterned form of repetitive transcranial magnetic stimulation (rTMS) to depress cortex excitability, with a lower stimulation intensity and a shorter time of stimulation than common rTMS [32,33]. The cTBS stimulation over right DLPFC increased choice for LL reward and reduced decision-making impulsivity [34,35]. These studies showed that tDCS and TMS brain stimulation effect on choice behaviors hasn't consistency.

The aim of this study is to investigate the effect of non-invasive brain stimulation over DLPFC on intertemporal choice behavior for self and others. We used tDCS and cTBS to stimulate bilateral DLPFC in two experiments respectively. After stimulation, subjects were asked to complete an intertemporal choice task. We hypothesized that tDCS and cTBS stimulation over DLPFC regulate the choice preference of intertemporal choice for self and others.

2. Method

2.1. Experiment 1: Intertemporal choice based on tDCS

2.1.1. Subjects

Twenty-seven students (13 females; mean age: 23.26 years; age range: 20–26 years) were recruited in experiment 1. All subjects were healthy, right-handed, and had normal or corrected-to-normal vision. Before the experiment, all subjects filled in the informed consent form to understand the experimental process. After the experiment, subjects got monetary compensation. This study was approved by the Ethics and Human Protection Committee of the University of Electronic Science and Technology of China.

2.1.2. Intertemporal choice task

This experiment was 3 (tDCS stimulation types: F3 +F4 −, F3 −F4 +, sham) × 3 (decision-makers: choose for self, parents, strangers) × 2 (time-types: immediate-delayed, delayed-delayed) within-subjects design. After each stimulation, subjects completed an intertemporal choice task.

The intertemporal choice task was adopted to record choice preference [11] (Fig. 1**a**). Present Inclusion of Other in the Self Scale (IOS) before the cue for parents and strangers was used to measure the degree of intimacy between self and others. The IOS scale was used to measure the closeness between the self and others [36]. Seven different combinations (7-point scale) indicate different degree of closeness. Each combination consists of two circles, one representing the self and the other representing others. The degree of overlap between the two circles reflected the closeness of self and others. If the two circles do not overlap at all, the combination is scaled as "1", which means that self and others are completely strange. If the two circles overlap almost completely, the combination is scaled as "7" which means the self and others are very close (Fig. 1**b**). Subjects pressed the button with the corresponding number on circles. Each trial began with a fixation of 2 s. Then, a SS reward and a LL reward were presented simultaneously for 5 s. The SS reward consisted of sooner and smaller monetary amount, which was presented on the left side of the screen. The LL reward consisted of later and larger monetary amount, which was presented on the right side of the screen. Subjects pressed "F" key to choose SS reward and "J" key to choose LL reward.

Intertemporal task had 3 blocks, each including 64 trials, with a total of 192 trials. To reduce the fatigue effect, subjects took a break for 2 min after each block. If subjects felt very tired, they can take a longer break to keep sober and stable state before each block. The trials had varying reward times (SS time and LL time) and monetary amounts (SS monetary and LL monetary), which have four reward times (including today, in two weeks, in four weeks, and in six weeks) and eight percentages of monetary difference between SS reward and LL reward (including 1%, 3%, 5%, 10%, 15%, 25%, 35%, and 50%) (Supplementary Table 1). Before formal trials, subjects completed 12 practice trials. The trials were presented randomly. To minimize order effect, we balanced the order of choices for self, parents, and unrelated strangers. We used E-prime 2.0 software to present stimuli and record behavioral performance.

2.1.3. Transcranial direct current stimulation

A pair of circular sponge electrode pads (3.6 cm in diameter) soaked in 0.09% saline deliver continuous current stimulation (DROIAN2019, Droian, Hangzhou, China). The experiment was conducted for three consecutive days for three different tDCS stimultion types. According to international 10–20 EEG system, left DLPFC and right DLPFC correspond to electrodes F3 and F4 respectively (Fig. 2). For F3 +F4 −, the center of anode electrode was placed at F3, and the center of cathode electrode was placed at F4. For F3 −F4 +, the center of cathode electrode was placed at F3, and the center of anode electrode was placed at F4. The constant stable current lasted for 20 min at 1.5 mA. For sham stimulation, two electrodes were still placed at F3 and F4. The initial current increased from 0 mA to 1.5 mA and last current decreased from 1.5 mA to 0 mA for 60 s. To reduce the order effect, the order of stimulation types was balanced. During tDCS stimulation process, subjects filled out the tDCS sensation questionnaire to declared whether feel headache, tingling, or other sensations (Supplementary material). No one report any adverse side effects concerning pain or headaches during the experiment, and they reported the mild tingling sensation and tolerated tDCS stimulation well. Experiment 1 was a single-blind design that subjects did not know the tDCS stimulations types. There was no significant difference between three types of tDCS stimulation (i.e., anodal, cathodal, sham stimulation).

2.2. Experiment 2: Intertemporal choice based on cTBS

2.2.1. Subjects

Thirty-six subjects (18 females; mean age: 22.23 years; age range: 20–26 years) from the University of Electronic Science and Technology

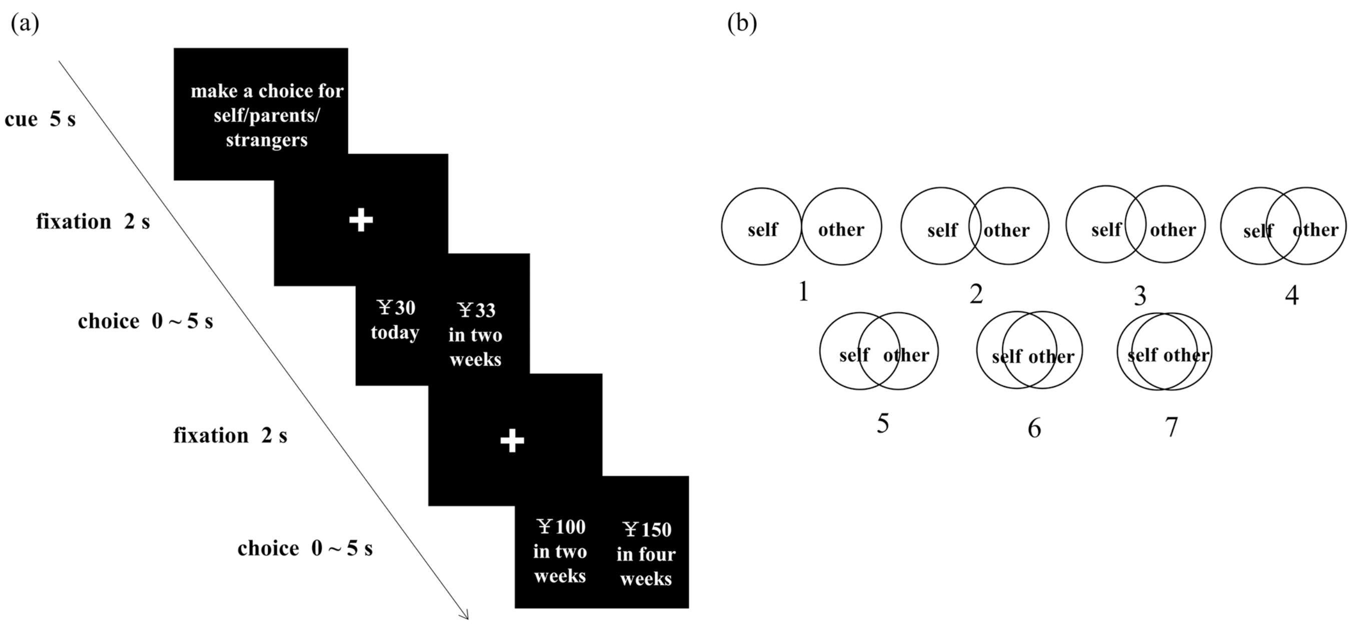

Fig. 1. (a) The intertemporal choice task. For each trial, subjects were required to choose between a Smaller-Sooner (SS) reward and a Larger-Later (LL) reward. Subjects choose for themselves, their parents, and unrelated strangers. (b) Inclusion of Other in the Self Scale (IOS). The degree of overlap between the two circles reflecting the closeness of oneself and others. "1" represents that self and others are completely strange, "7" represents that self and others are very close. Subject were asked to complete IOS before the choice for parents and strangers.

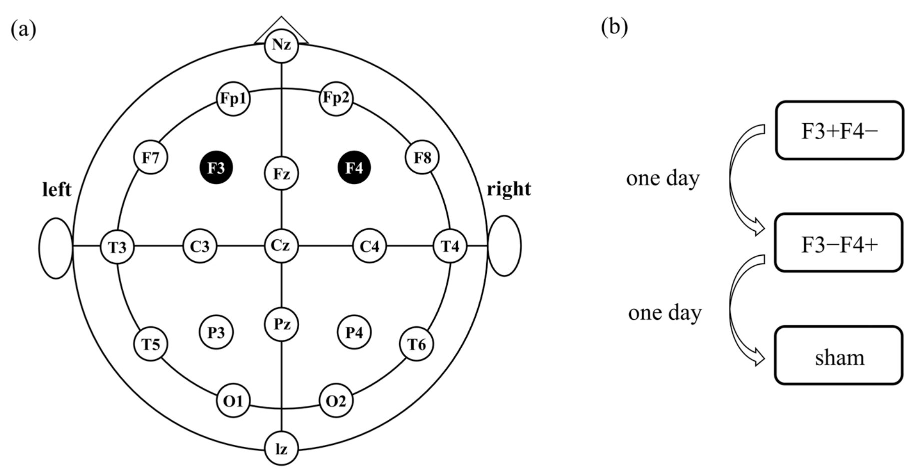

Fig. 2. (a) International 10–20 EEG system. F3 represents left DLPFC; F4 represents right DLPFC. (b) The interval time of stimulation types was one day. The order of three stimulation types was balanced. F3 +F4 − represents left DLPFC anode and right DLPFC cathode stimulation. F3 −F4 + represents left DLPFC cathode and right DLPFC anode stimulation.

of China participated in this experiment. All subjects were healthy, right-handed, and had normal or corrected-to-normal vision. Before experiment, subjects participated in fMRI scanning and filled out a TMS adult safety screening form (including head injuries, brain-related diseases, headaches, etc.). The experiment was conducted in strict accordance with published TMS safety manual guidelines [37,38]. After experiment, the subjects got a certain monetary compensation. This study was approved by the Ethics and Human Protection Committee of the University of Electronic Science and Technology of China.

2.2.2. *Experiment task*

This experiment was 3 (cTBS stimulation locations: left DLPFC, right DLPFC, vertex) × 3 (decision-makers: choose for self, parents, strangers) × 2 (time-types: immediate-delayed, delayed-delayed) within-subjects design. The intertemporal choice task was the same as experiment 1 (Fig. 1). After each location was stimulated, subjects were required to conduct intertemporal choice task. The time difference between each TMS stimulation location was one day, so the whole experiment lasted for three consecutive days.

2.2.3. *Continuous theta burst stimulation*

The TMS stimulator (Magstim Company Limited, Whiteland, United Kingdom) was an air-cooled figure eight coil with an outer winding diameter of 70 mm. The coil was placed target cortex location, guided by the online BrainSight frameless stereotaxy navigation system (Rogue Research, Montreal, Canada).

The off-line stimulation was 29% intensity of the TMS maximum stimulator output and lasted for 40 s. Each burst consisted of 3 pulses (50 Hz) repeated every 200 ms, with total of 200 bursts included 600 pulses (5 Hz). The cTBS stimulation locations included left DLPFC ($x = -41$, $y = 24$, $z = 25$), right DLPFC ($x = 41$, $y = 24$, $z = 25$), and vertex ($x = 0$, $y = 0$, $z = 90$) in Montreal Neurological Institute (MNI) coordinate [39] (Fig. 3). In order to avoid that induced magnetic field caused by any significant stimulation of primary motor (M1) cortex, the vertex was stimulated as control location [40,41]. No one reported any side effects concerning pain or headaches, and subjects tolerated cTBS stimulation well.

2.3. Data analysis

We used repeated measures ANOVA and paired t-test to analyze choice proportion of rewards by SPSS 20.0 software. The independent variables included tDCS stimulation types (F3 +F4 −, F3 −F4 +, sham), decision-makers (choose for self, parents, strangers), and time-types (immediate-delayed, delayed-delayed) in experiment 1. In experiment 2, the independent variables were cTBS stimulation locations (left DLPFC, right DLPFC, vertex), decision-makers (choose for self, parents, strangers), and time-types (immediate-delayed, delayed-delayed). The choice proportion of SS rewards was dependent variable in two experiments.

3. Results

3.1. Experiment 1 results

Regardless of the tDCS stimulation types, subjects were more likely to choose SS reward. There was no significant difference between SS reward and LL reward in three stimulation types (F3 +F4 −: $t_{(26)} = 2.035$, $p = 0.052$; F3 −F4 + : $t_{(26)} = 1.651$, $P = 0.111$; sham: $t_{(26)} = 1.336$, $P = 0.193$)(Fig. 4**a**). The IOS scores of self and parents were significantly higher than those of self and strangers ($t_{(26)} = 13.281$, $P < 0.001$), indicating that subjects were closer to their parents (Fig. 4**b**). Therefore, the behavior analysis can be more focused on the decision-makers. Three-way repeated-measures ANOVA (tDCS stimulation types, decision-makers, and time-types) showed a main effect of decision-makers ($F_{(2,52)} = 3.896$, $P = 0.027$, $\eta_p^2= 0.13$), a main effect of time-types ($F_{(1,26)} = 5.161$, $P = 0.032$, $\eta_p^2 = 0.166$), and no main effect of tDCS stimulation types ($F_{(2,52)} = 0.252$, $P = 0.778$, $\eta_p^2 = 0.01$) (Supplementary Result, Table 2, and Fig. 1).

To investigate the effect of time-types on choice preference, we made two-way repeated-measures ANOVA of time-types and decision-makers under sham stimulation. Results showed a main effect of time-types ($F_{(1, 26)} = 7.27$, $P = 0.012$, $\eta_p^2= 0.219$), no main effect of decision-makers ($F_{(2, 52)} = 2.594$, $P = 0.101$, $\eta_p^2 = 0.091$), and no interaction effect of time-types and decision-makers ($F_{(2, 52)} = 1.636$, $P = 0.205$, $\eta_p^2= 0.059$). When subjects made choice for their parents, the choice preference of SS reward was significantly higher for immediate-delayed time than delayed-delayed time ($t_{(26)} = 3.433$, $P = 0.002$)(Fig. 5**a**).

To investigate the effect of monetary amount on choice preference, we made repeated-measures ANOVA of monetary difference and decision-makers. The results showed a main effect of monetary difference ($F_{(1, 26)} = 179.299$, $P < 0.001$, $\eta_p^2= 0.873$), no main effect of decision-makers ($F_{(2, 52)} = 2.601$, $P = 0.101$, $\eta_p^2= 0.091$), and an interaction effect of monetary difference and decision-makers ($F_{(2, 52)} = 6.446$, $P = 0.009$, $\eta_p^2= 0.199$). Further paired t-tests showed that subjects chosen more SS reward for self and others, when the monetary difference between SS reward and LL reward was small (self: $t_{(26)} = 13.642$, $P < 0.001$; parents: $t_{(26)} = 12.79$, $P < 0.001$; strangers: $t_{(26)} = 6.209$, $P < 0.001$)(Fig. 5**b**). As the percentage of monetary difference increased, the choice proportion of SS reward decreased in different decision-makers. The self-other difference of choice preference was existent under small monetary difference percentages (1%: $F_{(2, 52)} = 7.484$, $P = 0.001$, $\eta_p^2= 0.224$; 3%: $F_{(2, 52)} = 3.56$, $P = 0.036$, $\eta_p^2= 0.12$; 5%: $F_{(2, 52)} = 6.499$, $P = 0.003$, $\eta_p^2= 0.2$; 10%: $F_{(2, 52)} = 5.466$, $P = 0.013$, $\eta_p^2= 0.174$. . Subjects chose more SS rewards for self than for strangers, when the monetary difference percentage were 1%, 3%, 5%, and 10% (Fig. 5**c**).

3.2. Experiment 2 results

Although subjects preferred SS reward, there was no significant choice difference between SS reward and LL reward for three stimulation locations (left DLPFC: $t_{(35)} = 1.236$, $P = 0.225$; right DLPFC: $t_{(35)} = 1.666$, $P = 0.105$; vertex: $t_{(35)} = 1.513$, $P = 0.139$)(Fig. 6**a**). The IOS scores of self and parents were significantly higher than those of self and strangers ($t_{(35)} = 27.84$, $P < 0.001$), indicating that subjects were indeed closer with their parents(Fig. 6**b**). Therefore, we can further analyze the choice preference in terms of decision-makers.

We used the three-way repeated measure ANOVA (cTBS stimulation locations, decision-makers, and time-types) to analyze the choice proportion of SS reward (Supplementary Table 3). The results reveled a main effect of cTBS stimulation locations ($F_{(2, 70)} = 5.542$, $P = 0.006$, $\eta_p^2 = 0.137$) and a main effect of decision-makers ($F_{(2, 70)} = 4.108$, $P = 0.021$, $\eta_p^2 = 0.105$). There were an interaction effect of cTBS stimulation locations and time-types ($F_{(4, 140)} = 7.447$, $P = 0.001$, $\eta_p^2 = 0.175$), an interaction effect of decision-makers and time-types ($F_{(4, 140)} = 10.394$, $P < 0.001$, $\eta_p^2 = 0.229$), and an interaction effect of cTBS stimulation locations, decision-makers, and time-types ($F_{(4, 140)} = 8.635$, $P < 0.001$, $\eta_p^2 = 0.198$). No main effect of time-types ($F_{(2, 70)} = 0.008$, $P = 0.928$, $\eta_p^2 = 0.0002$) and no interaction effect of cTBS stimulation locations and decision-makers ($F_{(4, 140)} = 2.296$, $P = 0.062$, $\eta_p^2 = 0.62$) were observed.

To identify the effect of cTBS stimulation locations, we made two-way ANOVA (cTBS stimulation locations and decision-makers) in immediate-delayed and delayed-delayed time-types. In immediate-delayed time, results showed a main effect of cTBS stimulation loca-

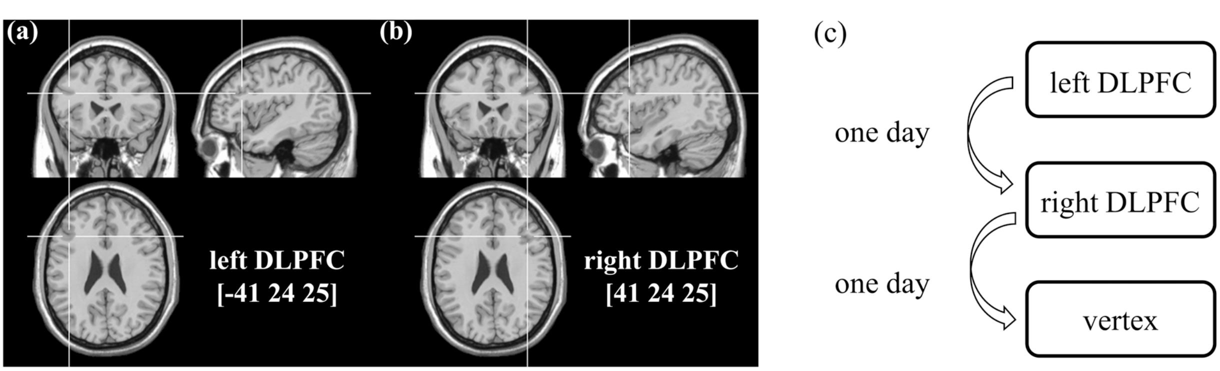

Fig. 3. The cTBS stimulation locations. (a) The location of the left DLPFC (−41 24 25) in MNI coordinate. (b)The location of the right DLPFC (41 24 25) in MNI coordinate. The control site was vertex (0 0 90). (c) The order of three stimulation locations was balanced. The interval time of stimulation locations was one day.

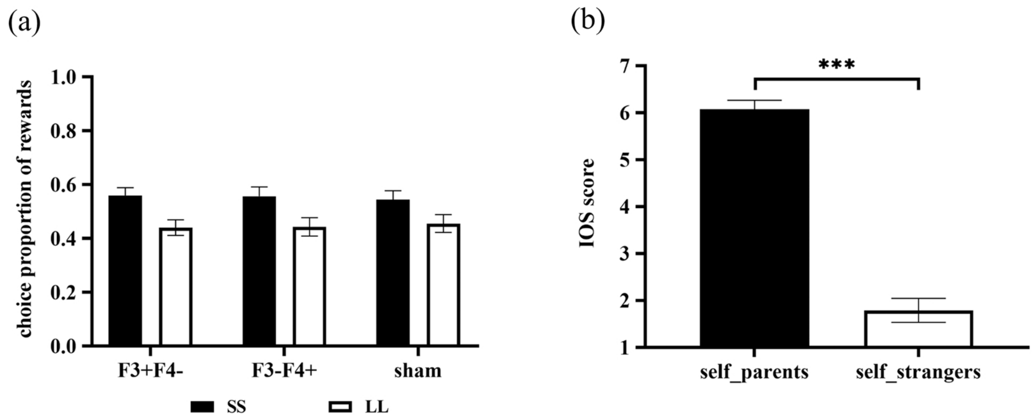

Fig. 4. (a) The choice proportion of Smaller-Sooner reward (SS) and Larger-Later reward (LL) in three stimulation types. (b) The Inclusion of Other in the Self Scale (IOS) scores between self and parents, self and strangers in experiment 1. The higher the score, the closer the relationship between self and others is. Error bar represents standard error of mean (SEM). *** $P < 0.001$.

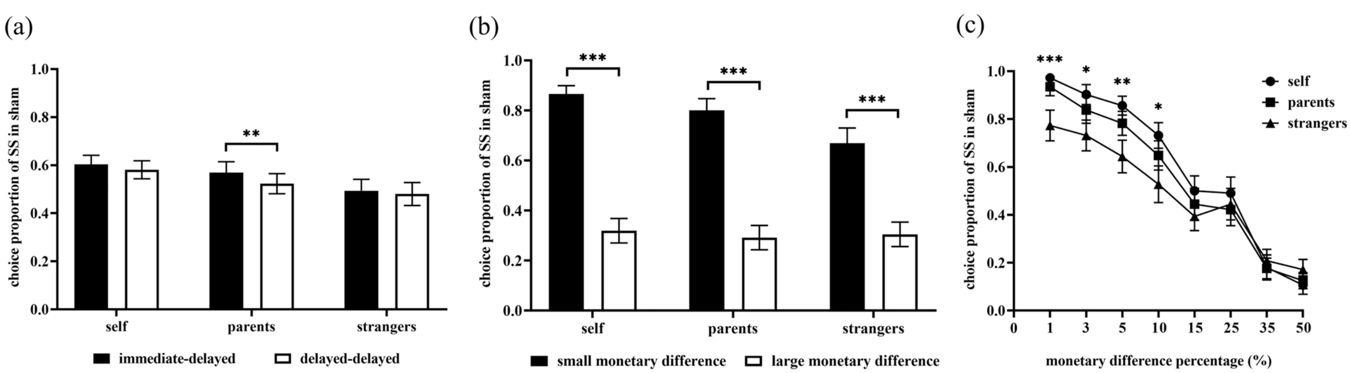

Fig. 5. The choice proportion of SS reward under sham stimulation. (a) The choice proportion of different time-types and decision-makers; (b) The choice proportion of different monetary difference and decision-makers. (c) The choice proportion of eight monetary percentages. Error bar represents standard error of mean (SEM). * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

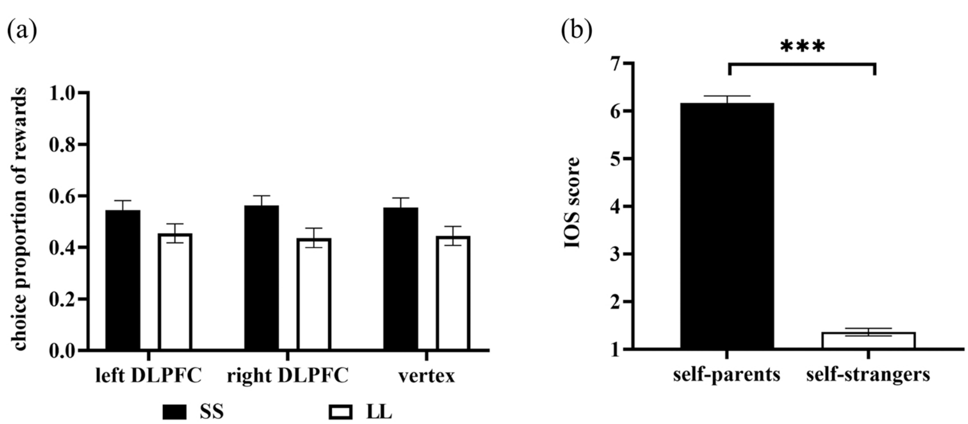

Fig. 6. (a) The choice proportion of SS reward and LL reward. (b) The IOS scores between self and parents, self, and strangers in experiment 2. Error bar represents standard error of mean (SEM). *** $P < 0.001$.

tions ($F_{(2, 70)} = 9.626$, $P < 0.001$, $\eta_p^2 = 0.216$), a main effect of decision-makers ($F_{(2, 70)} = 3.451$, $P = 0.037$, $\eta_p^2 = 0.09$), and an interaction effect of cTBS stimulation locations and decision-makers ($F_{(4, 140)} = 5.155$, $P = 0.001$, $\eta_p^2 = 0.128$). The cTBS stimulation over left DLPFC caused significantly less SS choice for self in immediate-delayed time than that over right DLPFC and vertex (left DLPFC vs. right DLPFC: $t_{(35)} = -3.238$, $P = 0.003$; left DLPFC vs. vertex: $t_{(35)} = 2.72$, $P = 0.01$)(Fig. 7**a). That is to say, the stimulation effect on the left DLPFC increased the choice preference of LL reward. The stimulation over the left DLPFC increased the SS preference for self than parents in immediate-delayed time ($t_{(35)} = -2.509$, $P = 0.017$). When cTBS stimulation over the left DLPFC, there was no significant difference between choice for self and strangers in immediate-delayed time ($t_{(35)} = 1.502$, $P = 0.142$). And there was no significant difference between choice for parents and strangers ($t_{(35)} = -2.01$, $P = 0.052$). Although there was a main effect of decision-makers ($F_{(2, 70)} = 3.451$, $P = 0.037$, $\eta_p^2 = 0.09$), stimulation over the

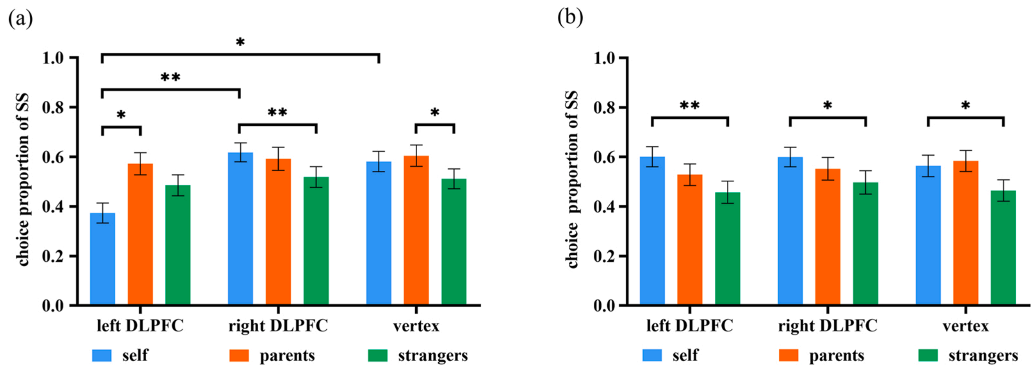

Fig. 7. (a) The choice proportion of SS reward in immediate-delayed time. When the cTBS stimulated left DLPFC, subjects choose less SS reward for self in immediate-delayed time than that over right DLPFC and vertex. (b) The choice proportion of SS reward in delayed-delayed time. Subjects preferred SS reward for self than strangers. Error bar represents standard error of mean (SEM). * $P < 0.05$, ** $P < 0.01$.

right DLPFC caused choice difference between self and strangers ($t_{(35)} = 2.951$, $P = 0.006$). The stimulation over the vertex caused choice difference between parents and strangers ($t_{(35)} = 2.385$, $P = 0.023$). The stimulation over the left DLPFC decreased the choice preference of SS reward for self and strangers, so the difference between self and strangers was not significant. The cTBS stimulation over the left DLPFC eliminated the difference between self/parents and strangers**.** As to delayed-delayed time, the results showed a main effect of decision-makers ($F_{(2, 70)} = 6.61$, $P = 0.002$, $\eta_p^2 = 0.159$), an interaction effect of cTBS stimulation locations and decision-makers ($F_{(4, 140)} = 2.57$, $P = 0.041$, $\eta_p^2 = 0.068$), no main effect of cTBS stimulation locations ($F_{(2, 70)} = 0.546$, $P = 0.582$, $\eta_p^2 = 0.015$). Regardless of cTBS stimulation locations, subjects preferred SS reward for self than for strangers (left DLPFC: $t_{(35)} = 3.698$, $P = 0.001$; right DLPFC: $t_{(35)} = 2.718$, $P = 0.01$; vertex: $t_{(35)} = 2.181$, $P = 0.036$)(Fig. 7**b)**.

We used two-way ANOVA to analyze the effect of time-types and decision-makers, there were a main effect of time-types ($F_{(1,35)} = 16.302$, $P < 0.001$, $\eta_p^2 = 0.318$, a main effect of decision-makers ($F_{(2,70)} = 5.151$, $P = 0.018$, $\eta_p^2 = 0.128$), but no an interaction effect on time-types with decision-makers ($F_{(2,70)} = 1.432$, $P = 0.246$, $\eta_p^2 = 0.039$). When subjects chosen for strangers, the presence of immediate time increased the choice preference of SS reward ($t_{(35)} = 3.382$, $P = 0.002$)(Fig. 8**a)**. When subjects chosen for parents, the choice proportion was higher than strangers in immediate-delayed time ($t_{(35)} = 2.385$, $P = 0.023$) and delayed-delayed time ($t_{(35)} = 3.006$, $P = 0.005$). And the choice for self was more likely to SS reward than strangers in delayed-delayed time ($t_{(35)} = 2.181$, $P = 0.036$).

In addition, a two-way ANOVA of choice proportion of SS reward was analyzed with monetary difference and decision-makers. The results showed a main effect of monetary difference ($F_{(1, 35)} = 142.092$, $P < 0.001$, $\eta_p^2 = 0.802$), a main effect of decision-makers ($F_{(2, 70)} = 5.189$, $P = 0.017$, $\eta_p^2 = 0.129$), and no interaction effect of monetary difference and decision-makers ($F_{(2, 70)} = 3.262$, $P = 0.06$, $\eta_p^2 = 0.085$). Compared with large monetary difference, small monetary difference increased the choice preference of SS reward in three decision-makers (self: $t_{(35)} = 12.241$, $P < 0.001$; parents: $t_{(35)} = 11.245$, $P < 0.001$; strangers: $t_{(35)} = 7.792$, $P < 0.001$)(Fig. 8**b)**. When subjects faced small monetary difference rewards, the choice proportion of SS reward for self and parents was higher than for strangers (self vs. strangers: $t_{(35)} = 2.358$, $P = 0.024$; parents vs. strangers $t_{(35)} = 2.782$, $P = 0.009$). When subjects faced large monetary difference rewards, the choice proportion for parents was higher than for strangers ($t_{(35)} = 2.338$, $P = 0.025$). And there was significant difference between choice for self and strangers in delayed-delayed time ($t_{(35)} = 2.181$, $P = 0.036$). As the percentage of monetary difference increased, the choice proportion of SS reward decreased. The self-other difference was limited to monetary percentage and was removed above 15% (1%: $F_{(2, 52)} = 3.966$, $P = 0.046$, $\eta_p^2 = 0.106$; 3%: $F_{(2, 52)} = 6.588$, $P = 0.006$, $\eta_p^2 = 0.158$; 5%: $F_{(2, 52)} = 6.625$, $P = 0.006$, $\eta_p^2 = 0.159$; 15%: $F_{(2, 52)} = 6.979$, $P = 0.002$, $\eta_p^2 = 0.166$). Subjects chose more SS reward for self than for strangers, when the monetary difference percentage were 1%, 3%, 5%, and 15% (Fig. 8**c**).

4. Discussion

The present study found that cTBS stimulation over left DLPFC could reduce the choice preference of SS reward in immediate-delayed time (i. e. increased the choice preference of LL reward) which suggest the cTBS

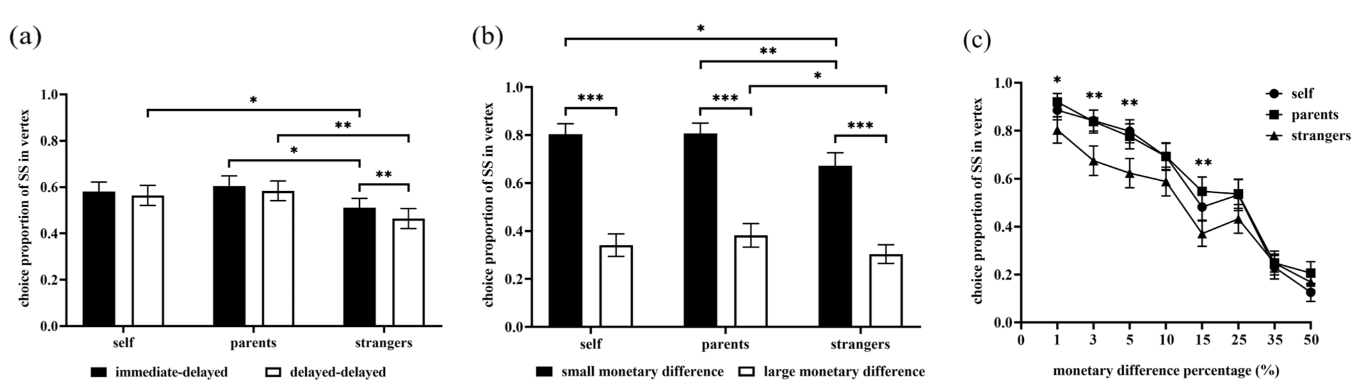

Fig. 8. The choice proportion of SS reward under vertex. (a) The choice proportion of different time-types and decision-makers; (b) The choice proportion of different monetary difference and decision-makers. (c) The choice proportion of eight monetary percentages. Error bar represents standard error of mean (SEM). * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

stimulation could change choice preference behavior. The intertemporal choice preference for self-others was different and regulated by cTBS stimulation. In addition, time-types and monetary differences of rewards had vital role of choice preference.

When cTBS stimulation over left DLPFC, the choice preference for self was changed in immediate-delayed time. Figner et al. used the low-frequency rTMS to inhibit the activity of left DLPFC, the stimulation increased choice preference of SS reward [30]. The cTBS stimulation on right DLPFC didn't regulate behavior of the Montreal card sorting task [42]. The cTBS (40 s, 600 pulses) decreased the size of motor evoked potentials (MEPs) and had an inhibitory effect on motor cortex excitability [32,43]. The cTBS stimulation reduced cortical excitability of the right DLPFC and impulsive decision level, compared with the sham stimulation [34]. The regulation effects of TMS stimulation are not consistent and there may be lateralization on intertemporal choice preference. In addition, the active tDCS stimulation on DLPFC didn't change choice preference compared to sham stimulation, which was inconsistent with our hypothesis. Individual differences may eliminate the stimulation effect on the group level. The neurochemical concentrations and cortical thickness of individuals were related to tDCS effect [44]. Compared to HD-tDCS, conventional tDCS produced more diffuse current flows with shorter after-effect duration, which may have no regulation effect on choice [27,45].

The decision-makers had effect on choice preference of intertemporal choice. Individuals had self-other differences in mind and preferred SS when choosing for self rather than for strangers in experiments 1 and 2. The choice preference of intertemporal choice could be explained cognitive representation according to construal level theory [46-48]. The construal level states that individuals have different characteristics representations of event or object. When events are far away, high construal level is abstract and structured cognitive representations. In contrast, when events are close, low construal level is concrete and contextualized representations. According to the construal level theory, when subjects made choice for themselves, they were more likely to represent rewards with low construal level. In contrast, when making choice for strangers, they were more likely to represent rewards with high construal level. In addition, we found that cTBS effect on left DLPFC caused self-parents difference. When individual made choice for their intimates in normal state (i.e. without brain stimulation), there was no difference of choice preference [16]. The cTBS stimulation regulated the activity of left DLPFC and reduced the choice preference of SS reward, so it caused the difference between choosing for self and parents. In addition, medial prefrontal cortex was also involved in reward tasks and monetary decision [49]. The relative subjective value for self and others in intertemporal choice modulated the activity of dorsomedial prefrontal cortex [50].

In the present study, subjects preferred SS reward when they made a choice between an immediate reward and a delay reward. Because presence of immediate time increased greater delay discounting rate and impulsivity, individual preferred the immediate reward [51,52]. When immediate reward was absent (i.e. a shorter-delayed reward versus a longer-delayed reward), the LL reward was chosen more [20]. The immediate sign and certainty effect can explain the preference reversal. The absence of immediate time increased the risk and uncertainty to get rewards, because immediacy played a vital role in intertemporal choice with regard to whether or not the reward was certain [53]. The delay and risk were equivalent and interchangeable psychologically to influence choice preference [54]. In addition, time perception causally mediated the influence of delay on risk perception, longer objective delay caused higher levels of risk perception and delay discounting [55,56]. The greater the perceived temporal difference, the more likely individuals prefer SS reward [57]. When the monetary difference of two rewards options was small, subjects preferred SS reward. In contrast, when subjects faced options with large monetary difference, they preferred LL reward. This was consistent with previous studies which found the effect of profit size on choice preference. The larger the profit size between the two rewards options, the more the choice preference of LL reward was [25].

There were some limitations for this study. Firstly, the sample size was small and may cause that there was no tDCS stimulation effect on intertemporal choice preference. The sample size of experiment 1 and 2 was 27 and 36 separately. We use repeated-measure within factors ANOVA and post hoc analysis to get statistical power by G.Power. We calculate the effect size value 0.3984 according to partial η^2 0.137 of cTBS effect. When sample size is 27 in experiment 1, the statistical power is 0.9956. When sample size is 36 in experiment 2, the statistical power is 0.9997. The sample size was enough, but smaller sample size may have larger sampling error. We can increase the sample size or use between-subjects design to try to get more significant stimulation effect in the future. Secondly, subjects were directed to make choice for others by sample words cue. A concrete and true choice situation for others could arouse more realistic feeling [58]. Thirdly, the delay time (in two, four, and six weeks) and interval time of two rewards options (two and four weeks) were short, so individuals were inclined to choose SS reward in delayed-delayed time rewards because of lower risk and more certainty. It caused that there was no main effect of cTBS stimulation locations in delayed-delayed time rewards. In the future, we can delay time range and interval time to reduce the choice preference impact of short time. In addition, it is necessary for individuals to complete the fatigue questionnaire after tasks to ensure sober and serious state, such as checklist individual strength (CIS) questionnaire [59].

5. Conclusion

In sum, our study demonstrates that brain stimulation on the left DLPFC can effectively modulate intertemporal choice behavior. Specifically, cTBS stimulation over the left DLPFC reduced the choice preference of SS reward when individual faced immediate-delayed time rewards and make choice for themselves. And cTBS stimulation caused choice difference between choosing for themselves and parents. Time-types and monetary difference of rewards had effect on choice preference. These results provide behavior mechanism of brain stimulation on intertemporal choice.

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Ethics approval

The study was approved by the Ethics Committee of the University of Electronic Science and Technology of China. The study was performed in accordance with the ethical standards as the Declaration of Helsinki.

CRediT authorship contribution statement

Qiuzhu Zhang: Formal analysis, Data curation, Methodology, Writing - original draft. **Song Wang:** Data curation, Investigation. **Qian Zhu:** Data curation, Investigation. **Jing Yan:** Writing - review & editing. **Tingting Zhang:** Visualization, Writing - review & editing. **Junjun Zhang:** Supervision, Writing - review & editing. **Zhenlan Jin:** Supervision, Writing - review & editing. **Ling Li:** Methodology, Supervision, Writing - review & editing.

Conflict of interest

The authors have no conflicts of interest to declare.

Data availability

The data and materials are available and can be accessed on reasonable request.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.bbr.2022.114265.

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